CERTIFICATION OF AN AIRCRAFT ENGINE ON ETHANOL FUEL

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ABSTRACT

In order for an aircraft to engage in civil commercial operations, it must be licensed in the certified category. In the case of a new fuel both the engine and the airframe must undergo Federal Aviation Administration (FAA) tests. The document issued by the FAA for such approval is called a Supplemental Type Certificate(STC). No non-petroleum fuel had yet received an engine certification which applied to an entire series of engines.

An STC application was submitted to operate the Lycoming IO-540 series of aircraft engines on ethanol. The fuel used in this test was 200 proof ethanol denatured with regular unleaded gasoline.

In order to satisfy the FAA certification requirements a test plan was submitted which followed guidelines established for fuel approval testing. This plan was reviewed by the FAA and discussed during several meetings between the applicants, the Designated Engineering Representative (DER) and FAA personnel.

The applicants elected to use Federal Air Regulations(FAR) Part 33 for the basis of the certification process. This requires an engine endurance test consisting of a 150 hour run on a test stand according to a specified schedule of power settings and engine temperatures. Prior to the test the engine was disassembled and the components of the engine affected by fuel were inspected and measured. The engine was then assembled and installed on an approved, calibrated test stand. At that point it was run with a dynamometer to assure that it produced rated power.

The plan required that engine operating parameters be measured by calibrated equipment and recorded. At the completion of the endurance run, a power test and detonation test were performed. The engine was then again taken apart for inspection and measurement of all designated components. All FAA requirements for the 150 hour endurance test were met or exceeded.

A Supplemental Type Certificate was granted on March 12, 1990.

1. INTRODUCTION

Over the past 10 years this project has been working toward the development of ethanol as an aviation fuel. The initial motivation was the possibility of fuel supply interruptions as a result of political instability in the Middle East. Extensive flight testing and demonstration flying was performed. Six aircraft were modified and flown on ethanol, accumulating over 1300 hours of flying time. In the course of this development and testing it was found that ethanol, in addition to being renewable and domestically available, costs less per mile as a fuel than aviation gasoline (avgas), produces more power, burns cooler and resists detonation. These properties make ethanol the best candidate to replace avgas. Thus it was decided to obtain a Supplemental Type Certificate for the use of ethanol as an aviation fuel.

The certification of a fuel begins with the submission of an operational plan to the FAA. Once this is accepted, an authorization to inspect the engine for conformity and condition is obtained. On completion of this inspection, the engine is mounted on a test stand and run on a dynamometer to determine if the full rated power of the engine is developed. If the results of this test are within acceptable limits, the engine is then run for 150 hours on the test stand according to a specified plan. On completion of this endurance run, the engine is again tested for power development and a detonation test is performed. The engine is then disassembled and inspected for condition and wear. The measurement, before and after the endurance test, of fuel affected components provides a quantification of the wear experienced during the run. Throughout the program, the fuel used is tested for conformity while samples of the engine oil are tested for concentrations of wear metals.

The endurance test is designed by the FAA to exceed the demands on an engine occuring during use between overhauls. The time between overhaul (TBO) specified by the manufacturer for this engine is 2000 hours.

The certification testing was conducted using an Avco Lycoming AEIO-540-D4A5, a 6-cylinder, parallel valve, fuel injected engine which develops 260 horsepower at 2700 RPM.

2. ENGINE MODIFICATION AND CONFORMITY INSPECTION

The engine used in this test is the powerplant for a SIAI Marchetti SF-260, which uses a Hartzell HC-C2YKBF constant speed propellor.

The fuel injection system, a Bendix RSA-5AD1, was modified to increase the fuel/air ratio to permit running on ethanol. The lower idle valves and the mixture control valves were replaced to allow the appropriate fuel/air ratio for ethanol. Injector nozzles with larger orifices were installed allowing an increase of fuel flow at the same pressure drop.

To begin the certification process it was necessary to obtain a Type Inspection Authorization (TIA) from the FAA. The TIA called for an inspector from the FAA to:

1. Obtain a completed Statement of Conformity to assure that the engine configuration matched the Lycoming AEIO-540-D4A5 overhaul manual and the engineering drawing submitted in the STC application.

