A99H Durability Testing

Rev. 2.3

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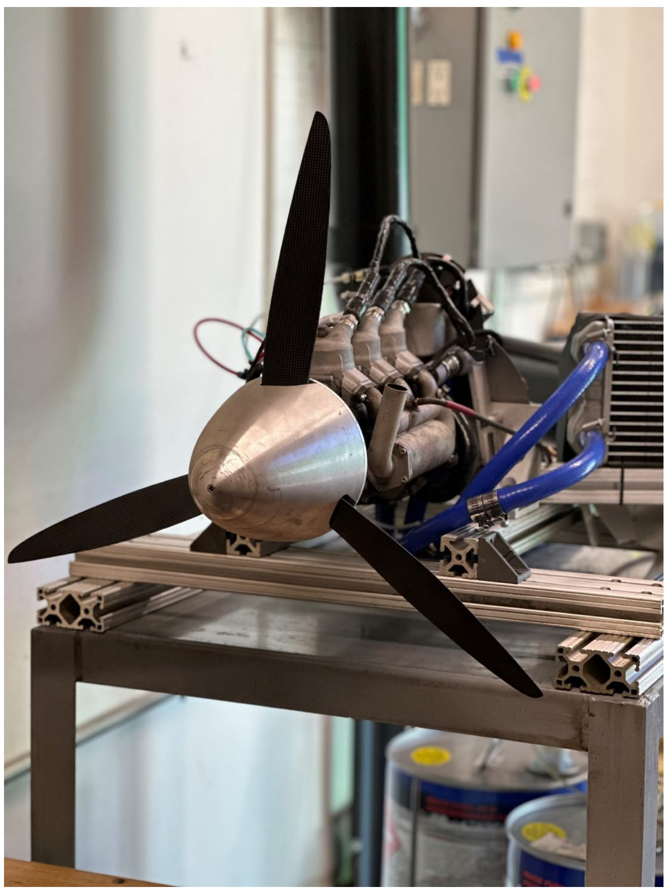
Executive Summary

Propulsion systems on Unmanned Aerial Vehicles (UAVs) need to provide reliable, continuous power. Although engines are the most mission-critical component on a UAV, they are also known to be the least reliable. In response to this trend, the Cobra Aero team tested the 101cc fuel-injected A99H engine to demonstrate endurance using a high-stress run profile. After a 150-hour test period, the A99H engine successfully completed the test with no overhaul and no perceptible power denigration.

This report documents the test background, setup, criteria and results used to qualify the A99H engine.



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I. INTRODUCTION

A. The Engine

The A99H engine is a liquid-cooled, 2-stroke, three-cylinder reciprocating engine with a displacement of 101.4 cubic centimeters (cc). The engine utilizes an Electronic Fuel Injection (EFI) system provided by Power4Flight to regulate ignition and fuel delivery. The engine runs on JP-5 Kerosene at a 50:1 oil premix ratio. Power output with a quiet exhaust is rated at 6.0 kW (8.0 hp) with a dry weight of 7.5 kg (16.5 lbs.). The engine is designed for a direct-drive propeller in pusher or tractor configuration. It also drives a generator to provide up to 400 W continuous power (600 W intermittent) to the user's aircraft electrical busses.

B. Test Summary

The A99H was set up on a static propeller test stand and run per a specified max temperature and speed profile for 19 separate test segments until the test period of 150 hours was complete. Some days, a single segment was run, while on others the engine was run for three continuous segments (or 22.5 hours). Component hours, engine telemetry, environmental conditions, fuel consumption and any other noteworthy events were recorded. Noninvasive inspections were conducted at the end of each daily test cycle against a checklist, and any anomalies were noted and addressed. The same engine serial number was used for the duration of the test. At the end of the test, the engine was removed from the stand and a full teardown was conducted on the top-end and exhaust.

II. TEST OBJECTIVES

A. Top level goals.

Design of the test procedure for the A99H was framed by the following objectives:

1. Determine upper limits of stress under which the engine can operate in a specified period of time and identify items that need improvement
2. Provide customers with endurance data to meet engine selection requirements
3. Increase airworthiness confidence by qualifying engine durability against known FAA standards
4. Collect data to be used in determining product maintenance schedules and, ultimately, hourly operating cost with respect to product life cycle.

Section III provides a detailed description of the test setup. In Section IV.H, results are evaluated against these objectives.

B. Why an endurance test?

Endurance and durability both play significant roles in engine reliability. For the purpose of this study, engine longevity was of primary concern because regardless of what conditions an engine may operate in, time is always the enemy and is the variable that TBOs and maintenance schedules are measured against. Other aspects such as resistance to shock or harsh environmental exposure are also life-limiting but it would not be practical to test such impacts until the engine demonstrates that it can withstand its own wear and tear.

C. Airworthiness Standards

At the time of writing, there are no official airworthiness standards pertaining to engines specific to unmanned aircraft. The Federal Aviation Regulation (FAR), Part 33, while not intended for unmanned applications, is the closest set of regulations related to aircraft engine durability. Subpart D, relating to reciprocating aircraft engines, is commonly used by UAV engine manufacturers as a “standard” to compare against. A detailed wording of the Part is not included in this report, but the key points are summarized below along with notes describing which details are included and excluded from the A99H test objectives.

33.41 Applicability – Included. This section clarifies that subpart relates to block tests and inspections for reciprocating aircraft engines.

33.42 General – Included. Requires that anything having an adjustment, calibration, setting or configuration independent of test stand installation be established (with noted limits) and recorded.

33.43 Vibration Test – Excluded. Outlines tests to compare vibration characteristics in the crankshaft, due to torsion and bending or the stress resulting from peak amplitude, to the endurance stress limit of the crank shaft material. Vibration characteristics and peak stresses were not recorded during this test, however, these data will be collected during a future FAR33 test effort for the purpose of better understanding fatigue life of the crankshaft. Note that the digital modal analysis we conducted as part of our Computer Aided Engineering (CAE) effort showed that vibration induced by the running engine were at frequencies far below any natural frequencies of the crank train.

33.45 Calibration Tests – Included. Requires baseline calibration tests to establish the power characteristics and test conditions of the test engine. The power characteristics of the test engine were established before the endurance test using shaft power output and maximum RPM as metrics. The requirement allows the final portion of the endurance test to be used as part of the data set to determine power degradation.

33.47 Detonation Test - Included. Requires that the engine can operate throughout its range without detonation (i.e. undesired ignition of end-gas after the primary combustion event). The engine type has been tested early in its development for detonation. The relatively small bore diameter (39mm) allows rapid advancement of the flame front across the chamber, and thus does not provide much dwell time for the end-gasses to auto ignite. No signs of detonation were visible in the combustion chamber upon inspection at any time during the test.

