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Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Anti-Knock and Power Performance Evaluation of Swift Fuels 100SF Fuel Blended With Commercial 100 Low-Lead Aviation Gasoline in a Full-Scale Engine

February 2015

Final Report

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16. Abstract

The Federal Aviation Administration (FAA) William J. Hughes Technical Center (WJHTC) Propulsion and Airpower Engineering Research (POWER) Laboratories evaluated blends of an unleaded Swift fuel—100SF—meeting ASTM International Specification D7719, and commercial 100 low-lead (100LL) aviation gasoline meeting ASTM Test Specification D910. The base Swift fuel tested was blended to be near the minimum ASTM D2700 motor octane number (MON) per the D7719 specification.

Recent extensive research at the FAA WJHTC POWER Laboratories has shown nonlinear blending MON (per ASTM D2700) behavior of high-concentration aromatic fuel when blended in 100LL. Past POWER laboratory research showed that unleaded fuels of equivalent laboratory octane to leaded fuels typically do not perform as well in terms of full-scale engine antiknock performance. This research was performed to address full-scale engine detonation performance of blends of Swift fuel and 100LL.

The FAA WJHTC POWER Laboratory researchers also performed detonation tests on a special laboratory-manufactured leaded fuel. These blends were tested in both a Lycoming IO-540-K and a Continental IO-360-DB engine. The Lycoming IO-540-K is considered to be a high-octane requirement engine in the fleet. A laboratory analysis was performed on all blends and the results were compared with both the current leaded aviation gasoline specification ASTM D910 and the Swift fuel specification ASTM D7719. The detonation performance of these blends showed a nonlinear response from 100% commercial 100LL to 100% Swift fuel in regard to motor octane and supercharge performance number. All blends tested had better detonation onset equivalence ratios in the IO-540-K than the special leaded fuel. None of the fuels tested reached detonation onset in the IO-360-DB. Swift fuel produced 1% less power in the IO-540-K than the 100% commercial 100LL. There was a 4% reduction in take-off power with Swift fuel in the IO-360-DB. The differences in fuel composition between the 100% Swift fuel and the leaded test fuels produced a 40°F–70°F increase in average exhaust gas temperature in both engines.

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LIST OF ACRONYMS AND ABBREVIATIONS

100LL	100 low-lead
AVGAS	Aviation gasoline
BSFC	Brake-specific fuel consumption
CRC	Coordinating Research Council
EGT	Exhaust gas temperature
FAA	Federal Aviation Administration
GA	General aviation
HP	Horsepower
m/m	Mass-to-mass ratio
MON	Motor octane number
POWER	Propulsion and Airpower Engineering Research Laboratories
RPM	Revolutions per minute
SC PN	Supercharge performance number
WJHTC	William J. Hughes Technical Center

EXECUTIVE SUMMARY

Swift Fuels has obtained an ASTM International Specification D7719 for their high-octane binary blend.

The base Swift fuel used in this study was blended to have a 102.6 motor octane number (MON) per ASTM D2700 to be near the minimum MON limit of 102.2 listed in the ASTM test specification, ASTM D7719. The commercial 100 low-lead (100LL) used in this study was also a below-average fuel in terms of MON (102.2) as compared to the Federal Aviation Administration Propulsion and Airpower Engineering Research Laboratories' commercial fuel survey mean of 103.8. The Swift fuel was blended into a commercial 100LL ranging from 0%–100% in increments of 20% mass-to-mass ratio (m/m). A special laboratory, noncommercial leaded fuel was also evaluated that was designed to have close to the minimum MON (per ASTM D2700) and supercharge performance number (per ASTM D909) with the maximum allowable lead per ASTM D910.

Laboratory evaluations of all the blends were performed to compare their properties to those of the current Swift fuel test specification, ASTM D7719. The goal of this research was to determine the full-scale engine detonation performance of the blends in both a Lycoming IO-540-K engine and a Continental IO-360-DB engine, under extreme hot- and dry-day test conditions. For this research effort, under some test conditions, the engines were operated outside their normal operating limitations to test the detonation boundaries of the blends.

In the IO-540-K, under extreme hot- and dry-day sea-level intake air test temperatures, only the 40% m/m Swift blend performed as well as the commercial 100LL or the 100% Swift fuel. All blends performed better than the laboratory special leaded fuel. In the IO-360-DB, none of the fuels tested exhibited limiting detonation, as defined in this testing, at any of the power settings tested.

1. INTRODUCTION

1.1 PURPOSE

This research addressed the power and anti-knock performance of a near-minimum specification Swift fuel 100SF blended from 0% to 100% in increments of 20% mass-to-mass ratio (m/m) in a commercial 100 low-lead (100LL) fuel in both a Lycoming IO-540-K and a Continental IO-360-DB naturally aspirated engine.

1.2 BACKGROUND

Federal Clean Air Act Amendments prohibit the sale of leaded fuels for on-road vehicles, but not for off-road vehicles, such as aircraft, racing cars, farm equipment, and marine engines. Whereas most of the other transportation industries have transitioned from using leaded fuels, there are serious safety concerns with the removal of lead from aviation gasoline (AVGAS).

The general aviation (GA) community has become the largest domestic consumer of leaded fuel. With environmental pressures increasing worldwide against the use of leaded fuels and lead-scavenging agents, the future of the Environmental Protection Agency exemption for GA is uncertain and is increasingly a subject of debate.

Traditionally, most GA spark ignitions, reciprocating engines, and airframes have been certified on leaded fuels that meet the ASTM D910 standard AVGAS specification [1]. Use of unleaded alternative fuels can result in performance differences caused not only by different fuel properties, but also by combustion performance differences. Swift Fuels currently has a production fuel specification with ASTM D7719 [2].