2. Verify and record on appropriate FAA forms the Conformity Inspection Record, the engine model and serial number, engine total time and maintenance history.

3. Witness removal, inspection and measurement of cylinders, valves, pistons and rings. Record by sketch, measurement or photographs the significant conditions on any of these components:
   a. Piston Diameter, Top and Bottom
   b. Cylinder Bore Diameter
   c. Cylinder Taper and Out-of-Round
   d. Valves and valve guides.

4. Obtain a completed Statement of Conformity from the applicant that the fuel injection system and the fuel injector nozzles match the appropriate part number configuration.

5. Witness and record the results of the flow check of the fuel injection system and the fuel injector nozzles per the manufacturers established test procedures.

The measurement of the designated components before the endurance test allows quantification of the wear experienced during the run.

The conformity inspection was performed as required. The engine was then assembled and installed on on the test stand for the 150 hour endurance test.

3. PRE-ENDURANCE POWER TEST

Prior to the endurance test, to insure that the engine develops rated power on ethanol, power output was determined using a dynamometer. The following data established the required performance (test cell: Clayton Water Dynamometer C-1700-500).

PERFORMANCE DATA

TEST RPM	2700
TEST TORQUE	465 FT-LB
DRY BULB TEMP	91 DEG. F
WET BULB TEMP	83 DEG. F
HUMIDITY	75%
BAROMETRIC PRESSURE	29.0 IN. HG.

The psychrometric chart in Airmotive Engineering Report 8807-2 provides the following correction:

HUMIDITY/TEMP. 75%/91 DEG. F.
VAPOR PRESSURE CORRECTION (IN.HG.):
0.92

Friction horsepower for the Lycoming 540 series is 48 HP.

Corrected Brake Horsepower is given by the following formula (in "basic notation"):

CBHP= ((OBPH+FHP)* 29.92/PO*((460+TO)/ 520)^.5-FHP
where :
CBHP=corrected brake horsepower
OBHP=observed brake horsepower=torque*RPM/5252
FHP=friction horsepower
TO=observed air inlet temperature (deg. F.)
PO=observed dry air inlet pressure (in. Hg.)

The engine produced 266 H.P. which is greater than rated power. A study of the test cell showed that the air inlet system was choking the injector, this inlet line having been designed for the 0-470 Lycoming engines. The inlet system was changed to eliminate the necked down area, but since the FAA criteria was met and exceeded, no further power test was performed until the completion of the endurance test.

4. ENDURANCE TEST

After completion of the power test, the dynamometer was removed and the Hartzell propellor was installed. The following schedule was followed throughout the endurance test:

Endurance test sequence

Legend:

TO= Take off power
MRC= Maximum recommended cruise power
MCP= Maximum continuous power
MBEC= Maximum best economy cruise power
TOS= Take off speed (RPM)
MCS= Maximum continuous speed (RPM)

BLOCK TIME	CYCLE TIME	POWER	SPECIAL NOTES
BLOCK 1 30 HOURS	5 MIN. 5 MIN.	TO & TOS MBEC OR MRC	NOTE 1
BLOCK 2 20 HOURS	1 1/2 HOURS 1/2 HOUR	MCP & MCS 75%MCP 91%MCS	NOTE 2
BLOCK 3 20 HOURS	1 1/2 HOUR 1/2 HOUR	MCP & MCS 70% MCP 89% MCS	NOTE 2
BLOCK 4 20 HOURS	1 1/2 HOURS 1/2 HOUR	MCP & MCS 65% MCP 87% MCS	NOTE 2
BLOCK 5 20 HOURS	1 1/2 HOURS 1/2 HOUR	MCP & MCS 60% MCP 84.5% MCS	NOTE 2
BLOCK 6 20 HOURS	1 1/2 HOUR 1/2 HOUR	MCP & MCS 50% MCP 79.5% MCS	NOTE 2
BLOCK 7 20 HOURS	2 1/2 HOURS 2 1/2 HOUR	MCP & MCS MBEC OR MRC	NOTE 2

NOTES:
1. One cylinder must be at limit temperature and all others within 50 degrees of limit. Oil temperature must be within +/- 10 degrees of limit.
2. Conditions of note 1 apply for at least 35 hours of MCP.