33.49 Endurance Test

a) General – Majority included. Specifies endurance length, order of test intervals, speed variability, temperature set points, propeller thrust loads and accessory loads. The engine ran for the specified endurance length and RPMs were maintained within 3% of their rated speed except the maximum continuous power. For the test engine, such a power setting occurs at WOT, so the throttle can open no more to correct for deviation from the rated max continuous power. Run order was not defined by an Administrator. See Section III.E for run order. A limiting temperature as measured at the cylinder head was established and maintained throughout the test. A propeller was fitted which applied thrust loads to the engine, although these loads were not the maximum thrust loads that the engine was designed to resist. A direct-driven generator was installed during the test, but the generator was not loaded.

b) Unsupercharged engines – Included. This section outlines the individual run phases in the endurance program, and includes 6 runs totaling 20 hours each plus one run lasting 30 hours. The runs are divided into various intervals of maximum continuous power, rated takeoff power, and lower specified power settings. In the case of the A99H maximum continuous power and rated takeoff power both occur at the same engine speed. The runs were not completed in uninterrupted 20 or 30 hour intervals but were further divided into shorter but more numerous intervals such that the speed transitions intended by 33.49 (b) and the total hourly requirements of each phase were satisfied.

(c) – (e) Calls out endurance phases for different engine classes; not applicable.

33.51 Operation Test – Excluded. This test did not receive Administrator involvement and thus did not undergo a formal Operation Test. However, the example items mentioned in this section (e.g. starting, idling, acceleration) are characterized early in the engine development process and checked during individual engine acceptance procedures.

33.53 Engine System and component tests – Excluded. Requires additional testing for those components and systems that were not verified adequately by the endurance test to demonstrate functionality in all declared operating and environmental conditions, including temperatures at the rated temperature limit of the component. An example component would be the integrated ECU / fuel pump assembly, which was mounted on the test stand in such a way that it was not exposed to the same vibration or heat as it might on an airframe. While the A99H components were not subjected to further durability or environmental tests, the same components had been tested through extensive and high-stress use on other systems in lab and field environments.

33.55 Teardown inspection – Majority included. See Section 4-D. This section requires the engine disassembled and each component checked that it maintains settings and functioning characteristics within the limits established in Section 33.42.

33.57 General conduct of block tests – Included. This requirement states that a) separate engines may be used for the various tests in this subpart; b) minor repairs are permitted without requiring retest; and c) all test facilities and personnel must be provided by the applicant. Only one engine serial number was used for the duration of the test.

D. Additions to FAR Part 33

With respect to the test objectives, data was gathered not only to establish airworthiness confidence but also to support future product development efforts and test procedure improvements.

Exhaust Design – The exhaust is the focus of substantial engineering effort because of its impact on engine efficiency and noise. It is also one of the highest risks for test failure when one considers its exposure to temperature, pressure and vibration stresses.

Fuel Flow – Because fuel starvation is the leading cause of engine failure in UAVs, fuel consumption and the ability to measure it are subject to continuous calibration and scrutiny. The fuel-used calculation of the ECU can be reported to the operator on the ground and used in determining the range of a given mission. Although other methods are recommended for maintaining a safe fuel reserve margin, it helps if this reported fuel-used figure is as accurate as possible.

Noise – Knowing the noise signature of the test itself is useful in determining the feasibility of future tests. It is also helpful for making relative comparisons between different engine configurations, such as exhaust or propeller changes.

III. Test Setup

A. Engine Configuration

The engine selected for the endurance test was a customer-owned A99H that had a moderate amount of running hours already logged (approximately 60). The engine and its installed components are collectively serialized as a Build according to the crank case serial number, EXP6. Specifications, adjustments and settings are listed below.

Cylinder	Cobra AERO ECA90060HF V5.0
Case	Cobra AERO ECA90007
Crankshaft	Cobra AERO EAA90001 Tri-Spline
Piston	Cobra AERO ECAX0019
Spark Plug	NGK-R PMR9B
Reeds	Cobra AERO RCAX0004 – Carbon
Exhaust	Cobra AERO XAA90001 Log-Style Manifold
Intake Manifold	Cobra AERO A99 Log-Style with 19mm Throttle body
Throttle Servo	Cobra AERO ECAX0058P - Futaba BLS173SV
Injector	Cobra AERO ECAX0060 - KEIHIN 16450-K25-901
Ignition	Cobra AERO ECAX0164 (CE432-01A) (3 units)
CHT Sensor	Cobra AERO ECAX0106 (CE214B)
MAT Sensor	Cobra AERO ECAX0109 (CE215-001B)
CHT Max	160°C at WOT

Propeller	Mejzlik 24x12 3-blade in pusher (CW) rotation
Generator	Not operational during this test
ECU	Power4Flight IntelliJect 3-cyl (ECA90016)
Fuel Pump	Cobra AERO ECA90122 - CE464-008 (Type E – 120g/min)

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All fasteners were torqued per current build instructions and torque-striped with the exception of the spinner screw, which required removal at the end of every cycle to inspect the prop screws inside.

B. Test Stand

The engine was mounted to the test stand via a Rev 1.0 focal engine mount. All four isolators had a Shore A durometer of 50. The crankshaft was horizontal with the cylinders perpendicular to the ground plane. The propeller spun inside a steel guard allowing starter access to the spinner. See Figure 1.

The testing took place in a purpose-built test chamber that enabled 24/7 remote testing. The chamber contained two separate rooms: One for the running engine, and the other for control and data acquisition equipment. The chamber was outfitted with wireless communications and a wireless camera such that remote operation and monitoring could be executed easily.

C. Fuel

Engine fuel was USN supplied JP-5 premixed with Amsoil Sabre 2-stroke oil at a 50:1 ratio. Fuel was fed into a 10-micron fuel filter which in turn was fed to the fuel pump attached to the ECU. The fuel pump, which duty-cycles based on pressure feedback from the ECU, fed to the fuel rail on the engine in a dead-head configuration.

