# Fuel Development & Testing Considerations 2014 through 2022

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# 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 Considerations

# DIFFERENCES IN PROPERTIES FROM D910

Differences (from ASTM D910) in fuel density, electrical conductivity, photosensitivity, Reid vapor pressure (RVP), aromatic content, distillation curve, and additive package content can have a significant impact on the acceptability and deployment of a given fuel formulation.

- ❑ Density directly affects mass fuel flow, if no fuel system adjustments are made, causing overly rich or overly lean fuel/air mixtures.
  - Adjustments (fuel pump setting on Continental Fuel Injection System, Recalibration of carburetors and RSA Fuel Injection Systems) can be made
    - Transition Period causes tremendous issues
    - Cost of conversion
  - Aircraft Volumetric Fuel Flow / Fuel Consumption measurements do not reflect a known relationship to engine performance
- ❑ Electrical conductivity can adversely affect capacitance type fuel quantity instrumentation. Fuel quantity sensors may require recalibration.
- ❑ Aromatics are known to affect elastomers to a greater extent than other components in aviation gasoline.
- ❑ Unleaded fuels with significant differences in the distillation curve from ASTM D910 100LL have impacted engine starting characteristics.
- ❑ Vapor pressure is a major, but not the only fuel characteristic that drives hot fuel testing results.

# FUEL DENSITY

- **Fuels with densities significantly higher than 100LL exhibited several issues during engine and aircraft testing.**
  - Spark Plug Fouling / Carbon Deposits / Soot
  - Afterburning / Exhaust Flames / Black Smoke
  - Higher EGT and TIT
    - Inability to reach Lean of Peak Best Economy due to TIT Overtemp
  - Inability to complete Durability Test due to Deposits
    - Leading to excessive Crankcase Pressure (Combustion Gas Blow-By)
  - Changes in Magneto RPM Drops
  - Rough Idling
  - Inability to determine Fuel Mass Flow from cockpit instrumentation
  - Can force Aircraft & Engine Fuel Flow <u>out of Type Design / ICA Limits</u>
    - Volumetric Fuel Flow is required for aircraft range and economy calculations
    - Mass Fuel Flow is required to characterize engine performance and proper engine operation

# FUEL DENSITY (ASTM D910 X1.3)

**X1.3 Fuel Metering and Aircraft Range**

X1.3.1 *Density*—Density is a property of a fluid and is of significance in metering flow and in mass-volume relationships for most commercial transactions. It is particularly useful in empirical assessments of heating value when used with other parameters such as aniline point or distillation.

X1.3.3 No great variation in density or heat of combustion occurs in modern aviation gasolines, since they depend on hydrocarbon composition that is already closely controlled by other specification properties.

# Cirrus SR22T

## ❑ Cirrus de-rates the Continental TSIO-550-K

- Engine: 315 HP @ 2500 rpm, 37.5 inHg
  Fuel Flow: 210 – 220 lb/hr
- SR22T: 310 HP @ 2500 rpm, 36.5 inHg
  Fuel Flow: 219 – 237 lb/hr

## ❑ Accident History

- 07/13/2017: N821SG, 2 Fatal, 1 Serious, 1 Minor
- 02/21/2018: N707DF, 1 Fatal

## ❑ Cirrus Service Advisory SA18-02

- “Boost – but not High Boost”
- Never Exceed 41 gph (240.7 lb/hr)