As prescribed by FAR 39.49, all instruments used to record test data were calibrated in accordance with the guidelines established by the FAA. These instruments were:

1. Tachometer
2. Manifold Pressure Gage
3. Cylinder Head Temperature Measuring System
4. Exhaust Gas Temperature Measuring System
5. Fuel Flow Meter
6. Fuel Pressure Meter
7. Oil Temperature Gage
8. Oil Pressure Gage

The endurance run was begun on November 13, 1989 and completed on December 13, 1989. The actual temperatures the engine was subjected to during the test were more severe than specified by the FAA plan. Despite this, the oil pressures throughout the test remained greater than 70 psi..

5. POST-ENDURANCE PERFORMANCE AND DETONATION TEST

The performance and detonation tests following the endurance run were performed while the engine was operated on a Clayton Dynamometer. Using the same procedure as in the pre-endurance performance test, a corrected brake horsepower of 285 was measured. This measurement was considerably higher than the pre-endurance performance measurement despite the severity of the endurance test. This result is attributed to the adjustment of the air inlet system noted in the discussion of the pre-endurance performance result.

The detonation testing was conducted with the use of a Sperry Engine Analyzer System and according to the following protocol:

A. Warm up

B. Stabilize at power condition as follow:

(1) 2700 RPM & MAX. MAN. PRES.
(2) 2400 RPM & 24.5 IN. MAN. PRES.
(3) 2350 RPM & 21.5 IN. MAN. PRESS.
(4) 2281 RPM & 22.2 IN. MAN. PRESS.
(5) 2146 RPM & 20.8 IN. MAN. PRESS.

At each power condition the cylinder head was maintained at 500 deg. F on at least one cylinder and 450 deg. F minimum on the other three. The oil temperature was maintained between 235 and 255 deg. F.

C. The mixture was leaned slowly until just above cut-off. The engine was stabilized at the lean setting.

D. Mixture was enriched to best power, and then enriched as much as possible.

E. Data was recorded at each power setting and fuel flow. The Sperry analyzer was checked to monitor pre-ignition or detonation.

F. Change timing and repeat testing

Throughout this test an attempt was made to produce pre-ignition and/or detonation. Cylinder head temperatures were as high as 550 deg. F. and for most of the test, oil temperatures were above 235 deg. F.

All cylinders were sampled to verify that no pre-ignition or detonation existed for the test condition.

Timing was changed to 30 degrees before top dead center and all of the test points repeated .

The finding of the detonation tests were reported as follows:

"No pre-ignition or detonation could be induced for any test condition. The engine would smoothly transition and stabilize after the mixture changes were made, even to just above cut-off. For many of the test points, as the mixture was leaned, the cylinder head temperature came down from the 500 degree F. values."

The DER concluded that the use of ethanol fuel extends the limits of detonation over avgas.

6. POST-ENDURANCE TEST ENGINE INSPECTION

The engine was removed from the test stand and engine disassembly was conducted under FAA surveillance. A detailed inspection following FAA guidelines produced the following results:

1. Cylinders: The cylinders exhibited the characteristic evidence of extended operation at very high temperatures. All cylinder bores were within the overhaul service limits established in Lycoming Overhaul Manual 60294-7. In fact, the maximum wear was at the ring step of cylinder #1, of .001 inch. The wear measurements on all other cylinders were less than .0025 at the step, and .001 or less in other locations. The barrels were smooth and showed no evidence of distress.

2. Valve Seats: All valve seat faces were smooth, and showed no evidence of wear, re-grinding would render the seats ready for operation.

3. Valve Guides: Valve guide wear was almost nonexistent for this engine. The guides measured .500-.501 after the test with pre-test measurements of .49865. The Lycoming table of limits states:

"1/2 inch diameter exhaust valves may have exhaust valve guides that are .003 inches over the maximum inside diameter anytime up to 300 hours of service. After 300 hours of service, inside diameter of exhaust valve guide may increase .001 inch during each 100 hours of operation up to the recommended overhaul time for the engine, or not to exceed .015 inch over the basic inner diameter. "

The intake guide wear was even less than the exhaust guide wear. The concern that alcohol fuel might impair the guide/valve lubrication was unfounded, and in fact wear was extremely low. The build up of lead salts usually found with the use of aviation gasoline in Lycoming exhaust valve guides was not found in this test.