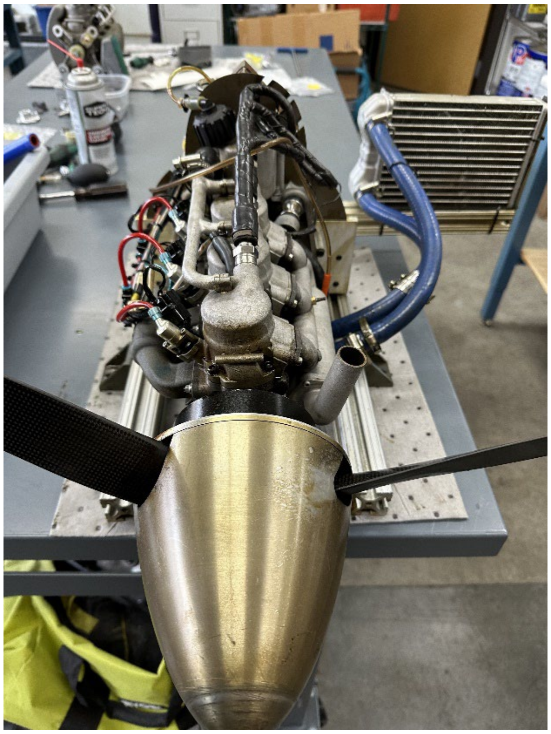

Figure 1: Front of engine test stand

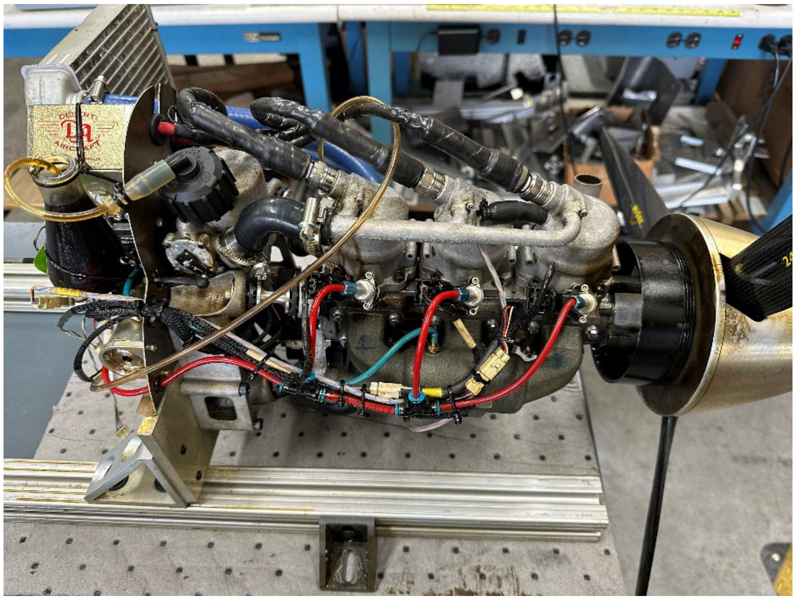

Figure 2: Side of engine stand

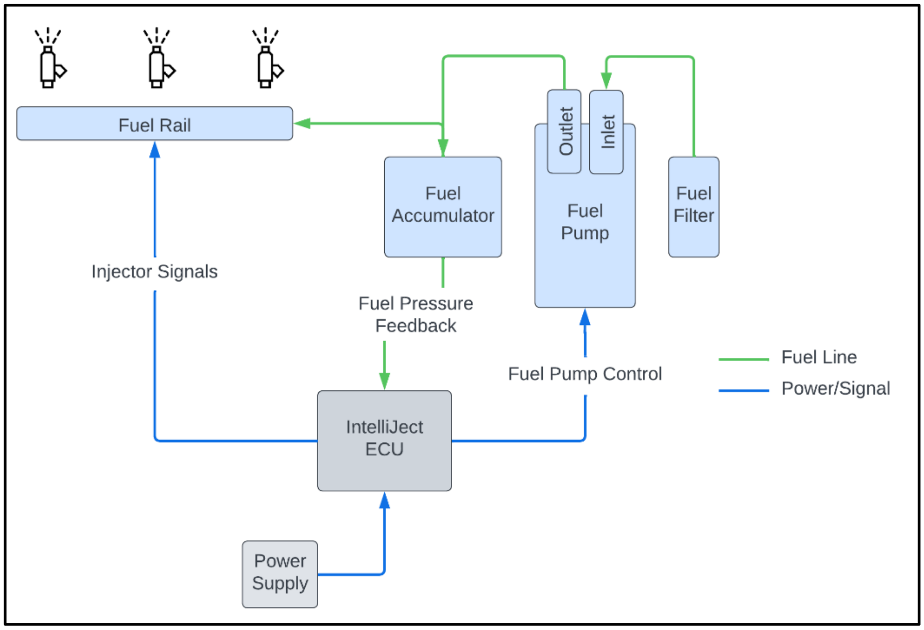

Figure 3: Fuel system schematic.

D. Test conditions

Cycle 1 began on August 22, 2023 and ended on November 8, 2023. No weather phenomena were observed worthy of invalidating any portion of the test.

E. 33.49 (b) Run Profiles

The endurance runs are defined in FAR 33.49 (b) as follows.

Run 1: 30 hour run consisting of alternate periods of 5 minutes at rated takeoff power with takeoff speed, and 5 minutes at maximum best economy cruising power.

Runs 2 – 6: 20 hour runs each consisting of alternate periods of 1-1/2 hours at rated maximum power with maximum continuous speed and ½ hour at 91% maximum continuous speed (Run 2); 89% maximum continuous speed (Run 3); 87% maximum continuous speed (Run 4); 84.5% maximum continuous speed (Run 5); and 79.5% maximum continuous speed (Run 6).

Run 7: 20 hour run consisting of alternate periods of 2-1/2 hours at maximum continuous speed, and 2-1/2 hours at maximum best economy cruising power.

For the A99H, the following speeds were selected for each speed or power setting called out in 33.49 (b).

Condition	Engine Speed
Rated Takeoff Speed	6150 RPM
Maximum Continuous Speed (MCNe)	6150 RPM
Cruise	5000 RPM
Idle	3000 RPM
87% MCNe	5350 RPM
85% MCNe	5230 RPM
81% MCNe	4980 RPM
76% MCNe	4675 RPM

Table 1: A99H profile Reference Speeds

F. AMRDEC Adaptation

To make the endurance intervals manageable in a single workday, the run intervals defined in 33.49 (b) were reorganized into daily run profiles by the US Army AMRDEC (Aviation & Missile Research Development & Engineering Center). This allows one to operate the engine through all the power settings specified in 33.49 (b) in a 7.5-hour cycle, which can be accomplished in one working day including additional time for setup and inspection. A total of 20 cycles is required to reach the full 150-hour requirement, so each of the runs defined in 33.49 (b) is truncated to 1/20th of the interval specified. The accumulated time the engine spends at each power setting is the same as the original profile in 33.49 (b). The 5-minute transitions in Run 1 remain at 5 minutes each (rather than being scaled down) in order to preserve the objective of testing engine transients.

5-minute warm-up and cool-down periods were added at idle (3000 RPM) at the beginning and end of each cycle.

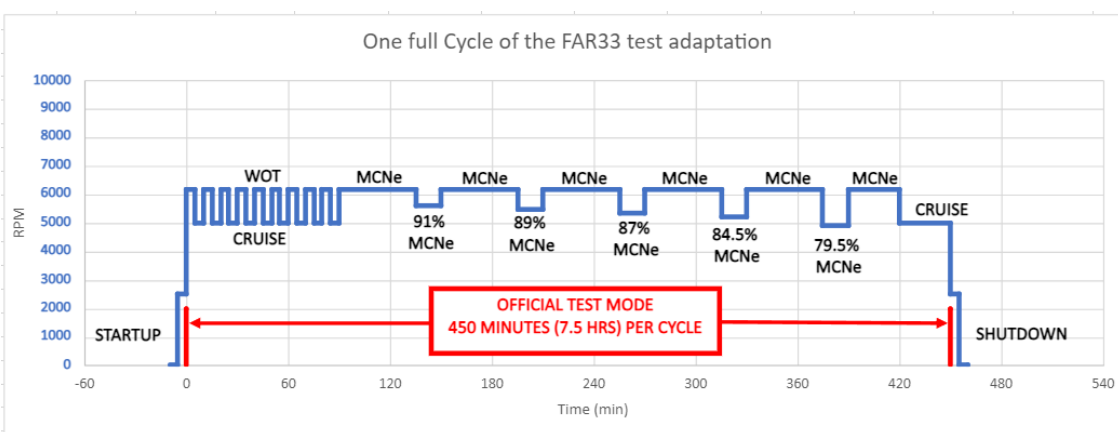

Figure 4. 7.5-hour AMRDEC profile.

