FUEL DEVELOPMENT & TESTING BEST PRACTICES 2014 THROUGH 2022

EXECUTIVE SUMMARY

The objective of this document is to share the valuable lessons related to the collaborative work done by industry and the FAA through the Piston Aircraft Fuels Initiative (PAFI) and other important information in order to facilitate the development and approval of unleaded aviation gasoline(s) through a Fleet Authorization process or a Supplemental Type Certification process.

These lessons and best practices describe findings from fuel, engine and aircraft testing, observations, considerations as well as process related findings from the investigations. The photographs within are some of the more striking observations made during the course of testing different fuel formulations.

The considerations and recommendations provided are based on the observations and findings from previous testing and are not intended to reflect a singular path towards successful unleaded fuel development.

FUEL DEVELOPMENT TEST BEST PRACTICES

DETONATION TEST – TURBOCHARGED ENGINE

Detonation testing of the turbocharged engine model should be conducted at simulated critical altitude with hot day conditions at the inlet of the compressor and at the exit of the turbine.

- For naturally aspirated (non-turbocharged) engine models, the critical design point for detonation is SEA LEVEL takeoff with rich mixture with hot day inlet conditions.
- For turbocharged engines, the critical design point for detonation is at the maximum allowable power at critical altitude, with hot day conditions, at the leanest allowable mixture setting that is rich of peak TIT.

CRITICAL ENGINE MODELS – DETONATION TESTS

The Lycoming IO-540-K1A5 and TIO-540-J2BD models represent the most critical engines across the fleet for detonation testing. It is recommended that unleaded fuel qualification programs include these engines in their detonation test matrix if approval of multiple high power engine models is being pursued.

- Consistent with FAA and industry experience, there are two engine models that represent critical worse case engines for detonation testing.
  - Lycoming IO-540-K1A5
  - Lycoming TIO-540-J2BD
- The 6 engine models cover critical detonation attributes.
  - Lycoming IO-540-K1A5 (Naturally Aspirated, RSA Fuel Injection)
  - Lycoming TIO-540-J2BD (Turbocharged, RSA Fuel Injection)
  - Continental IO-550-D (Naturally Aspirated, CMI Fuel Injection)
  - Continental O-470-U (Naturally Aspirated, Carbureted)
  - Continental TSIO-520-VB (Turbocharged, CMI Fuel Injection)
  - Pratt & Whitney R-1830 (Radial Engine)

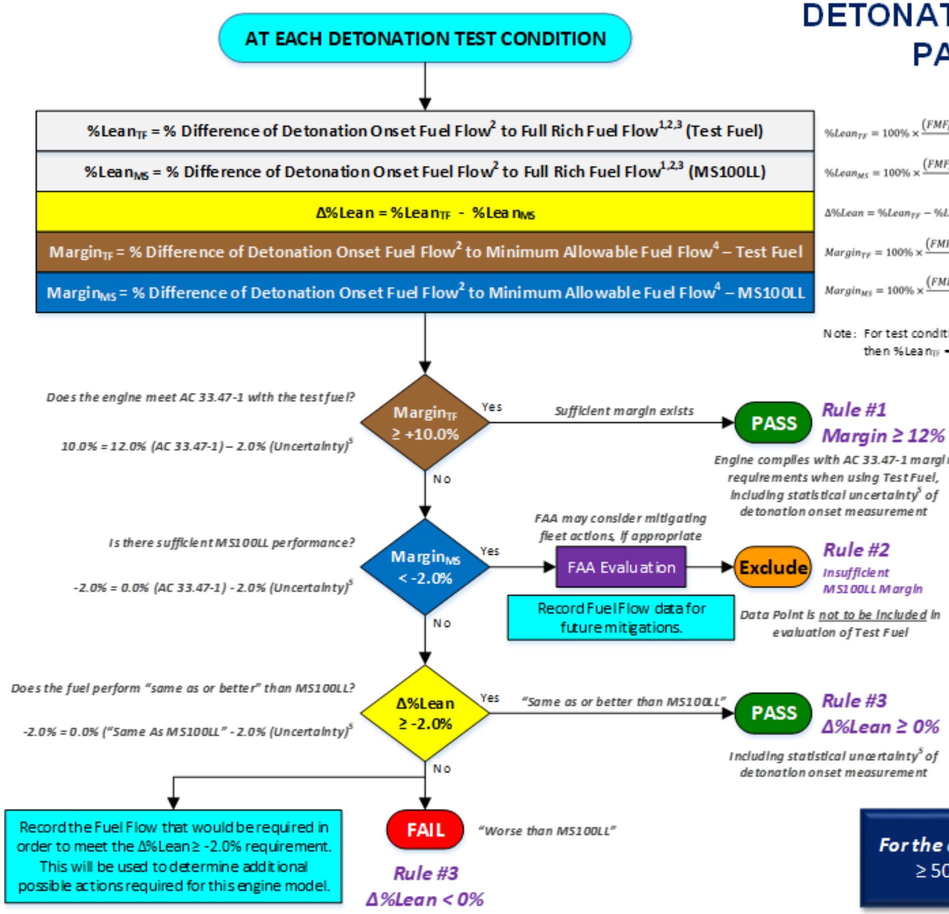
DETONATION TEST – TURBOCHARGED ENGINE (CONT.)