The Federal Aviation Administration (FAA) Propulsion and Airpower Engineering Research Laboratories (POWER) at the William J. Hughes Technical Center (WJHTC) has been providing full-scale engine test results of unleaded fuels to FAA certification officials, the petroleum industry, airframe and engine manufacturers, regulatory agencies, aircraft user and owners associations, universities, and chemical companies. The primary goal of the team in this area is to facilitate the development of a safe, unleaded, high-octane alternative to the current 100LL AVGAS.

Introduction of any such fuel will not take place immediately in the marketplace and there will likely be a transition period. This period would inevitably result in users flying on various mixtures of 100LL and any approved new fuel because a 100LL phase out will be occurring alongside the new fuel introduction. As such, an investigation of the laboratory and full-scale engine testing of blends ranging from 0%–100% was needed.

Research suggests that blends of high-aromatic, unleaded AVGAS and 100LL exhibit nonlinear blending effects regarding motor octane response, and the detonation performance of leaded fuels can vary from the performance of unleaded fuels with the same ASTM D2700 motor octane number (MON) in a full-scale engine [3]. The addition of as little as 20% Swift fuel to 100LL resulted in a blend that no longer meets the D910 specification for heat content and 50%

and 90% distillation limits, which could potentially have a detrimental impact on in-flight performance.

The objective of this research was to determine the backwards and forwards compatibility of Swift fuel and D910 100LL for detonation protection in a full-scale engine. This research did not evaluate other impacts of the use of Swift fuel or blends of 100LL and Swift fuel on other performance characteristics of the engine or airframe. The Lycoming IO-540-K engine used in this research is considered a high-octane demand engine in the fleet and was used in previous testing of Swift fuel at the FAA POWER Laboratories [4]. The blends detailed in section 2 were also tested in a Continental IO-360-DB.

2. TEST PROCEDURES

2.1 TEST FUEL BLENDS

Swift Fuels provided blends of 100SF Swift fuel and 100LL, and the FAA POWER laboratory provided a specially leaded fuel. All laboratory testing was performed by an outside independent test lab, except for the distillation, vapor pressure, and density tests. Blends ranged from 100% Swift fuel to 100% 100LL in increments of 20% mass. All compositional percentages are based on an m/m; therefore, a blend listed as 20% Swift fuel and 80% 100LL refers to a blend in which 20% of the total blend mass is Swift fuel and 80% of the total blend mass is 100LL. The base Swift fuel used in this testing was 80% mesitylene and 20% isopentane by mass.

2.1.1 Compositions and Properties of Swift Fuel 100SF and Commercial 100LL Blends

Swift Fuels supplied the FAA WJHTC POWER Laboratory with six test blends: 100% Swift fuel (0% commercial 100LL), 80% Swift fuel (20% commercial 100LL), 60% Swift fuel (40% commercial 100LL), 40% Swift fuel (commercial 100LL), 20% Swift fuel (80% commercial 100LL), and 100% commercial 100LL (0% Swift fuel), as shown in figure 1. As noted in figure 1 and shown in figure 2, for the blends with a mass % concentration of Swift fuel greater than 40%, the supercharge response—as measured by the ASTM D909 [5] test—exhibited a nontypical response of leaded and *iso*parrafinnic fuels per the D909 test.

Table 1 shows the critical fuel blend properties and the specification limits for the respective fuel property. The addition of 20% Swift fuel to the commercial 100LL resulted in a blend that no longer met the D910 specification limits for net heat of combustion and 50% and 90% distillation points. The net heat of combustion of a fuel is a measure of how much work can be derived from the fuel and, therefore, impacts aircraft range. The distillation curve characterizes the volatility of the fuel. Fuels with high concentrations of low-boiling-point compounds typically make engine starting easier, but may be more prone to vapor lock; fuels with high concentrations of high-boiling-point compounds are typically less likely to vapor lock but may result in maldistribution in the intake system and engine. Figure 3 shows the differences in distillation curves for the blends tested. The D910 specification includes density only as a reported value, but it is important to note that the 84 kg/m^3 (0.7 lb/gal) difference in density between the Swift and commercial 100LL fuel may need to be evaluated regarding any impact on an aircraft's range and payload. The addition of 100LL to Swift fuel also has the same effect with the blends no longer meeting the Swift test specification density limits.

Sample	Description
A	100 % 100LL
B	20 % Swift Fuel, 80 % 100LL
C	40 % Swift Fuel, 60 % 100LL
D *	60 % Swift Fuel, 40 % 100LL
E *	80 % Swift Fuel, 20 % 100LL
F *	100 % Swift Fuel

* It was not possible to acquire a standard D909 Supercharge rating for the sample because its knock-limited power curve did not follow the response typical of the leaded primary reference fuels. (See attached graph of power curves). However, the peak power obtained for this sample was greater than that of the iso-octane + 6.00 mL TEL reference fuel, which has an assigned performance number of 161.