G. Engine Control

The test engine maintained the speed references in Table 1 via RPM control feedback which adjusts throttle servo position as required for a particular speed target. The commanded RPMs were generated on an operator's PC which was connected to the ECU via CAN. Once the AMRDEC profile and associated speed references were decided, an RPM profile was loaded and executed so that the PC could control engine RPM throughout each test segment.

For WOT cases (i.e. takeoff speed and MCNe), an arbitrary RPM was selected that was higher than the engine could achieve, thus keeping the throttle commanded to 100%.

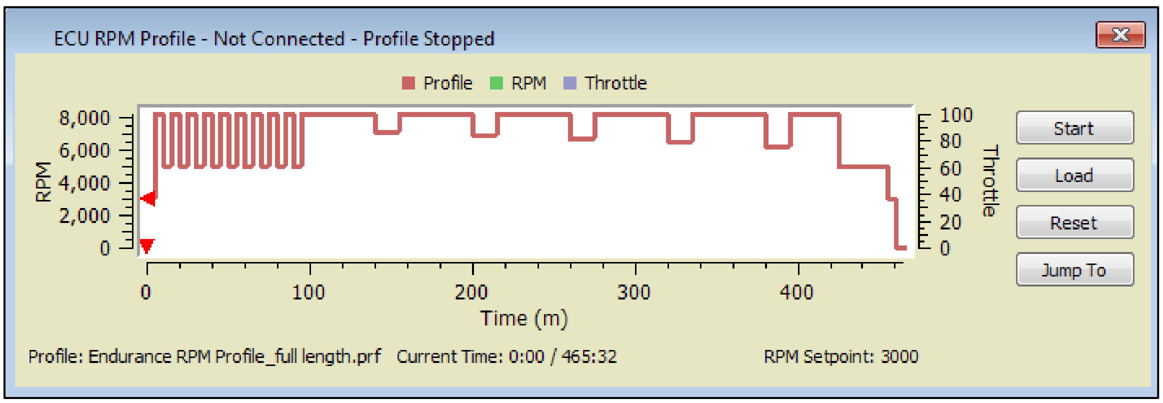

Figure 5: Sample RPM profile for one cycle as shown in IntelliJect Display software.

H. Overall test plan

The test was conducted with the goal of running one profile each day, start to finish. The daily process of testing the engine consisted of the following:

1. Load RPM profile and establish communications with the ECU.
2. Check all hardware and electrical connections per the checklist.
3. Set a throttle or RPM command.
4. Start engine on gasoline and note the time. Switch over to JP-5 after 3 min of warmup. Coolant setpoint was 140C.
5. On shutdown, note the time and conduct post-run inspection per the checklist.
6. Address any repairs or replacements as required.
7. Fill the fuel tank and reset ECU fuel-used value.

IV. Test Results

The A99H Completed 20.5 cycles (7.5 hour test cycle) without major failure. All major components and systems were in good condition at the end of the test. This includes the crank train, cylinders, mount, and electronics (note: Radiator was mounted next to the engine on the test stand. Exact location of this component is airframe dependent).

One key desired outcome of this FAR33 test was to identify weaknesses and provide recommendations for design and assembly improvements. Below are detailed descriptions of the improvements that were identified and implemented after this test:

A. Leaks

Several sealing improvements were identified over the course of this test. Exhaust and cooling leaks were both observed. Exhaust leaks occurred mainly at the sealing face between the cylinders and the exhaust manifold, and these will be controlled in future iterations with improvements in sealing surface flatness and with improved gasket designs and materials. Coolant leaks occurred in several locations. Leakage at the outlet manifold (see Figure 6) will be eliminated by using a larger O-ring, and by redesigning the connection feature between the cylinder and the manifold.

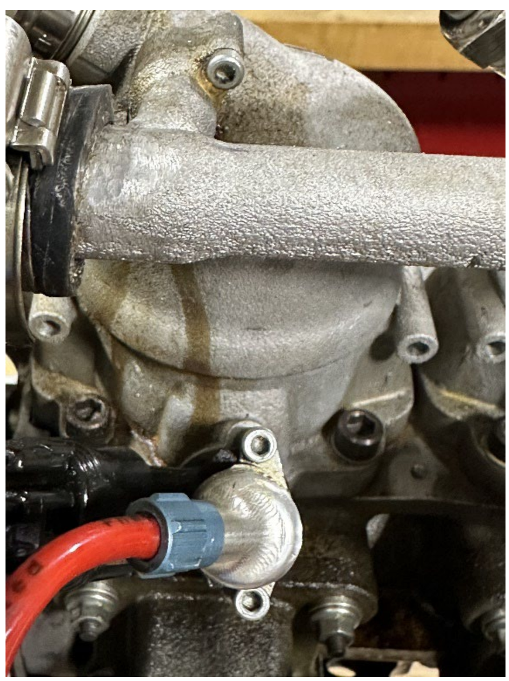

Figure 6. Observed coolant leak between head and coolant manifold.

Coolant leakage was also observed at the cylinder base gasket, and this will be fixed with the addition of sealant around the portion of the gasket that seals the coolant passage between the cylinder and the case.

B. Coolant Pump Improvements

During the course of the test we observed two coolant pump issues. Early in the test, we failed a pump belt, and we observed pump internals coming loose. Figures 7 and 8 illustrate the updates to the system that were made in accordance with these observations.

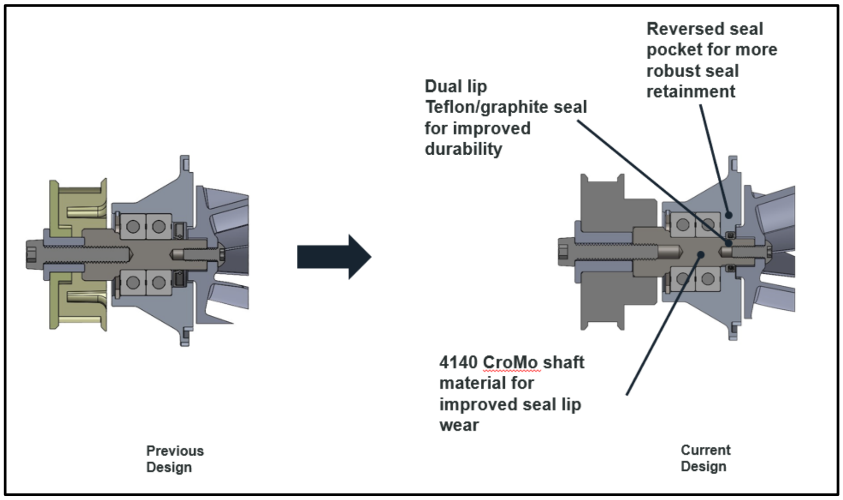

Figure 7. Internal coolant pump updates.