**CIRRUS** SR22T Service Advisory

**Number:** SA18-02
Issued: 7 May 2018

**SUBJECT:** Use of the Fuel Pump HIGH BOOST/PRIME Position

1. **EFFECTIVITY**

   SR22T Serials 0001 and subs

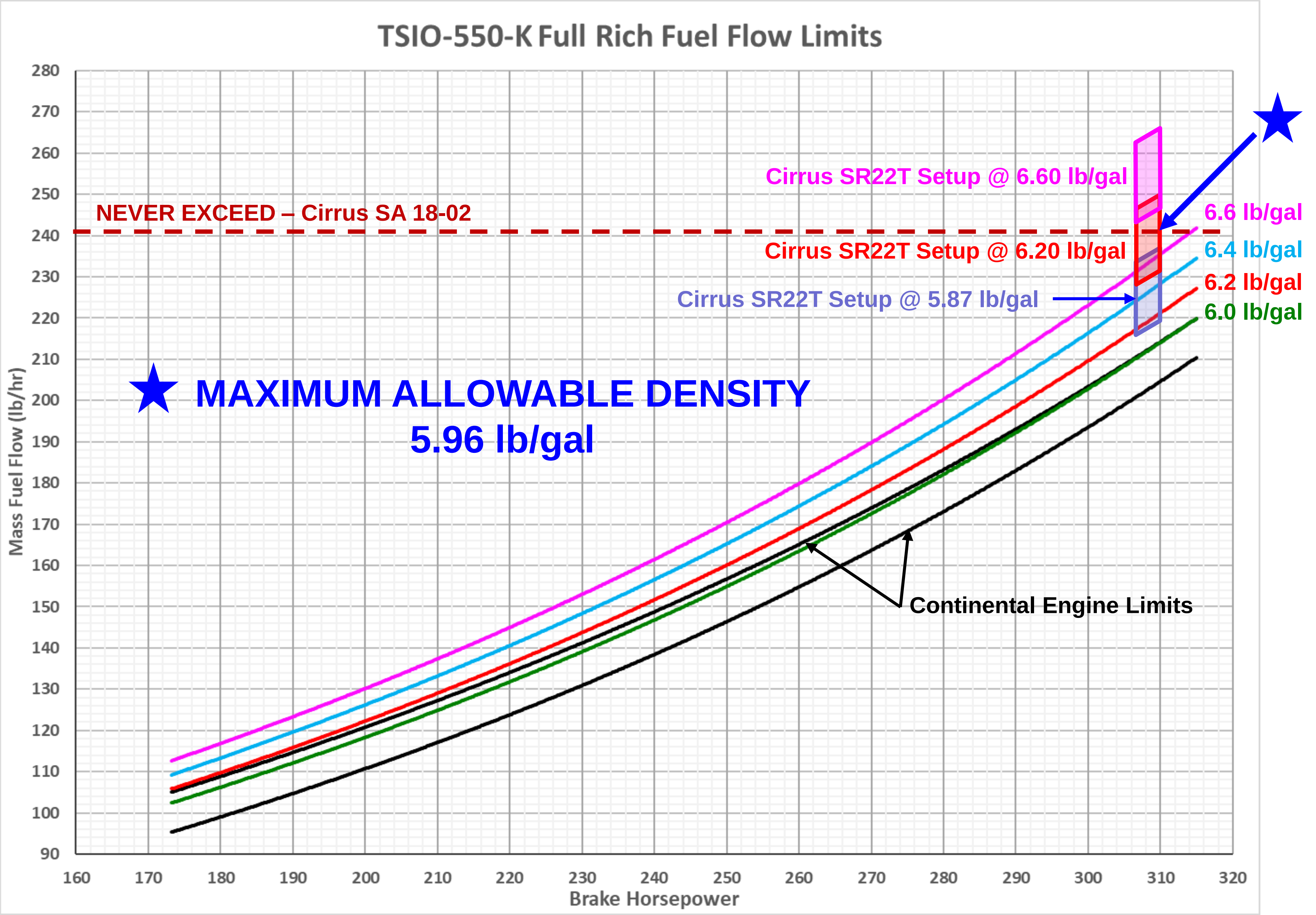
2. **DESCRIPTION**

   In accordance with, and as a reminder about, the language in the Pilot's Operating Handbook, the intended use of the fuel pump HIGH BOOST/PRIME position is priming prior to engine start, and suppressing vapor formation in flight above 18,000 feet with hot fuel.

   The fuel pump must be set to BOOST - but not HIGH BOOST/PRIME - for takeoff, climb, landing, and for switching fuel tanks.

   The pilot should monitor fuel flow during takeoff. Fuel flow should never exceed 41 gallons per hour (GPH) at 36.5 inches of manifold pressure. Higher fuel flow rates may result in a rough running engine and/or loss of power.