Figure 1. Composition of Blends (m/m%)

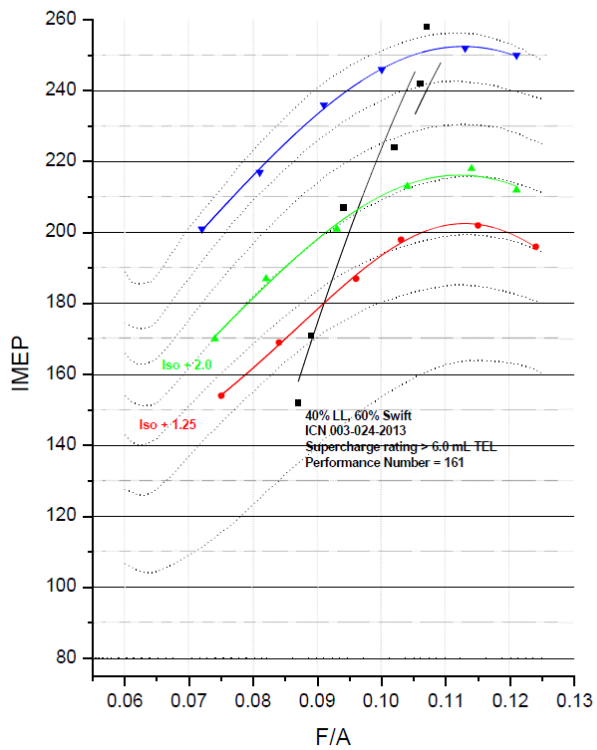

Figure 2. Supercharge Performance Curve Response per ASTM D909 With High Levels of Swift Fuel

Table 1. Properties of Fuels Tested

Property	Specification Limit D910–100LL	Specification Limit D7719–Swift Fuel Production Specification	100% Swift Fuel	80% Swift Fuel + 20% 100LL	60% Swift Fuel + 40% 100LL
MON - ASTM D2700	99.6 Minimum	102.2 Minimum	102.6	101.2	100.8
SC/Performance Number - ASTM D909	130.0 Minimum	N/A	161	161	161
TEL Content (ml/gal) - ASTM D5059	2.01 Maximum	0.01 g Pb/L Maximum	0.01	0.33	0.62
Net Heat of Combustion (MJ/kg) - ASTM D4809	43.5 Minimum	41.5 Minimum	41.76	42.01	42.00
Hydrocarbon Type (v/v%) - ASTM D1319					
Aromatics	N/A	N/A	73.3	56.9	43.9
Olefins	N/A	N/A	0.3	0.3	0.4
Saturates	N/A	N/A	26.4	42.8	55.7
Distillation - ASTM D86					
Initial Boiling Point (°C)	Report	Report	27.6	31.8	33.3
10% Evaporated (°C)	75 Maximum	75 Maximum	52.2	54.7	59.3
40% Evaporated (°C)	75 Minimum	75 Minimum	161.1	143.9	122.7
50% Evaporated (°C)	105 Maximum	165 Maximum	161.3	153.5	134.3
90% Evaporated (°C)	135 Maximum	165 Maximum	161.5	161.3	161.5
Final Boiling Point (°C)	170 Maximum	180 Maximum	176.2	169.4	170.2
Sum of 10% and 50% (°C)	135 Minimum	135 Minimum	213.5	208.2	193.6
Recovery (%)	97 Minimum	97 Minimum	99.7	99.7	99.4
Residue (%)	1.5 Maximum	1.5 Maximum	0.3	0.4	0.5
Loss (%)	1.5 Maximum	1.5 Maximum	0	-0.1	0.1
Vapor Pressure (kPa) - ASTM D5191	38.0 Minimum 49.0 Maximum	38.0 Minimum 49.0 Maximum	47.8	45.9	43.0
Density (kg/m^3)	Report	790 Minimum, 825 Maximum	792	768	756

Table 1. Properties of Fuels Tested (Continued)

Property	Specification Limit D910–100LL	Specification Limit D7719–Swift Fuel Production Specification	40% Swift Fuel + 60% 100LL	20% Swift Fuel + 80% 100LL	100% Commercial 100LL
MON - ASTM D2700	99.6 Minimum	102.2 Minimum	100.2	101.1	102.2
SC/Performance Number - ASTM D909	130.0 Minimum	N/A	135.6	135.0	133.1
TEL Content (ml/gal) - ASTM D5059	2.01 Maximum	0.01 g Pb/L Maximum	0.89	1.17	1.42
Net Heat of Combustion (MJ/kg) - ASTM D4809	43.5 Minimum	41.5 Minimum	42.96	43.40	43.81
Hydrocarbon Type (v/v %) - ASTM D1319					
Aromatics	N/A	N/A	30.6	20.5	10.1
Olefins	N/A	N/A	0.3	0.3	0.3
Saturates	N/A	N/A	69.1	79.2	89.6
Distillation -ASTM D86					
Initial Boiling Point (°C)	Report	Report	35.0	35.7	35.6
10% Evaporated (°C)	75 Maximum	75 Maximum	62.4	65.9	68.5
40% Evaporated (°C)	75 Minimum	75 Minimum	107.6	100.6	96.5
50% Evaporated (°C)	105 Maximum	165 Maximum	115.7	106.4	100.5
90% Evaporated (°C)	135 Maximum	165 Maximum	161.3	144.0	107.7
Final Boiling Point (°C)	170 Maximum	180 Maximum	173.5	169.4	126.7
Sum of 10% and 50% (°C)	135 Minimum	135 Minimum	163.7	172.3	169.0
Recovery (%)	97 Minimum	97 Minimum	99.6	100.1	99.9
Residue (%)	1.5 Maximum	1.5 Maximum	0.3	0.5	0.4
Loss (%)	1.5 Maximum	1.5 Maximum	0.1	-0.6	-0.3
Vapor Pressure (kPa) - ASTM D5191	38.0 Minimum 49.0 Maximum	38.0 Minimum 49.0 Maximum	40.5	42.1	39.8
Density (kg/m^3)	Report	790 Minimum, 825 Maximum	744	720	708