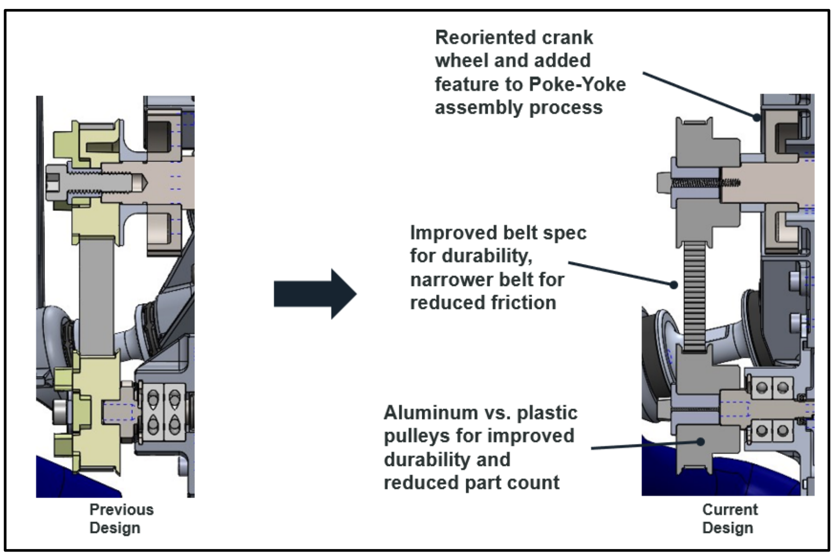

Figure 8. Coolant pump drive updates.

C. Coolant Proportional Valve

Early in the test sequence it was noted that the coolant proportional valve exhibited significant internal leakage, and as a result, the engine overcooled at low loads. This was not deemed significant for the test since the majority of the FAR33 cycle is conducted at high loads. Improvements were made, however, to enable more robust operation under conditions where the engine was required to operate at the temperature setpoint for good heavy fuel combustion while operating at low load. A descending aircraft is one such condition. Figure 9 illustrates this update:

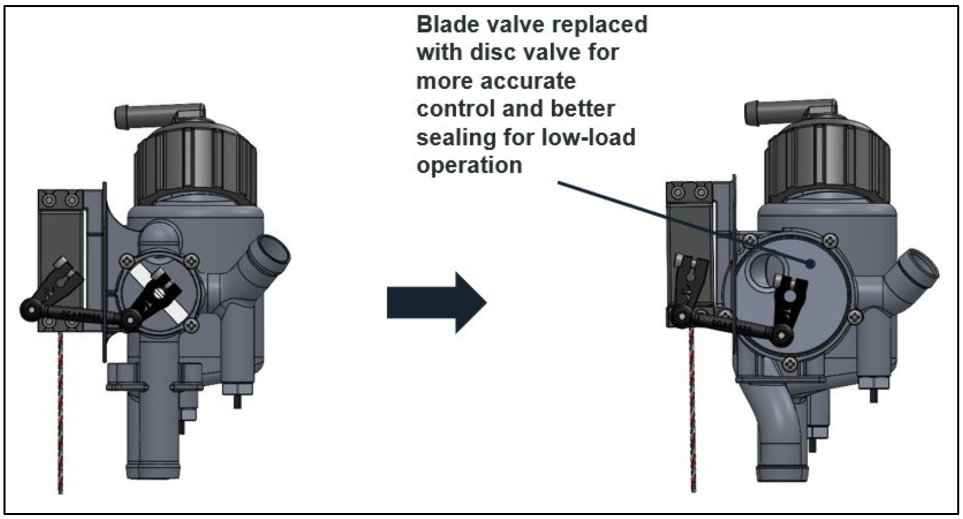

Figure 9. Coolant Proportional Valve update.

D. Teardown Results

A careful teardown analysis can provide a rich data set for understanding key factors affecting an engine's durability. In this case, there were three main areas of interest: 1) deposit buildup. Historically, heavy fuel engines exhibit large amounts of carbon buildup. This is often the deciding factor in determining TBO, 2) Piston and cylinder wear (including ring sticking), and 3) Main bearing and seal wear. Figure 10 shows the engine laid out after teardown:

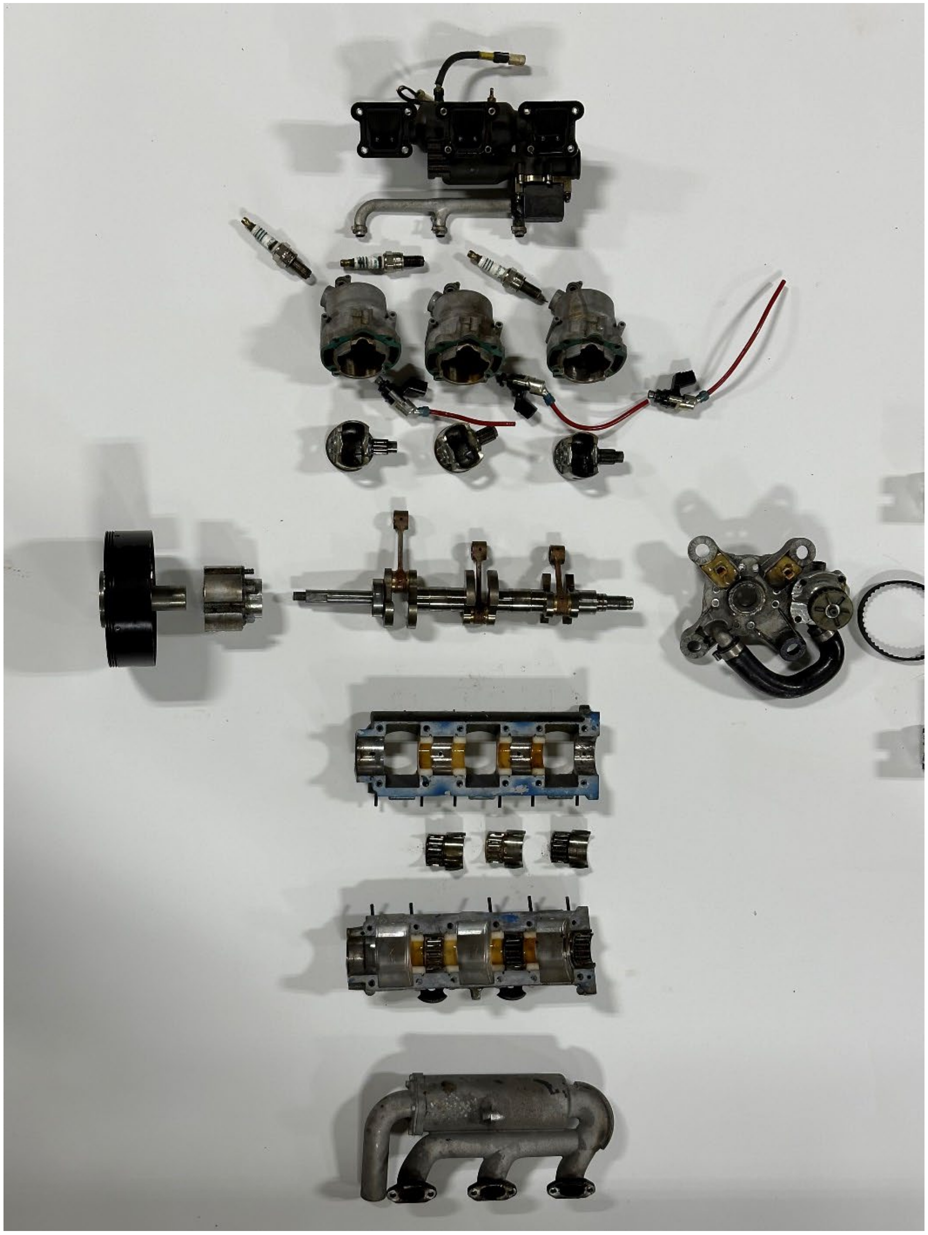

Figure 10. Post FAR33 teardown.