Comparative detonation testing with slow, continuous mixture sweeps from full rich to lean limit fuel/air ratios at RPM and MAP settings from cruise to T/O power were demonstrated to be preferred for validating acceptable detonation characteristics.

Critical engines that exhibit the least margin for detonation should be identified for detonation testing. For example, the Lycoming IO-540-K1A5 and TIO-540-J2BD represent the most critical engines in their model class relative to detonation. Testing of these models could potentially be sufficient to validate adequate detonation margin in other engines in these respective model classes.

PAFI FULL SCALE TEST PROTOCOL

DETONATION PERFORMANCE TEST PASS / FAIL CRITERIA



$$\%Lean_{TF} = 100\% \times \frac{(FMF_{FullRich(TF)} - FMF_{DetonationOnset(TF)})}{FMF_{FullRich(TF)}}$$ Test Fuel

$$\%Lean_{MS} = 100\% \times \frac{(FMF_{FullRich(MS)} - FMF_{DetonationOnset(MS)})}{FMF_{FullRich(MS)}}$$ MS100LL

$$\Delta\%Lean = \%Lean_{TF} - \%Lean_{MS}$$

$$Margin_{TF} = 100\% \times \frac{(FMF_{MinAllowable} - FMF_{Detonation\ Onset(TF)})}{FMF_{MinAllowable}}$$ Test Fuel

$$Margin_{MS} = 100\% \times \frac{(FMF_{MinAllowable} - FMF_{Detonation\ Onset(MS)})}{FMF_{MinAllowable}}$$ MS100LL

Note: For test conditions where Minimum Allowable Fuel Flow[4] is Full Rich[1], then $\%Lean_{TF}$ = $Margin_{TF}$ and $\%Lean_{MS}$ = $Margin_{MS}$

The term Margin is only used in the context of AC 33.47-1:
"The detonation tendencies should be observed by standard laboratory methods. The fuel mixture should be varied from full-rich to either limiting detonation, maximum allowable turbocharger temperature, best economy mixture, or power instability. Minimum fuel mixture margin should be 12 percent above limiting detonation. It is also necessary to show that the leanest fuel/air ratio allowable for the fuel metering device used is 12 percent richer than limiting detonation. The engine should not demonstrate any detonation characteristics at the minimum fuel flow specified for any operating condition. Engine power settings through the engine operating envelope should be tested to verify establishment of adequate detonation margins. The engine should not demonstrate limiting detonation at fuel flows down to 12 percent leaner than the minimum fuel flow recommended by the engine fuel flow chart."

Minimum Specification 100LL (MS100LL) shall be a fully compliant D910 aviation gasoline prepared in a manner such that the final fuel has a total aromatic content of less than 5% by volume and a lead content of 0.47 - 0.49 gPb/L. Blend components will be selected such that the resulting MON is 100 +1/-0 (ref. ASTM D2700), and the Supercharge PN is 130 +2/-0 (ref. ASTM D909), while meeting all other Table 1 specification requirements. The fuel shall also meet a target density range of 708.7 kg/m^3 ± 1% @ 15°C [5.855 – 5.974 lb/US gal] (ref. ASTM D4052). The fuel must be undyed.

For the detonation performance test to be considered:
≥ 50% of non-excluded Test Conditions = **PASS**

Notes:
1. Where practical, Full Rich Fuel Flow should be set to the minimum Full Rich Limit of the engine.
2. Numbers used in calculations are the average value taken from the available number of data points @ test condition. (4 data points each)
3. $FMF_{FullRich}$ to be corrected for Fuel Temperature deviations from 59°F.
4. $FMF_{Minimum\ Allowable}$ to be determined from data in the Engine Installation & Operation Manual for actual conditions using a fixed fuel density of 5.87 lb/gal.
5. The ± 2.0% uncertainty has been determined at the WJHTC as the statistically significant difference between the average detonation onset fuel flow expressed in percentage leaned from full rich of two fuels, based on 4 data points each. Testing performed at other locations will require a determination of uncertainty for the equipment, methods, and processes used.