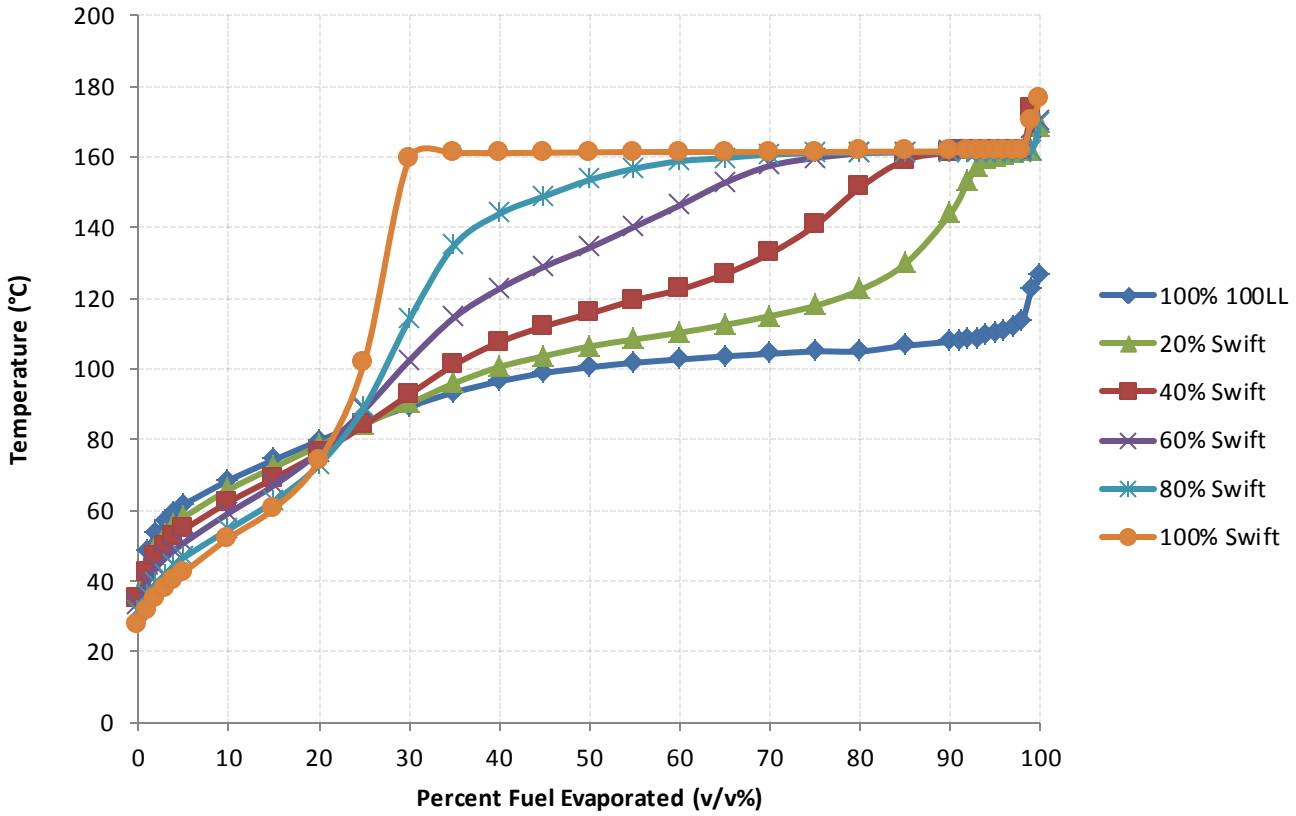

Figure 3. Distillation (ASTM D86 [6]) Curves for Swift Fuel Blends

2.2 SPECIAL LEADED TEST FUEL

The special leaded fuel was laboratory manufactured, which required a process of iterative blending and testing. This iterative process was necessary to make a laboratory fuel meeting near minimum octane ASTM D910 specification values for ASTM D2700 MON and ASTM D909 supercharge performance number (SC PN) with near-maximum allowable lead content. The laboratory fuel also met the current ASTM D910 fuel specification requirements for 100LL.

Figures 4 and 5 show the compositions and laboratory properties of these 21 iterative blends. Blend 21 was used as recipe to make the special leaded blend used in the engine tests. Figures 6 and 7 show the composition and detailed test results for the final special leaded fuel.

Because of the iterative nature of this fuel and the significant time and costs required to make it, it is highly unlikely to find such "minimum octane specification, maximum lead content" 100LL fuels in the marketplace. Published FAA commercial fuel survey results show the mean average values for ASTM D2700 MON, ASTM D909 SC PN, and ASTM D5059 [8] lead content (g Pb/L) of commercial 100LL being sold was 103.8, 133.5, and 0.46 (83% of max allowable), respectively [7]. Further, 95% of all fuels surveyed had an ASTM D2700 MON value higher than 102 (the ASTM D910 minimum MON requirement for 100LL is 99.5). The data suggest

that there is considerable MON giveaway by the fuel manufacturers in their attempt to meet the ASTM D910 supercharge rich minimum requirement.