   WARNING: **Fuel flow should never exceed 41 GPH at 36.5 inches of manifold pressure. If fuel flow exceeds 41 GPH, further flight operations should be discontinued until the engine fuel pump is serviced in accordance with the manufacturer's approved Instructions for Continued Airworthiness.**


TSIO-550-K Full Rich Fuel Flow Limits
Mass Fuel Flow (lb/hr)
Brake Horsepower
NEVER EXCEED – Cirrus SA 18-02
Cirrus SR22T Setup @ 6.60 lb/gal
Cirrus SR22T Setup @ 6.20 lb/gal
Cirrus SR22T Setup @ 5.87 lb/gal
6.6 lb/gal
6.4 lb/gal
6.2 lb/gal
6.0 lb/gal
MAXIMUM ALLOWABLE DENSITY
5.96 lb/gal
Continental Engine Limits
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
320

# Cirrus SR22T (cont)

- **Limit on Fuel Density**
  - @ Never Exceed Fuel Flow of 240.67 lb/hr (41 gal/hr), the maximum allowable fuel density is **5.96 lb/gal**.
  - This allows ZERO margin.
  - Sampled FBO 100LL density ranged from 5.75 to 5.96
- **Precedent: Turbine Fuels per ASTM D1655 are required to have a density of 6.47 – 7.01 lb/gal (775 – 840 kg/m$^3$)**