ENGINE PERFORMANCE VS. FUEL DENSITY

Comparison of Engine Performance Parameters – Test Fuel vs. 100LL

- Lycoming TIO-540-J2BD
- Full throttle, Full Rich, Hot Head Performance Runs - 100LL and Test Fuel comparison
  - Mass Fuel Flow and Brake Specific Fuel Consumption
  - EGT / TIT Values
  - Air to Fuel Ratio and Equivalence Ratio

SUGGESTED ENGINE TEST PASS/FAIL CRITERIA

Performance: Engine corrected performance test results should be within ± 5% of the corrected performance obtained when operating with 100LL Avgas during back-to-back testing of each test engine if approval of multiple engine models is being pursued.

- BHP vs. fuel flow for rich and lean lines of operation for the UL fuel should be within ± 5% of the BHP vs. fuel flow for rich and lean lines of operation with FBO 100LL.
- Engine rated power should be within ± 5% of the rated power demonstrated under the same operating conditions with FBO 100LL at the same RPM, MAP, mixture setting.
- Engine operation should be characterized by EGT characteristics and trends which indicate tendency for exhaust gas afterburning.

DURABILITY TESTING

Durability testing of a new UL fuel should be conducted early in the project.

Durability testing should simulate a time between overhaul (TBO) interval and not necessarily be limited to the FAA 14 CFR 33.49 150 hour cycle. Critical engines that exhibit the most challenging operating characteristics for long-term operation should be identified for durability testing. For example, the Continental TSIO-550-K and –C models represent the most critical engines in their model class relative to durability. Testing of these models could potentially be sufficient to validate adequate durability performance in other engines in these model classes.

DURABILITY TEST SIGNIFICANCE

Durability testing of a new UL fuel should be conducted by the fuel developer.

- Durability testing should be conducted early in the project. Completion of a 14 CFR 33.49 endurance test on a turbocharged engine should be planned and implemented as early as possible in a UL100 fuel program to surface potential engine durability issues at the earliest possible date.

WORST CASE TEST FUEL FORMATION

Test fuels should be formulated to represent a worse case fuel formulation as bounded by their specification limits and tolerances.

- A test fuel for an aircraft hot fuel test should be formulated to represent a worse case vapor pressure.
- A test fuel for endurance testing should be formulated as a worse case fuel relative to additives and compounds which may influence engine deposits.
- A test fuel for materials compatibility should contain the highest concentration of aromatics or other reactive components.
- A fuel for the durability test should contain the highest soot and deposit producing constituents that can be made to the specification.
- A test fuel for detonation testing should be formulated as a minimum spec MON (Motor Octane Number) fuel.

Other specification property limitations should be based on these worst-case fuels.

MIN SPEC 100LL (MS100LL)

Minimum Specification 100LL (MS100LL) shall be a fully compliant D910 aviation gasoline prepared in a manner such that the final fuel has a total aromatic content of less than 5% by volume and a lead content of 0.47 - 0.49 gPb/L.

Blend components will be selected such that the resulting MON is 100 +1/-0 (ref. ASTM D2700), and the Supercharge PN is 130 +2/-0 (ref. ASTM D909), while meeting all other Table 1 specification requirements.

The fuel shall also meet a target density range of 708.7 kg/m3 +/ 1% @ 15°C [5.855 – 5.974 lb/US gal] (ref. ASTM D4052).

The fuel must be undyed.

FBO 100LL

Commercially obtained (FBO) 100 Octane low-lead AVGAS meeting ASTM D910, Grade 100LL.

Laboratory results from national sampling (June 19, 2014)

	Sample Count	Min	Max	Mean	Std dev σ	Median	Mean - 2σ	Mean + 2σ	FBO 100LL			
Motor Octane Number	74	101.30	108.00	103.51	1.33	103.80	100.85	106.16	103.51	±	2.65	
Supercharge Rating Performance Number	56	130.10	137.50	133.44	1.94	133.50	129.56	137.32	133.44	±	3.88	
Net Heat of Combustion, MJ/kg	51	43.60	44.47	44.13	0.30	44.16	43.53	44.74	44.13	±	0.60	MJ/kg
Lead content, g Pb/L	74	0.29	0.56	0.47	0.06	0.48	0.34	0.59	0.47	±	0.12	g Pb/l
Tetraethyl Lead, mL TEL/L	74	0.32	0.53	0.44	0.06	0.45	0.33	0.55	0.44	±	0.11	ml TEL/l
Aromatic Content, Vol %	24	0.10	17.70	7.25	5.58	7.00	-3.92	18.41	7.25	±	10.47	Vol %
Vapor Pressure@ 38, kPa	83	38.60	49.00	43.63	2.09	44.10	39.46	47.80	43.63	±	4.17	kPa
Vapor Pressure@ 38, psi	83	5.60	7.11	6.33	0.30	6.40	5.72	6.93	6.33	±	0.60	psi
Initial Boiling Point, ºC	38	30.60	46.11	37.41	3.17	37.2	31.06	43.76	37.41	±	6.35	°C
10% Evap, ºC	66	60.50	74.40	69.90	3.30	70.5	63.26	76.46	69.90	±	6.65	°C
40 % Evap, ºC	64	86.20	102.22	96.08	4.45	97.0	87.17	104.99	96.08	±	8.91	°C
50 % Evap, ºC	66	95.00	104.50	100.69	2.55	101.0	95.60	105.78	100.69	±	5.09	°C
90 % Evap, ºC	66	100.40	128.20	110.22	4.19	110.0	101.84	118.59	110.22	±	8.37	°C
End Point, ºC	66	111.30	156.90	131.81	10.56	132.2	110.69	152.94	131.81	±	21.12	°C
Sum of 10% Evap + 50% Evap, ºC	64	137.10	196.67	180.98	13.04	185.6	154.90	207.06	180.98	±	26.08	°C
Gravity Average, ºAPI	75	64.40	73.00	69.67	2.68	70.70	64.32	75.02	69.67	±	5.35	°API
Density at 15 ºC, kg/m^3	75	691.9	722.3	703.4	9.3	699.8	684.8	722.1	703.4	±	18.7	kg/m^3
Density at 15 ºC, lb/gal	75	5.77	6.02	5.87	0.08	5.84	5.71	6.02	5.87	±	0.16	lb/gal