Fuel 1 Laboratory Blends

Blend No.:	1	2	3	4	5	6	7	8	9	10	11
Composition, vol-%											
AvGas1	100.0	90.0	90.0	88.0	90.0	86.0	80.0	82.0	86.0	84.5	84.0
AvGas2											
Methylcyclohexane			10.0	12.0	0	8.0	12.0	10.0	7.5	5.0	10.0
Heptane		10.0		0	10.0	4.0	4.0			2.0	
i-Pentane				0	0	2.0	4.0				
n-Pentane								8.0	6.5	6.5	6.0
Toluene										2.0	
n-Butane											
Volume, L	0.400	0.400	0.400	7.570	7.570	7.570	7.570	7.570	7.570	7.570	7.570
Blend TEL	1.49	1.35	1.35	1.31	1.34	1.28	1.19	1.22	1.28	1.26	1.25
mL/gal TEL to add	0	0.65	0.65	0.69	0.66	0.72	0.81	0.78	0.74	0.76	0.75
MON	103.1	100.6	101.8	101.7	100.7	101.2	100.8	101.0	101.7	101.5	101.6
D909 mL				1.27	0.21	0.64	0.72	0.63	1.32	0.75	1.03
D909 PN				129.8	107.8	119.0	120.6	118.8	130.5	121.2	126.2
Vapor Pres.				33.7	34.8	35.9	37.3	40.4	40.1	38.5	38.3
IBP				42.0	42.5	41.0	44.0	41.0	39.5	41.0	40.0
10				77.0	76.0	75.0	73.0	68.5	69.0	69.5	70.5
40				100.0	99.0	99.5	98.0	96.5	97.5	97.5	97.5
50				102.0	102.0	102.0	101.0	100.5	101.5	101.5	101.0
90				111.5	112.0	112.0	112.0	111.0	112.0	111.5	111.5
End				143.0	143.5	143.0	140.5	142.5	136.0	143.0	142.0
10 + 50				179.0	178.0	177.0	174.0	169.0	170.5	171.0	171.5
Recovery				98.0	98.0	98.5	98.0	98.0	98.0	98.5	98.0
Residue				0.7	1.1	1.1	1.1	1.2	1.3	1.1	1.0
Loss				0.7	0.9	0.4	0.9	0.8	0.7	0.4	1.0
TEL, mL/gal				1.97	1.98	1.98		1.98	2.02	2.01	1.98
D3338 Heat of Combustion											
Density, 15C											

Figure 4. Composition and Properties of Laboratory Blends 1-11 Used to Make Special Leaded Fuel

Fuel 1 Laboratory Blends

Blend No.:	12	13	14	15	16	17	18	19	20	21
Composition, vol-%										
AvGas1	80.0	82.0	75.0	70.0	69.00	65.00	69.0	66.0	66.0	
AvGas2										66.0
Methylcyclohexane	7.5	6.0	7.5	7.5	7.50	7.50	7.5	8.0	8.0	8.0
Heptane	5.0	5.0	5.0	5.0	5.00	4.00				
i-Pentane										
n-Pentane	7.5	7.0	7.5	7.5	8.50	10.50	9.5	10.0	10.0	10.0
Toluene			5.0	10.0	10.00	13.00	14.0	16.0	15.5	15.5
n-Butane									0.5	0.5
Volume, L	0.800	0.800	0.800	0.800	7.570	7.570	7.570	7.570	7.57	7.57
Blend TEL	1.19	1.22	1.12	1.04	1.03	0.97	1.03	0.98	0.98	1.06
mL/gal TEL to add	0.81	0.78	0.88	0.96	0.97	1.03	0.97	1.02	1.02	0.94
MON	100.2	100.4	99.5	99.6	98.7	98.2	100.6	100.3	100.8	100.4
D909 mL					0.35	0.45	1.20	1.39	1.09	1.36
D909 PN					111.9	114.6	128.7	131.5	127.2	131.1
Vapor Pres.	38.7	39.7	37.8	36.2	37.9	38.7	38.3	37.5	39.2	40.5
IBP					42.0	40.0			40.0	40.0
10					71.5	69.0			70.0	70.5
40					97.5	97.0			97.0	98.5
50					100.5	100.0			100.6	102.0
90					109.5	108.5			108.5	110.0
End					132.5	133.5			138.0	140.0
10 + 50					172.0	169.0			170.6	172.5
Recovery					98.0	98.0			97.9	98.5
Residue					1.1	1.0			1.0	1.0
Loss					0.9	1.0			1.1	0.5
TEL, mL/gal					1.96	1.97			2.010	1.88
D3338 Heat of Combustior									43.51	43.51
Density, 15C										724.09

Figure 5. Composition and Properties of Laboratory Blends 12-21 Used to Make Special Leaded Fuel

	Mass	Volume
AvGas2	0.6360	0.6602
Alkylate-E		
Alkylate-P		
iso-Octane		
iso-Pentane		
n-Pentane	0.0871	0.0999
n-Butane	0.0031	0.0039
Toluene, ASTM	0.1873	0.1552
Toluene-E		
Toluene-S		
Methycyclohexane	0.0864	0.0809
TEL, ml/gal		2.00

Figure 6. Final Special Leaded Fuel Composition

	Property	Fuel
D4052	Density, 15 °C, kg/m3	723.9
D2700	Motor octane number	100.1
D909	Supercharge rating, mL TEL/gal	1.34
	Performance number	130.8
D5191	Vapor pressure, kPa	40.61
D611	Aniline point, °C	52.10
D4529	Net heat of combustion, MJ/kg	43.73
D5059	Lead content, g Pb/L	0.55
D86	Distillation, °C, % evaporated	
	Initial boiling point	39.0
	10 %	69.5
	40 %	97.5
	50 %	101.0
	90 %	108.5
	Final boiling point	138.0
	Sum of 10%+50%	170.5
	Recovery, volume %	98.0
	Residue, volume %	1.2
	Loss, volume %	0.8

Figure 7. Final Special Leaded Fuel Properties

2.3 TEST ENGINES

One engine used in this test was the Lycoming IO-540-K, a naturally aspirated, air-cooled, 540- cubic-inch, fuel-injected, 6-cylinder engine, with a compression ratio of 8.7:1, a rated power of 300 horsepower (HP), and a rated revolutions per minute (RPM) of 2700. This engine was previously determined to be a high-octane-requirement engine and was used in recent testing by the FAA WJHTC POWER Laboratories for the Coordinating Research Council (CRC) Aviation Gasoline Octane Rating Working Group.

The other engine used in this test was the Continental IO-360-DB, a naturally aspirated, air-cooled, 360-cubic-inch, fuel-injected, 6-cylinder engine, with a compression ratio of 8.5:1, a rated power of 210 HP, and a rated RPM of 2800. This engine is type certificated for a minimum approved fuel of 100LL.