# LYCOMING TIO-540-J2BD

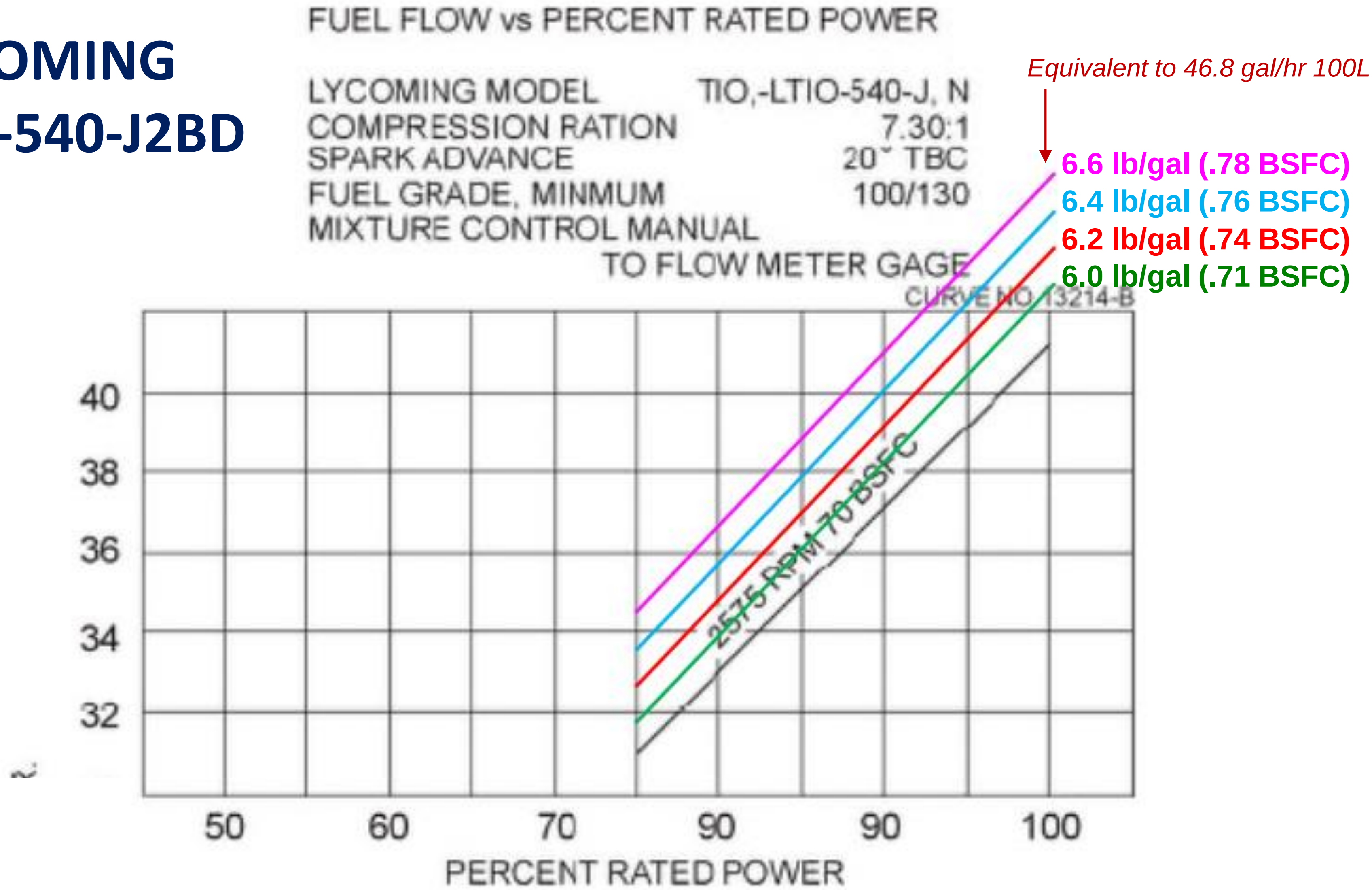



Figure 3-19. Fuel Flow vs Percent Rated Power – TIO-540-J2B, -J2BD, -N2BD

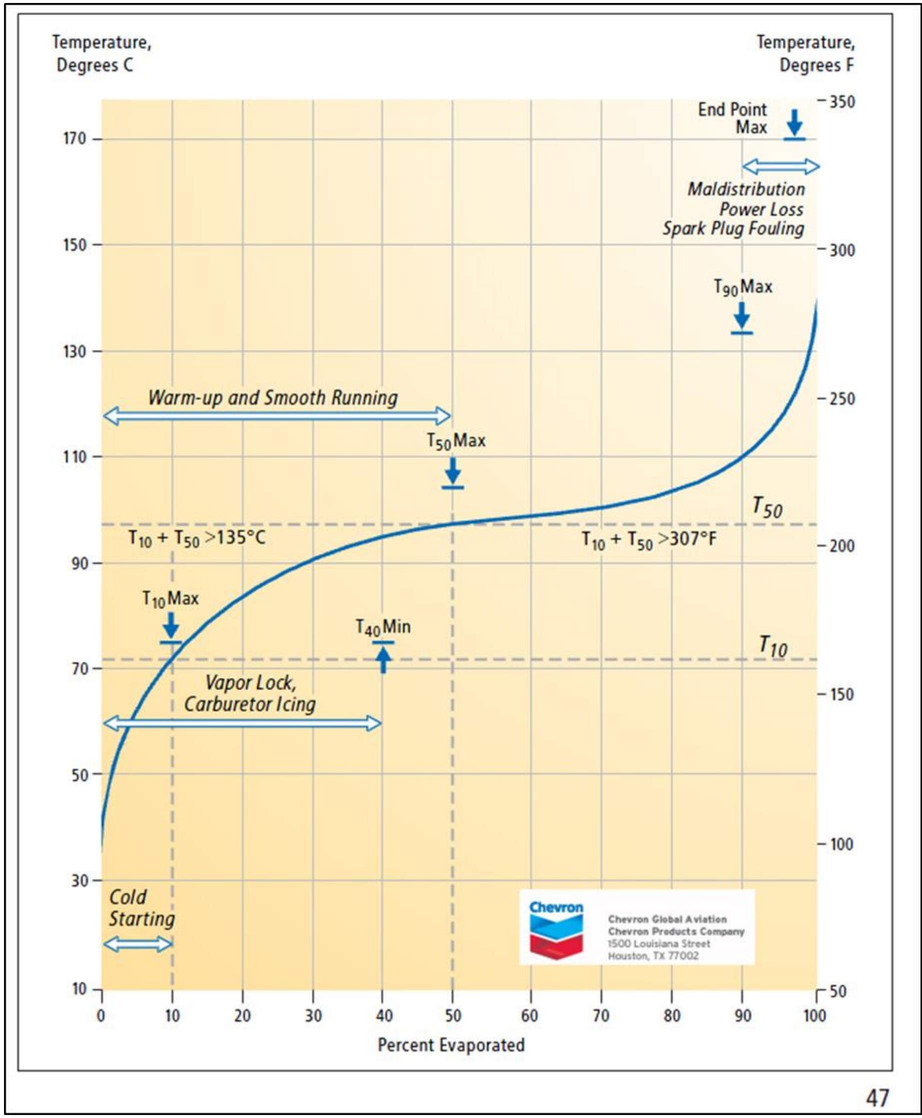
# FUEL PROPERTIES FOR EVALUATION

**For the Octane Enhancers other than TEL (Aromatics, Aromatic Amines, Oxygenates, non-Pb Metals), the following characteristics should be evaluated thoroughly:**