4. Valves: The maximum wear on any of the stems of the 12 valves was .0003 inches. All valves were still within new limits. The limits for the intake valves are .4022 - .4030 with .4010 as a service limit. All intake valves were .4025 minimum. The limits for the exhaust valve stems is .4935 - .4945 with .4915 as the service limit. The valve stems measured .4940 minimum.

5. Pistons and rings: All six pistons showed very low wear for the temperatures this engine was operated at. There was some metal from the tappets imbedded in the lower skirt, but the metal did not seem to detract from the performance of the piston.

The ring side clearance was still within service limits of .008 loose. As in the other components, the wear that was found was very consistent from cylinder to cylinder. The piston domes were very clean, and the edges of the dome were still sharp, with no significant wear pattern. As would be expected with ethanol fuel, there were no significant deposits on the piston or other parts of the combustion chamber.

The piston rings exhibited remarkable wear characteristics. The top ring was barely worn across the face of the ring, and the second compression ring was worn only about 2/3 of the way across. The oil rings were broken in, but not worn significantly beyond that point.

The oil consumption throughout the test was almost nil.

The temperatures required during the test are much greater than those at which the engine is operated normally. In the section on operating instructions, the Lycoming Operator's Manual specifies the desired oil temperature as 180 degrees F. It also recommends to maintain the CHT below 400 degrees F. for economy cruise and below 435 degrees F. during high performance cruise operations. The maximum allowable CHT is given as 500 degrees F.

The oil temperature was maintained between 230 and 245 degrees F. during the entire test as specified by FAA requirements. The test requires the CHT of at least one cylinder to be at 500 degrees F. and all others within 50 degrees of this limit for 65 of the 150 hours of the test. As severe as this requirement is, one cylinder was maintained at or above the 500 degree level throughout the 150 hours as a result of a misunderstanding between the DER and operators of the test stand. Despite the additional strain on the engine, the wear measured after the endurance test was much less than limits sets by the FAA.

The engineers involved in the detonation testing and the post-endurance engine inspection estimated that the use of ethanol as a fuel would extend the engine TBO by at least 50%.

7. CHARACTERIZATION OF PROPERTIES OF DENATURED 200 PROOF ETHANOL

In order to obtain independent, authoritative characterizations of certain key properties of the fuel being tested, the Fuels and Lubricants Research Division of Southwest Research Institute (SWRI) was engaged to conduct tests and data analysis on E-95. A brief summary of their findings is given:

1. Lubricity: Using a widely accepted method known as the Ball-on-Ring Lubricity Evaluator (BORLE), SWRI found that E-95 has about the same lubricity as gasoline and is within the range considered acceptable for aeronautical systems.

2. Luminosity: Flame luminosity was measured by a United Detector Technology Model 40X Optimeter System. SWRI's test found that the luminosity of E-95 was 60% that of gasoline. This is a level which provides adequate visibility to insure safety.

3. The FAA required periodic fuel and oil analysis during the endurance test. These tests were also performed by SWRI. All of these tests results were satisfactory.

8. ECONOMICS

Assuming current prices for engine overhaul and average yearly usage of 800 hours, annual saving resulting from a 50% extension of engine life would be approximately $2,000.00 per engine.

In extensive data from flight tests using a SIAI Marchetti SF-260 with the Lycoming IO-540 engine, it was estimated that the cost on ethanol was 4 cents per mile less than avgas. Using this figure and assuming an average annual usage, the saving per year for fuel alone would be approximately $4,000.00 per engine.

10. CONCLUSION

All of the test criteria established by the FAA were satisfied or exceeded during the certification process. The Supplemental Type Certificate was awarded on March 12, 1990.

This certification should open the door to the commercialization of ethanol as an aviation fuel. The results of this test and previous flight test data have demonstrated that ethanol is a low cost, superior performing, reliable aviation fuel.

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