Following each short test with leaded fuel, an unleaded fuel purge run of 30–45 minutes was performed. This testing was done using the unleaded fuel first, followed by increasing levels of lead content. The fuels were tested in the following order: 100% Swift fuel, 80% Swift fuel, 60% Swift fuel, 40% Swift fuel, 20% Swift fuel, 0% Swift fuel (100% commercial 100LL), and the special leaded fuel.

An eddy-current dynamometer was used for power absorption, and only the engine accessories required to operate the engine were installed. All engine testing involved the use of an AeroShell Type W, 15W-50 ashless dispersant oil.

In previous tests, the cylinder assemblies had been removed, drilled, and tapped in the fin area to install high-temperature, water-cooled piezoelectric pressure transducers. One transducer was installed in each cylinder head with the transducer face as flush as possible with the cylinder cavity. The transducers were connected to charge-to-voltage amplifiers, and the amplifiers were connected to a data-acquisition system. Analog cylinder pressure signals were digitized at the rate of 50 kHz per channel. The pressure data were fed to a numerical knock quantification analysis routine, as detailed in ASTM D 6424 [9].

The engine was instrumented and engine parameter data recorded at a rate of at least 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 tests. After the instrumentation was calibrated, a series of maintenance runs were performed to verify the engine system's integrity and instrumentation accuracy.

The fuel delivery system isolated multiple fuel sources, and the integrity of the fuel system was checked prior to each run to ensure that cross-contamination did not occur.

2.4 DETONATION TEST PROCEDURES

Prior to the start of any testing, the instrumentation was calibrated and a maintenance run was performed to verify the engine system's integrity and instrumentation accuracy. Prior to any engine operation, the mixture cutoff and full-rich settings were verified as well as the throttle stop and throw positions. Tables 2 and 3 show the engine parameters and power settings used for this testing.

Table 2. Engine Parameters for Detonation Testing

Parameter	Lycoming IO-540-K	Continental IO-360-DB
Maximum CHT	475 +5-0°F	460 + 5-0°F
All other CHTs	Within 50°F of maximum	Within 50° F of maximum
Inlet air temperature	103 ±3°F	103 ± 3°F
Humidity (relative %)	<2%	10 ± 3%
Inlet oil temperature	245 ±10°F	245 ± 10°F
Maximum EGT	1650°F (sustained), 1750°F(for less than 2 minutes)	1650°F (sustained), 1750°F (for less than 2 minutes)
Mixture adjustment	Start Full-Rich (F/R), adjust to setting in table 3	Start F/R, adjust to setting in table 3
Oil pressure (psi)	30-60	30–60
Ignition timing (BTDC)	20/20 (standard)	20/20 (standard)

F/R = Fuel mixture at full-rich stop; BTDC = Before top-dead-center; EGT = Exhaust gas temperature

Table 3. Engine Power and Mixture Settings

	Engine					
	Lycoming IO-540-K			Continental IO-360-DB		
	Take-off	Climb	Cruise	Take-off	Climb	Cruise
RPM	2700	2600	2450	2800	2600	2500
Corrected power at full-rich	Full throttle	284	218	Full throttle	175.5	154.5
Approximate power at best power		255	225		178.5	157.5
Nominal power (% of rated)	100%	85%	75%	100%	85%	75%
Mixture setting	F/R to heavy detonation	F/R to heavy detonation	F/R to lean of best economy or heavy detonation	F/R to lean of best economy or heavy detonation	F/R to lean of best economy or heavy detonation	F/R to lean of best economy or heavy detonation

F/R = mixture arm set at full-rich stop

3. RESULTS AND DISCUSSION

The equivalence ratio is calculated by dividing the blends' stoichiometric air-to-fuel ratio by the measured air-to-fuel ratio. The use of the equivalence ratio accounts for the significant chemical and density differences between 100LL and high-aromatic fuels. Operating the engine at cruise power with the fuel mixture strength near an equivalence ratio of 1.00 typically results in the highest average exhaust gas temperatures (EGTs) and is a mixture setting slightly rich of best economy performance. Mixture strength rich of this setting typically results in equivalence ratio values greater than 1.00, and leaning past peak EGT typically results in equivalence ratio values less than 1.00.

During Research and Development testing and evaluation on alternative fuels, engines are sometimes operated outside their approved operating envelope. This is done with highly instrumented engines, which are continuously monitored throughout testing so that the limitations of test fuels can be evaluated.

The results for the naturally aspirated Lycoming IO-540-K and Continental IO-360-DB engines are shown in sections 3.1 and 3.2, respectively.

3.1 LYCOMING IO-540-K

Table 4 shows the repeatability data for the IO-540-K testing regarding fuel flow, equivalence ratio, air-to-fuel ratio, brake-specific fuel consumption (BSFC), and EGT.

Table 4. Detonation Limited Repeatability Data

	Fuel Flow (lb/hr)	Equivalence Ratio	Air-to-Fuel Ratio	BSFC (lb/BHP hr)	Mean EGT(°F)
Average Standard Deviation	1.1	0.01	0.14	0.01	7
Maximum Standard Deviation	4.0	0.04	0.64	0.03	20
Average Difference (Maximum-Minimum)	2.0	0.02	0.24	0.01	12
Maximum Difference (Maximum-Minimum)	5.7	0.06	0.91	0.06	28
Average Relative Standard Deviation (% of mean)	1.06	0.97	1.00	1.15	0.43
Maximum Relative Standard Deviation (% of mean)	4.89	4.25	4.32	7.66	1.27

Figure 8 shows the typical detonation onset repeatability data, power, and average EGT for the IO-540-K engine for the three repeated test points. Figure 9 shows these same three repeats as averaged data. Table 4 and figures 8 and 9 demonstrate excellent repeatability of the IO-540-K test data.