- ❑ Combustion / Starting Issues
- ❑ Material Compatibility
- ❑ Low Temperature Viscosity
- ❑ Preignition
- ❑ Carburetor Icing
- ❑ Operational Issues
- ❑ EPA Limitation / Toxicity - State and National Substance Bans
- ❑ Odor
- ❑ Engine Deposits
- ❑ Required Modification to Maintenance Intervals
- ❑ UV Exposure

# Distillation (ASTM D910 X1.4.4)

- **10% Fuel Evaporated: ≤ 75°C**
  - ($T_{10}$Max) Ensures ease of starting and a reasonable degree of flexibility during the warm-up period
- **40% Fuel Evaporated: ≥ 75°C**
  - ($T_{40}$Min) Indirectly controls specific gravity and metering characteristics
- **50% Fuel Evaporated: ≤ 105°C**
  - ($T_{50}$Max) Ensures adequate evaporation in the induction system and prevents power loss
- **90% Fuel Evaporated: ≤ 135°C**
  - ($T_{90}$Max) Avoids maldistribution, spark plug fouling, low fuel economy, and lubrication oil dilution
- **Final Boiling Point: ≤ 170°C**
  - (End Point Max) Along with $T_{90}$Max, avoids maldistribution, spark plug fouling, power loss, low fuel economy, and lubrication oil dilution
- **Sum of 10% & 50% ≥ 135°C**
  - ($T_{10} + T_{50}$ Min) Guards against carb icing, vapor lock, or both



# Fuel Mixture Considerations

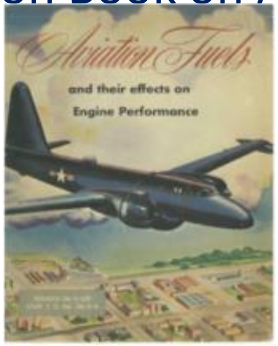
Changes to the engine full rich mixture fuel flow schedule should be fully assessed for safety and operational impact as changes to fuel controls could impact safety during a transition period where both 100LL and the new UL fuel would be used as full rich mixture is used for takeoff engine power.

Full rich fuel flow is determined by the size of the metering orifice in some fuel controls and fuel pressure in other types of fuel controls. Changes to the full rich flow schedule would require either a change in fuel pressure or a change in the metering orifice which is in an internal fuel control component.

# Materials Compatibility

## Aromatic Content

- Material compatibility with some aromatics has proven to be a challenge.
- Aromatic is a term used to describe compounds with certain molecular structure. Used in fuel to achieve desired MON characteristics.
- The 1951 Ethyl Corporation Book on Aviation Fuels states on page 36:




*Most aromatics, however, while inert have powerful solvent tendencies and either dissolve or cause severe swelling of rubber and rubber-like substances (unless special rubber types resistant to this action are used).*

- ASTM D910 States:

*X1.8.1 Aromatics Content—Low boiling aromatics, which are common constituents of aviation gasolines, <u>are known to affect elastomers to a greater extent than other components in aviation gasoline</u>.... Total aromatic levels above 25 % in aviation gasoline are, therefore, extremely unlikely*

# D1094 WATER REACTION

ASTM D1094, when applied to aviation gasoline, measures the water reaction volume change and reveals the presence of water-soluble / hydrophilic components such as alcohols. However, the test does not include the identification of water-soluble components nor their impact on fuel properties. In the case of alcohols, this is known to lead to a decrease in MON. In other cases, it may lead to the loss of co-solvents which can alter other fuel properties, including freezing point.

- ❑ Water soluble / hydrophilic components should be identified and the resultant impacts on fuel properties should be subjected to a risk assessment.
- ❑ The outcome of these risk assessments may lead to the application of additional test protocols.