FBO 100LL DENSITY (lb/gal) DISTRIBUTION

|----------------5.78--------------|---------5.88----------|---------5.87---------|-------5.81-------|

FUEL PROPERTY DRIVEN OPERATIONAL ISSUES

Operational indicators of degraded/ changed engine operation can reflect performance loss, premature engine wear and increased maintenance required.

- Overly Rich Mixture / Smoke / Soot
- Spark Plug Fouling
- Lean of peak exhaust gas temperature operation
- High EGT/TIT
- Cold weather starting / Extended Idle
- Co-mingling with 100LL (Changes in MON or SC No.)
- Mag Check Behavior
- Electrical Conductivity – Capacitive Tank Level Sensors
- Preignition
- Stuck piston rings

Soot Fouled

Glazed (No Spark)

CRITERIA FOR ACCEPTABILITY

Effect of fuel formulation on combustion chamber and crankcase deposits is a consideration with extent of impact influenced by fuel formulation and constituents.

Formation of significant carbon deposits in the piston squish and inter-ring land area were observed. These abrasive carbon compounds likely caused cylinder scuffing on the non-thrust side of the piston. Carbon spalling was seen at areas of highest accumulation, and shed particulates can interfere with the piston ring sealing action and led to periods of unusually high combustion gas blow-by, resulting in elevated crankcase pressure, the jettisoning of crankcase oil, and high piston temperatures.

ENGINE TEARDOWN AFTER DURABILITY TEST






ENGINE TEARDOWN AFTER DURABILITY TEST (CONT.)






CRITICAL ENGINE MODELS – CALIBRATION TESTS

The Continental Model TSIO-550-K represents a critical engine for the evaluation of turbocharged engine cruise power leaning protocols. It is recommended that unleaded fuel qualification programs for multiple high power engines include this engine in their calibration test matrix.

- FAA 14 CFR 33.45 requires calibration testing to establish the characteristics of the engine over its entire operating range of speed, manifold pressure, fuel/air mixture setting, and altitude.
- The POH instructions for setting of the cruise mixture ratio requires the detection of peak TIT. It has been discovered that some fuel formulations lead to EGT/TIT values that can run as much as 50°F hotter at near stoichiometric conditions when operating at authorized power ratings. EGT/TIT peak detection is difficult when the operating limitation of the engine is reached at a relatively rich mixture setting.

PROPELLER STRESS / VIBRATION TESTING

Tests were performed to evaluate propeller stress levels with new fuels to assess the impact of the fuel on combustion pressure characteristics.

- Lycoming IO-360-C1C
  - Hartzell HC-C2YR-1BFX/F7666A-2 Propeller
- Continental IO-550-B
  - Hartzell HC-J3YF-1RFX/F8068X Propeller
  - McCauley D3A32CC409/82NDB-2 Propeller
- Lycoming TIO-540-AJ1A
  - McCauley D3A32CC409/82NDB-2 Propeller
- Combustion pressure analysis (fuel vs. 100LL) may be performed to assess the similarity of the two fuels. If no significant differences in combustion pressure characteristics are noted, the combustion pressure analysis may be submitted in lieu of propeller vibration testing based on previous test results.

OTHER CONSIDERATIONS

Lubricating oil impact – Potential viscosity changes of the engine oil from exposure to soot and combustion byproducts should be investigated for the test fuels during testing. This is especially so with use of heavy aromatic compounds.

Thermal storage stability of test fuels has to be addressed to prevent formation of gums and significant loss of volatility (hot storage).

Test fuels should be investigated for cold flow ability and cold solvency issues (cold storage).