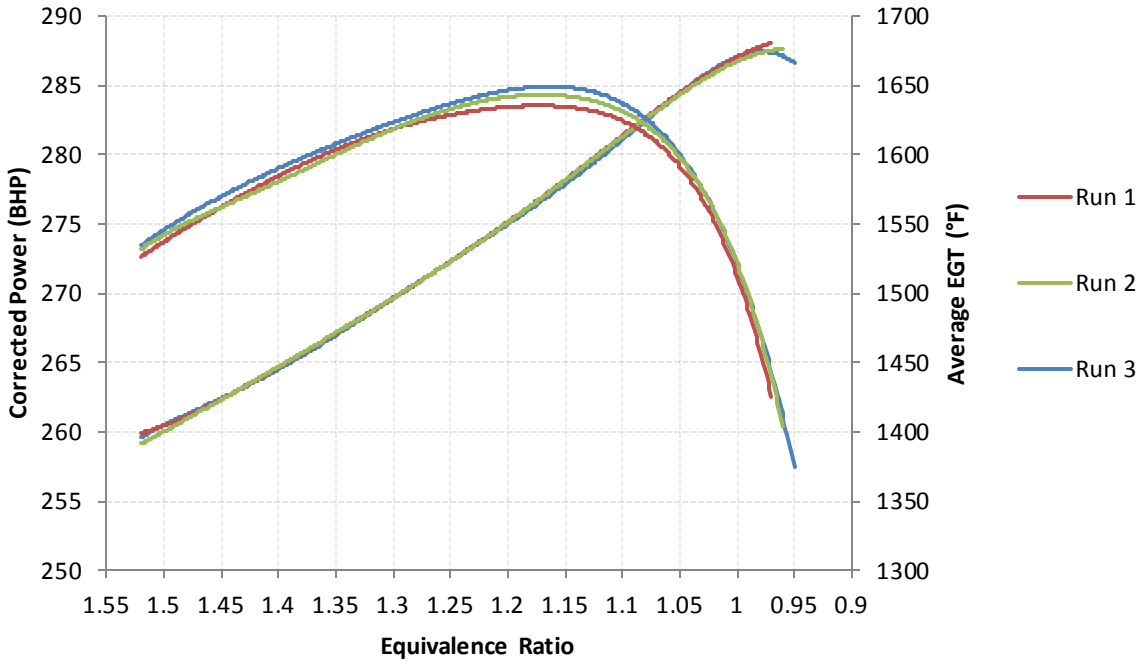

Figure 8. Repeatability of Detonation Testing

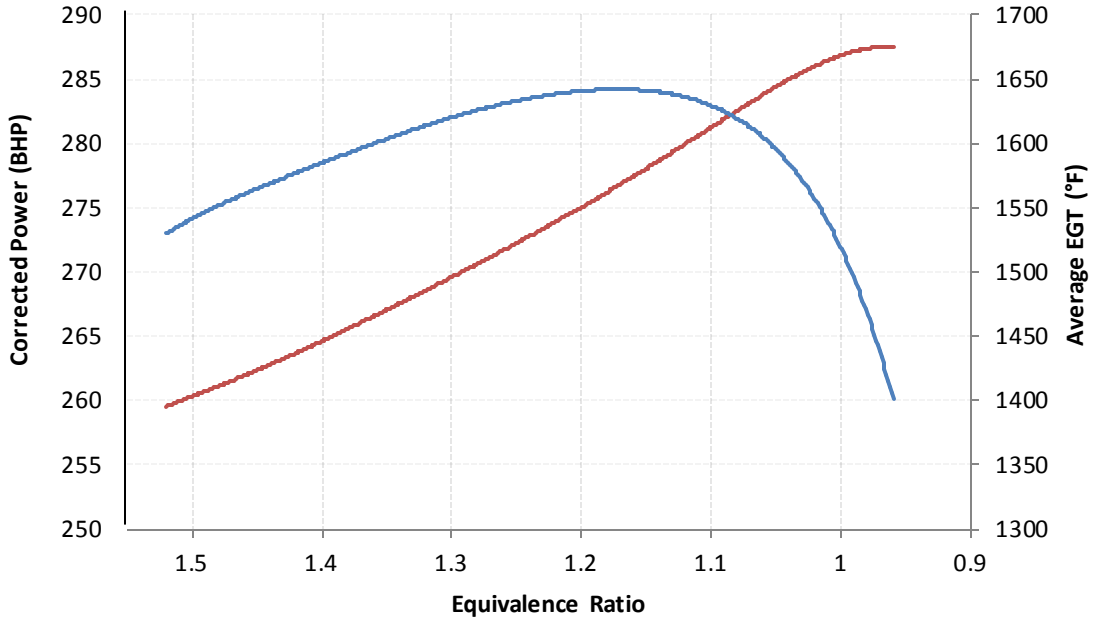

Figure 9. Average of Repeatability Data Shown in Figure 8

Figures 10 through 12 provide a general overview of the overall performance of the fuels tested in the IO-540-K engine.

At the full-rich, full-throttle condition, the blends produced slightly less power and slightly higher average EGTs as the percentage of Swift fuel in the blend increased. With Swift fuel, there was an approximate 50°–70°F increase in average peak exhaust EGT compared to the 100LL fuels, depending on the power setting.