# Fuel specification development considerations

At a minimum the fuel specification, whenever it is developed, should control the following fuel performance properties:

- Combustion
  - -Net Heat of Combustion
  - -Octane (MON- Motor Octane Number)
- Volatility
  - -Vapor Pressure
  - -Density
  - -Distillation
- Fluidity
  - -Freezing Point
- Corrosion
  - -Copper StripTst
- Contaminants
- Stability
  - -Potential Gum
  - -Existent Gum
- Water Reaction
- Additives
  - -Anti-oxidants
  - -Electrical Conductivity
  - -Fuel System Icing
  - -Corrosion Inhibitor

# Fuel specification development considerations

In addition, the fuel specification should adequately control either directly or indirectly with specification properties additional fit-for-purpose issues related to new formulations, such as:

New Fuel – Additional Fuel Fit-for-Purpose Properties

- Materials Compatibility
- Lubricating Oil Interaction
- Comingling with 100LL
- Lubricity
- Dielectric Constant
- Combustion – Flame Speed
- Fluidity – Latent Heat of Vaporization
- Compatibility with Ground Handling infrastructure

Each fuel performance property in the specification should have robust, widely accepted industry test methods with *precision statements that are applicable to the subject fuel's chemistry to evaluate the specific fuel property.
(*statement with statistically defined accuracy and bias.)

# Fuel specification development considerations

If a test fuel specification has constituent compositional limits, then specific and robust standardized test methods (with precision statements that are applicable to the subject fuel's chemistry) should be included in the specification to continuously ensure fuel quality compliance throughout the supply chain.

If formulations require additions of chemicals to aviation alkylate to complete the fuel, then each major additional component requires a stand-alone specification to adequately control the quality and performance properties of that additive.

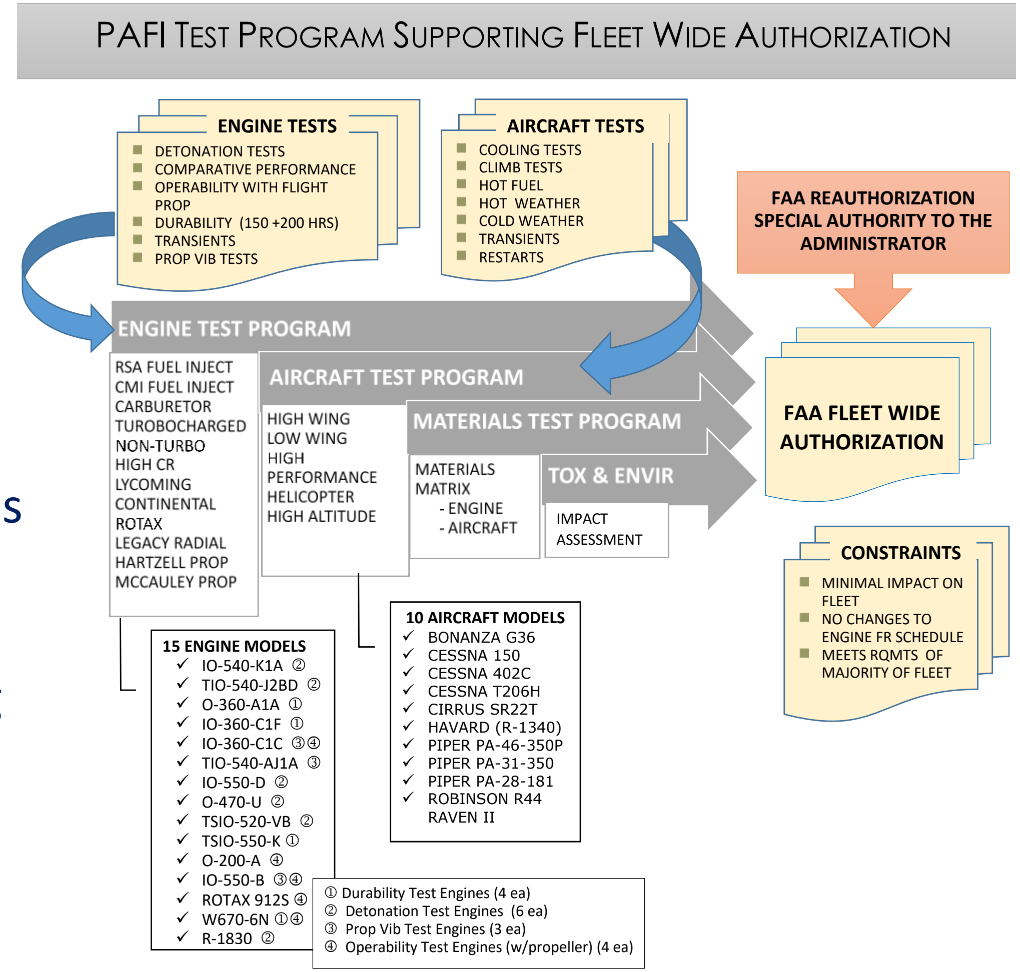
Should address specific isomer ranges, purity and test methods to assess those.