Deposit buildup was investigated in three locations: the combustion chamber, the spark plug, and the exhaust port. No significant buildup was noted in any of these locations. Only Cylinder #1 showed any significant Carbon level, and this was attributed to a partially blocked coolant passage. Figure 11 shows examples of the spark plugs, combustion chambers, exhaust ports, and piston crown.

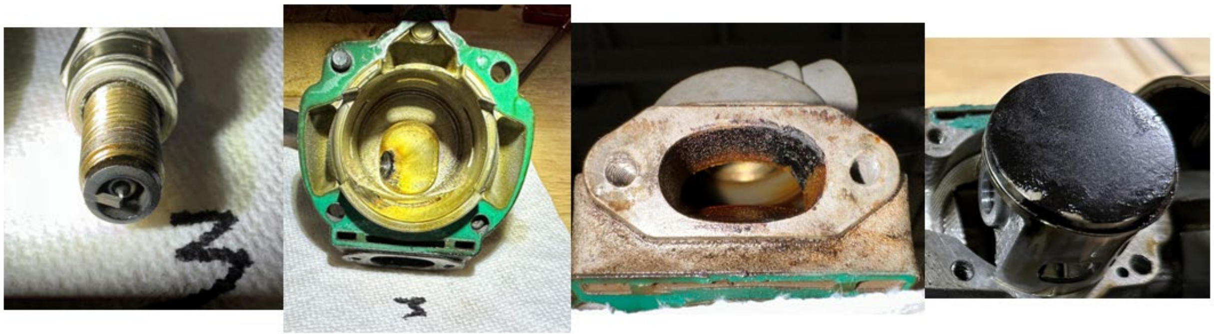

Figure 11. Deposit level post-test.

These low levels of deposits can be mainly attributed to good temperature control with a liquid cooled system. Keeping metal temperatures under coking temperatures is critical in controlling deposits, and this will have a significant impact on extending TBOs.

Piston and cylinder wear was minimal over the course of this test. Oil control grooves were still plainly visible on the surface of each piston, and likewise hatching patterns created by honing were also present on the cylinder walls. Only on Cylinder 1 was there evidence of ring sticking, however, this was attributed to the partially blocked coolant passage.

Piston pin wear was investigated for any abnormal wear characteristics that could indicate detonation, and other than some surface scratching, there was no wear signature (such as indentation marks from the bearing pins) that indicated the presence of detonation in the cylinder.

Finally, we looked closely at main bearing wear; especially the non-traditional roller element bearings at the center of the engine. Figure 12 shows good wear characteristics on both race surfaces and on the rollers.

Figure 12. Main bearing wear.

The Figures below illustrate the details of the three major combustion-related components: the cylinders, the pistons, and the spark plugs.

Cylinders:

Figure 13 shows a close-up of the exhaust side of each cylinder. Notable is the consistency and presence of honing cross-hatching in each cylinder. Lack of cross-hatch wear indicates that all three cylinders were able to maintain proper oil film thickness for the duration of the test. On Cylinder #1, excess deposits on the combustion chamber and a washed bore wall where the piston skirt does not contact the bore are signs of a minor coolant leak. Sealing between the water jacket and crankcase has been improved for future builds.

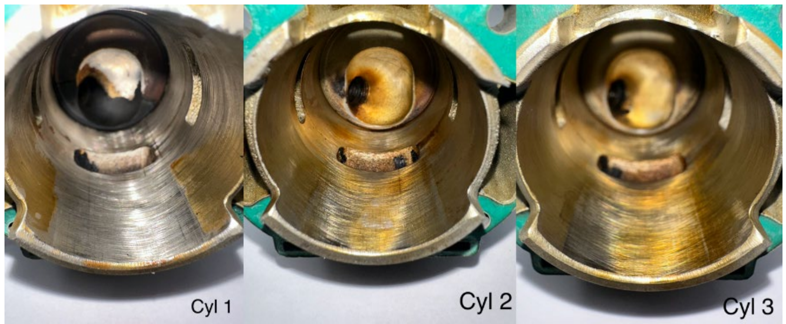

Figure 13. Exhaust-side cylinder bore and combustion chamber.

Pistons:

All three pistons show very little wear on the skirt as evidenced by the presence of oil retention grooves. Cylinders #2 and #3 show no signs of ring sticking, however, Cylinder #1 did show ring sticking in one location, and this may be attributable to the coolant leak mentioned above. No piston, pin, or top-end bearing shows any sign of overheating, nor is there any evidence of detonation on the piston crowns.

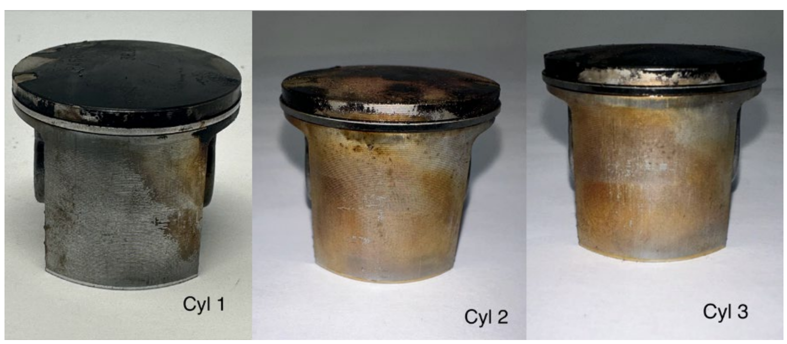

Figure 14. Pistons (exhaust side).

Spark Plugs:

Signs of fouling or electrode degradation is not present in any of the spark plugs. Our goal with a full-size fine-wire electrode plug is to eliminate spark plug maintenance between overhauls, and these plugs indicate that this will be possible.

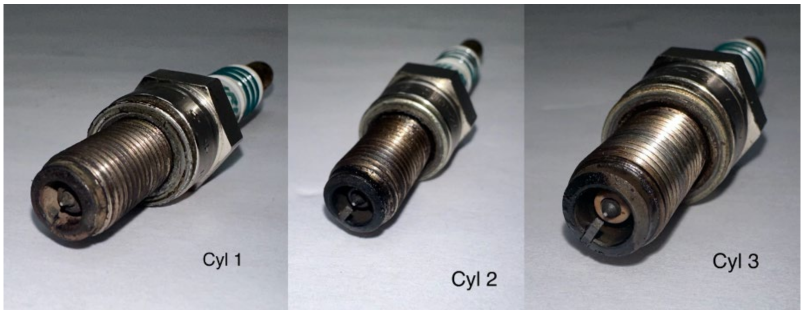

Figure 15. Spark plug electrodes.

E. Deviations

1. The total number of hours on this engine after testing was completed exceeded 200. This was because of two reasons, 1) the core engine already had approximately 75 hours of testing and calibration prior to the FAR33 test starting, and 2) The coolant pump and crank timing wheel were rebuilt after Cycle 6, and we re-started the test at that point.

2. The design updates shown above have not been durability tested yet. We deemed these changes to be low risk (already better than the hardware that went through the test). We will conduct another FAR33 test with finalized hardware soon.

3. The generator was not included in this test because a system has not been chosen yet. For all future FAR33 tests on this platform, the generator must be present.

F. Power degradation

The endurance engine, A99HF SN EXP06, was subjected to a standard run-in and check-out and the full throttle static RPM recorded at 6180 RPM with and intake air temperature of 34 C. This RPM was used to compute the required RPMs to meet AMRDEC test profile. In cycle 1 through 6 we worked through some technical issues with the engine discussed elsewhere. After repairs, the test was restarted at Cycle 7 and the test continued uneventfully, stopping only to add fuel and top off coolant, ending in cycle 27.

At the start of cycle 1, the average speed at the first WOT test point was 6210 RPM (4.1 hours total time)

At the start of cycle 7, the average speed at the first WOT test point was 6067 RPM (59.4 hours total time)

At the start of cycle 17, the average speed at the first WOT test point was 6099 RPM (141.7 hours total time)

At the start of cycle 27, the average speed at the first WOT test point was 6125 RPM ((209.5 hours total time)

G. Implications, conclusions, lessons learned.

1. Core Engine

The core engine system exhibited excellent durability and robustness with respect to wear and deposit buildup. Attributing to this success are both the up-front Computer Aided Engineering (CAE) that was conducted on the structure and modal behavior and liquid cooling.

2. Ancillary Systems

The coolant pump, coolant proportional valve, and various sealing systems all needed minor updates based on these test results.

3. TBO Objectives

The objective of this program is to market a propulsion system that has considerably greater TBO than other similar systems. These results indicate that this goal is within reach.

H. Test validation

The results of this test are validated below against the (5) objectives in II.A.

1. *Determine upper limits of stress under which the engine can operate in a specified period of time and identify items that need improvement*

- The primary stress imposed by the endurance test were the CHT set point at WOT and the timeframe of the test itself. All key crank train components looked very good after the 150 hour test, therefore the we are comfortable with suggesting a CHT setpoint of 130C.

- The results of this test can be applied to tests of subject engines of similar configuration.

2. *Provide customers with endurance data to meet engine selection requirements*

- This test represents initial results for a 150-hour endurance program. This is a first step in making longer endurance tests feasible. The data gathered from this testing and the methods to gather that data have been refined.

3. *Increase airworthiness confidence by qualifying engine durability against known FAA standards*

    - The FAR33 endurance requirement for reciprocating aircraft engines has been heavily referenced in the course of setting up and executing the endurance test.

4. *Calibrate reporting of fuel consumption from the ECU*

    - As provided above, ECU fuel calibration has been refined based on recorded fuel weights for the AMRDEC profile. A further refinement can be made by recording the reported ECU fuel used while running a different RPM profile.

5. *Collect data to be used in determining product maintenance schedules and, ultimately, hourly operating cost with respect to product life cycle.*

    - The length of time an engine can be run depends on how one approaches the system components: At what point is the engine proper "dead" and what components can be considered valid LRUs? This test helps to paint clues into which components have the most risk in terms of failure consequence (exhaust, piston) as well as probability (air filter). The data in this test is not fully conclusive but it meets the objective in that it can be used as part of a larger study in determining maintenance and operating requirements. A full system TBO will require more tests which continue to accumulate time on specified components such as the piston, cylinder, and crank shaft.

V. Appendix

A. Beginning, Middle, and End cycle logs. Throttle %, Cylinder Head Temperature (CHT), and Engine Speed (RPM) recorded. Note: Each test below was interrupted by a shut-down event (fuel starvation, end of day).

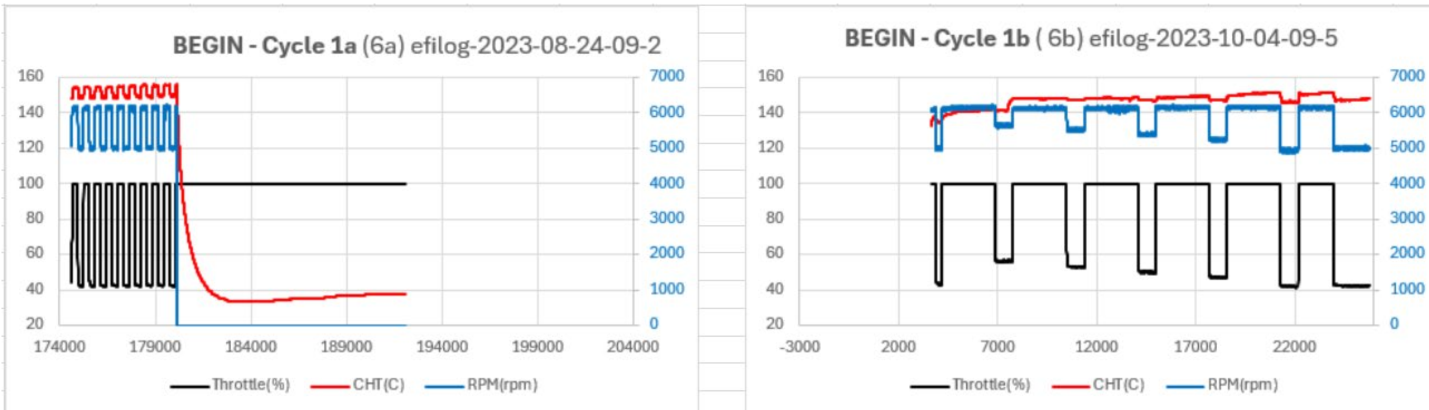

Figure 16A. Cycle 1 trace.

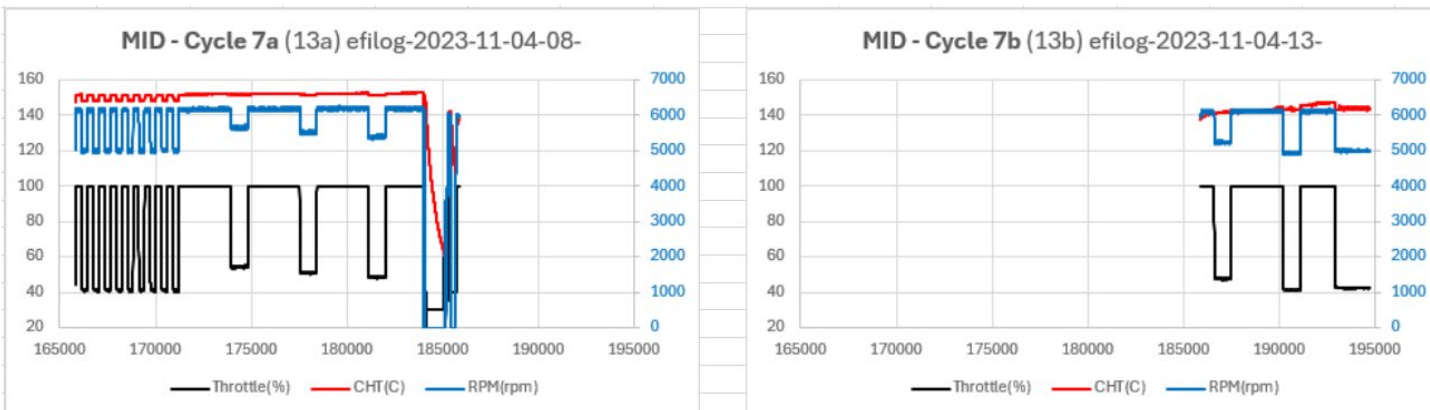

Figure 17A. Cycle 7 trace.