# PAFI Full Scale Test Protocol Description

# PAFI FULL SCALE TEST PROTOCOL

**The PAFI test protocol has been shown to be an effective plan for evaluating the acceptability of a new UL fuel for use in existing engines and aircraft.**

- The combination of test articles and specific tests for engines, aircraft, and materials provide an effective means of ensuring airworthiness for use with a new fuel.



# PAFI FULL SCALE TEST PROTOCOL

**The selection of representative engine test articles is best determined by a general assessment of engine key characteristics shown below, in conjunction with considerations of potential effects of the particular fuel chemistry.**

- ❑ Fuel System Type
  - RSA Fuel Injection
  - CMI Fuel Injection
  - Carburetor
- ❑ Engine Type
  - Naturally Aspirated
  - Turbocharged
  - High Compression Ratio
- ❑ Engine Manufacturer
  - Lycoming
  - Continental
  - Rotax
  - Legacy Radial
- ❑ Propeller Manufacturer
  - Hartzell
  - McCauley

**ENGINE TESTS**

- DETONATION TESTS
- COMPARATIVE PERFORMANCE
- OPERABILITY WITH FLIGHT PROP
- DURABILITY (150 +200 HRS)
- TRANSIENTS
- PROP VIB TESTS

**ENGINE TEST PROGRAM**

RSA FUEL INJECT
CMI FUEL INJECT
CARBURETOR
TUROBOCHARGED
NON-TURBO
HIGH CR
LYCOMING
CONTINENTAL
ROTAX
LEGACY RADIAL
HARTZELL PROP
MCCAULEY PROP

**15 ENGINE MODELS**

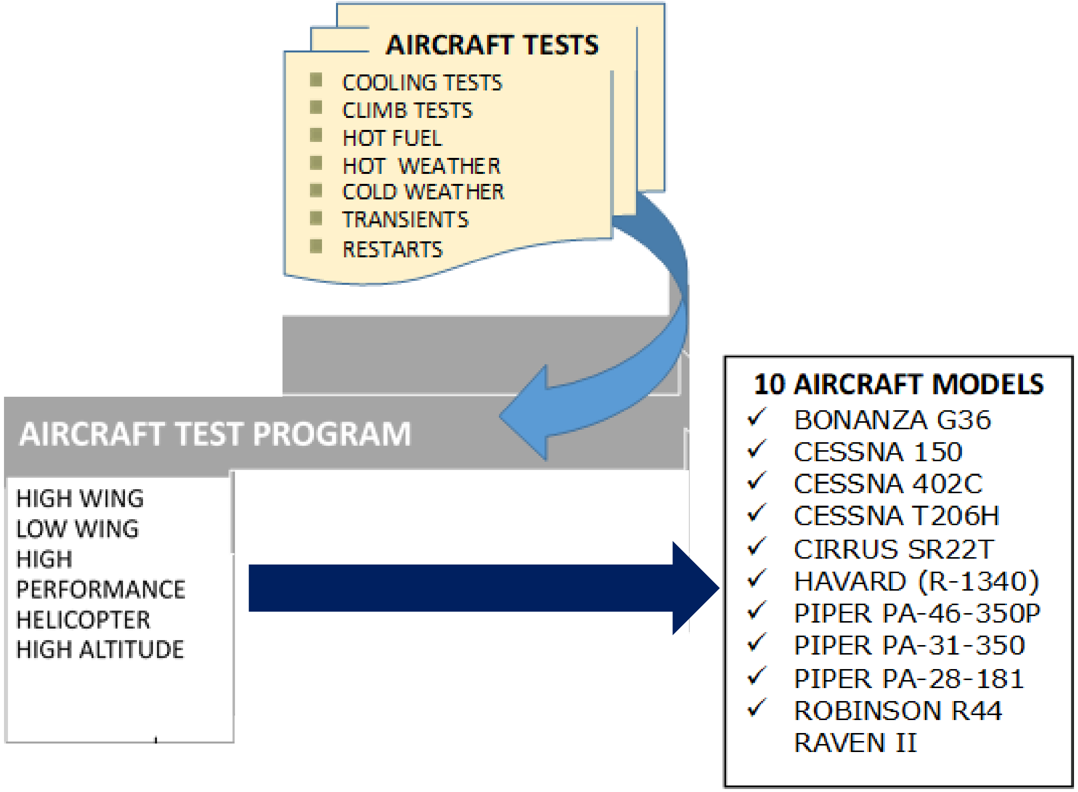
- ✓ IO-540-K1A ②
- ✓ TIO-540-J2BD ②
- ✓ O-360-A1A ①
- ✓ IO-360-C1F ①
- ✓ IO-360-C1C ③④
- ✓ TIO-540-AJ1A ③
- ✓ IO-550-D ②
- ✓ O-470-U ②
- ✓ TSIO-520-VB ②
- ✓ TSIO-550-K ①
- ✓ O-200-A ④
- ✓ IO-550-B ③④
- ✓ ROTAX 912S ④
- ✓ W670-6N ①④
- ✓ R-1830 ②