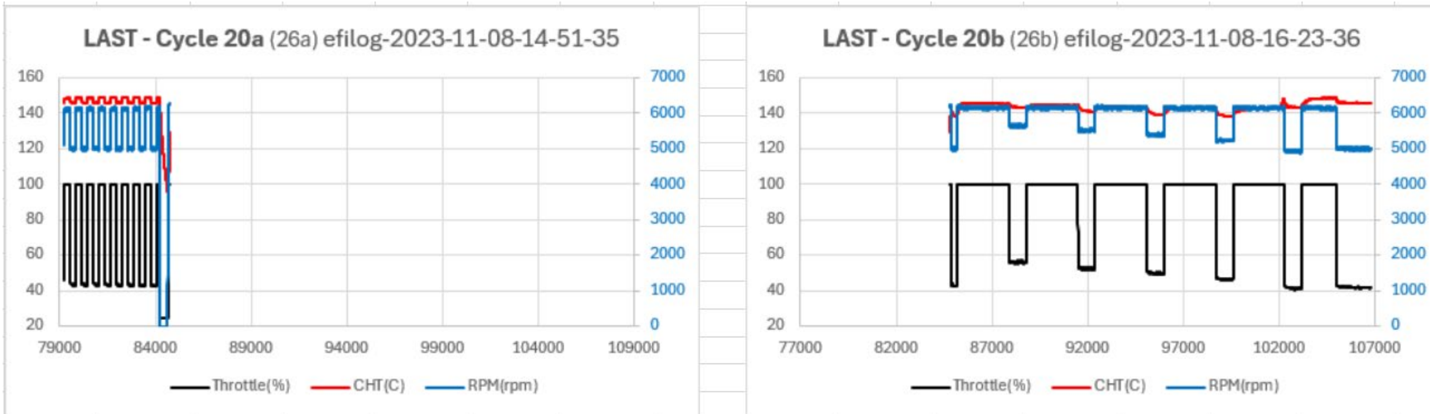

Figure 18A. Cycle 20 trace.

Raw notes as recorded during each day of testing:

8/22/23

- Engine EFI indicated about 75 hours of engineering testing was already performed on EXP6
- Verified cooling system function at WOT. Had to completely fill coolant tank. Used overflow bottle to maintain full colling system
- Switched to JP-5 and adjusted mixture for proper exhaust gas values 2.0-3.5%
- Validated cooling on JP-5 – fan at 20 Hz seems appropriate
- Engine over-cools at low power settings, like EXP10 – New cooling valve should fix this issue. determined to not be a factor for this test.
- Built test cycle RPM from AMRDEC spreadsheet.
- Ran first 20 minutes and decided to enable throttle curve so RPM controller is more responsive.
- 3 hours into test paused (shut down engine) for safety check.

8/23/23

- Out of fuel ~6:30 am – Cycle 3@~10700 seconds
- Re-fuel and start on Gasoline
- Switch to JP5@ 100C coolant temp
- Warmup to operating temperature and resume cycle 3 @10700 seconds.
- Switched coolant setpoint to 140.2
- 90 minutes into cycle 4 engine goes to WOT but does not achieve full RPM. (in retrospect, I suspect crank wheel impending failure caused this)

8/24/23

- Cycle 5 has similar failure to achieve full RPM at WOT as cycle 4. (In retrospect, I suspect crank sensor wheel impending failure caused this)
- Sticky crank sync error reported in cycle 6
- Crank error reported every few minutes at WOT. Part throttle seems OK
- Shut down test 90 minutes into cycle 6 due to increasing crank sense errors.

8/25/2023

- Discovered failed crank wheel key and keyway were damaged.
- Also found severely worn water pump belt

10/2/2023

- Replaced crank pickup ring and water pump belt
- Restarted cycle 6 at 90 minutes

10/3/2023

- Engine shutdown due to high CHT at 10 minutes into cycle 7
- Found low coolant
- Mechanical inspection revealed leaking coolant pump shaft seal
- Also found leaking coolant from base gasket of cylinder 3

11/1/23

- Replaced coolant pump seal and base gasket.
- In the process of replacing the base gasket found partially stuck piston ring on cylinder 3. Also found bore glazed.

11/2/23 restarted test at beginning of cycle 7.

- Note we are now 45 hours into 150 hour test.

- Pause for fuel can swap and retorque muffler fasteners

11/3/23

- Morning safety check and coolant top off
- Afternoon safety check and fuel can swap
- Start of cycle 10? In the afternoon, est 67.5 hrs through durability??

11/4/23

- Afternoon safety check and fuel can swap
- Found low coolant, cyl base gasket has evidence of slow leak. Topped off coolant
- Lower right engine mount bushing failed. Replaced with temporary fix
- Restarted test ??beginning of cycle 13 est 97.5 hours into test??

11/5/23

- Fuel exhausted about noon.
- Safety check, add coolant, fill fuel.
- Restart cycle 16 at 15700 seconds at about 1:30 PM

11/6/23

- Fuel exhausted at 24400 seconds into cycle 19
- Refilled fuel, topped off coolant safety inspection and restart at 24500 seconds into cycle 19

11/7/23

- Fuel exhausted about 4:00 PM 2400 seconds into cycle 23
- Refilled fuel, safety check
- found 2 loose Oetiker clamps, silicone hose soft due to oil exposure. Re-crimped clamps
- Restart at 2400 seconds into cycle 23 at ~4:30pm.

11/8/23

- Expected to complete 25 3:00 pm today
- Paused test during cycle 25 at about 4500 seconds
- Refilled fuel, only 10 gallons, and topped off coolant
- Safety check and restart test
- Expect fuel exhaustion part way through cycle 27

List of recommended design changes:

1. Revise water pump seal and belt drive
2. Loctite on crank pickup wheel
3. Improved hose clamps and/or improved hose materials/Norma FBS Clamp?
4. Improved base gasket sealing – maybe Loctite “glue stick”
5. Improved cylinder base fastener mounting area and finish
6. Consider Helicoil in case for cylinder base fasteners
7. Consider Helicoil in generator for propeller fasteners
8. Improved exhaust gasketing and fastening – to maintain flange preload
9. Needs coolant overflow (expansion) bottle of 50 ml capacity

10. Improved coolant control valve to reduce internal leakage
11. Improved water pump impeller design
12. Consider 130-degree coolant setpoint for improved performance. Verify that this change does not significantly affect BSFC
13. Improved spark plug boots (not tight enough) and terminal (terminals rattle and make metal dust)
14. Review fastener torques, specifically, case, cyl base and taper nose