① Durability Test Engines (4 ea)
② Detonation Test Engines (6 ea)
③ Prop Vib Test Engines (3 ea)
④ Operability Test Engines (w/propeller) (4 ea)

# PAFI FULL SCALE TEST PROTOCOL

**The selection of representative aircraft test articles is best determined by a general assessment of aircraft key characteristics shown below, in conjunction with considerations of potential effects of the particular fuel chemistry.**

- ❑ Aircraft Type
  - High Wing
  - Low Wing
  - High Performance
  - Rotary Wing (Helicopter)
- ❑ Conditions
  - Sea Level
  - High Altitude
  - Hot Day Conditions



# PAFI FULL SCALE TEST PROTOCOL

| Engine Test Articles | O-360-A1A | O-360-A4M | IO-360-C1C | IO-360-C1F | IO-540-AE1A5 | IO-540-K1A5 | TIO-540-AE2A | TIO-540-AJ1A | TIO-540-J2BD | O-200-A | O-470-U | IO-550-B | IO-550-D | TSIO-520-VB | TSIO-550-K | Rotax 912S3 | R-1340 | R-1830 | W670-6N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Fuel Sys. Type** | | | | | | | | | | | | | | | | | | | |
| RSA Fuel Injection | | | | | | | | | | | | | | | | | | | |
| CMI Fuel Injection | | | | | | | | | | | | | | | | | | | |
| Carburetor | | | | | | | | | | | | | | | | | | | |
| **Engine Type** | | | | | | | | | | | | | | | | | | | |
| Naturally Aspirated | | | | | | | | | | | | | | | | | | | |
| Turbocharged | | | | | | | | | | | | | | | | | SC | SC | |
| High Comp. Ratio | | | | | | | | | | | | | | | | | | | |
| **Engine Mfg.** | | | | | | | | | | | | | | | | | | | |
| Lycoming | | | | | | | | | | | | | | | | | | | |
| Continental | | | | | | | | | | | | | | | | | | | |
| Rotax | | | | | | | | | | | | | | | | | | | |
| Legacy Radial | | | | | | | | | | | | | | | | | | | |
| **Propeller Mfg.** | | | | | | | | | | | | | | | | | | | |
| Hartzell | | | | | | | | | | | | | | | | | | | |
| McCauley | | | | | | | | | | | | | | | | | | | |
| **Aircraft Feature** | | | | | | | | | | | | | | | | | | | |
| High Performance | | | | | | | | | | | | | | | | | R | | |
| High Wing | | | | | | | | | | | | | | | | | | | |
| Low Wing | | | | | | | | | | | | | | | | | | | |
| Rotary Wing | | | | | | | | | | | | | | | | | | | |
| Single | | | | | | | | | | | | | | | | | | | |
| Twin | | | | | | | | | | | | | | | | | | | |
| Sea Level | | | | | | | | | | | | | | | | | | | |
| High Altitude | | | | | | | | | | | | | | | | | | | |
| **Aircraft Test Articles** | | | | | Robinson R44 II | | Piper PA-46-350P | Cessna T206H | Piper PA-31-350 | Cessna 150 | | Beechcraft G36 | | Cessna 402C | Cirrus SR22T | | Harvard T6 | | |

Detonation
Durability
Operability
Prop Vibration
Aircraft Testing