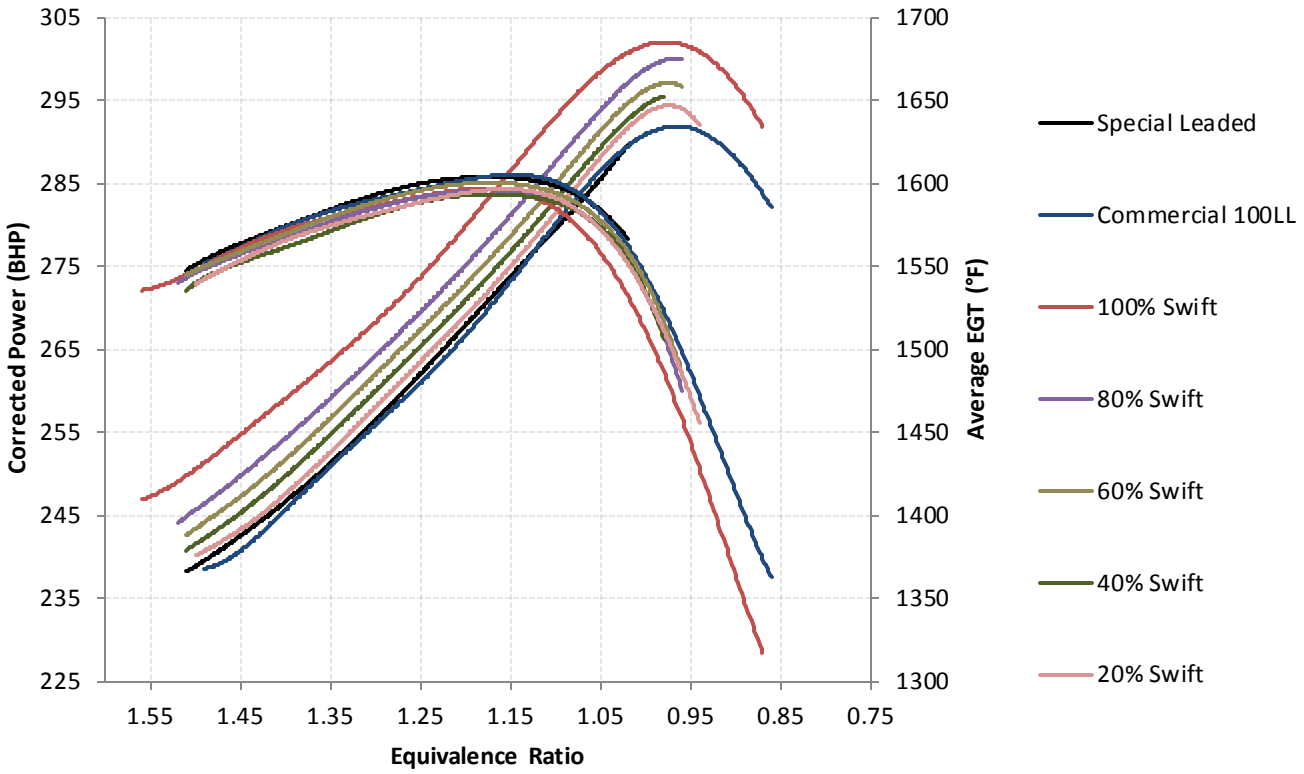

Figure 10. IO-540-K Engine Performance of All Blends at Take-off Power

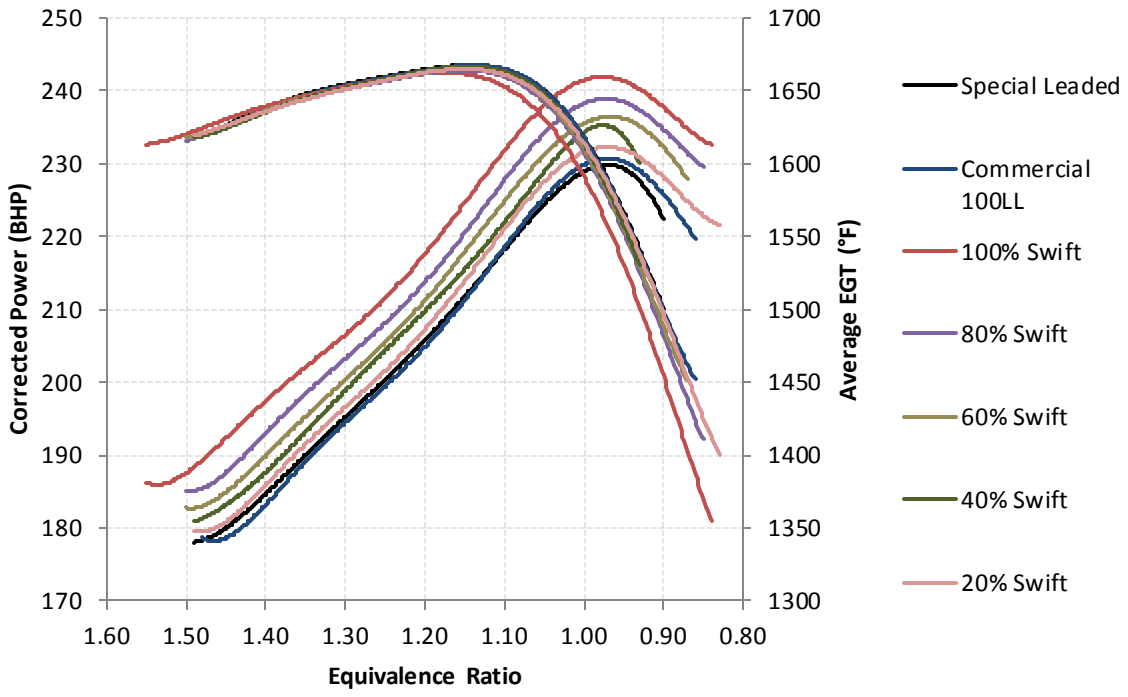

Figure 11. IO-540-K Engine Performance of All Blends at Climb Power

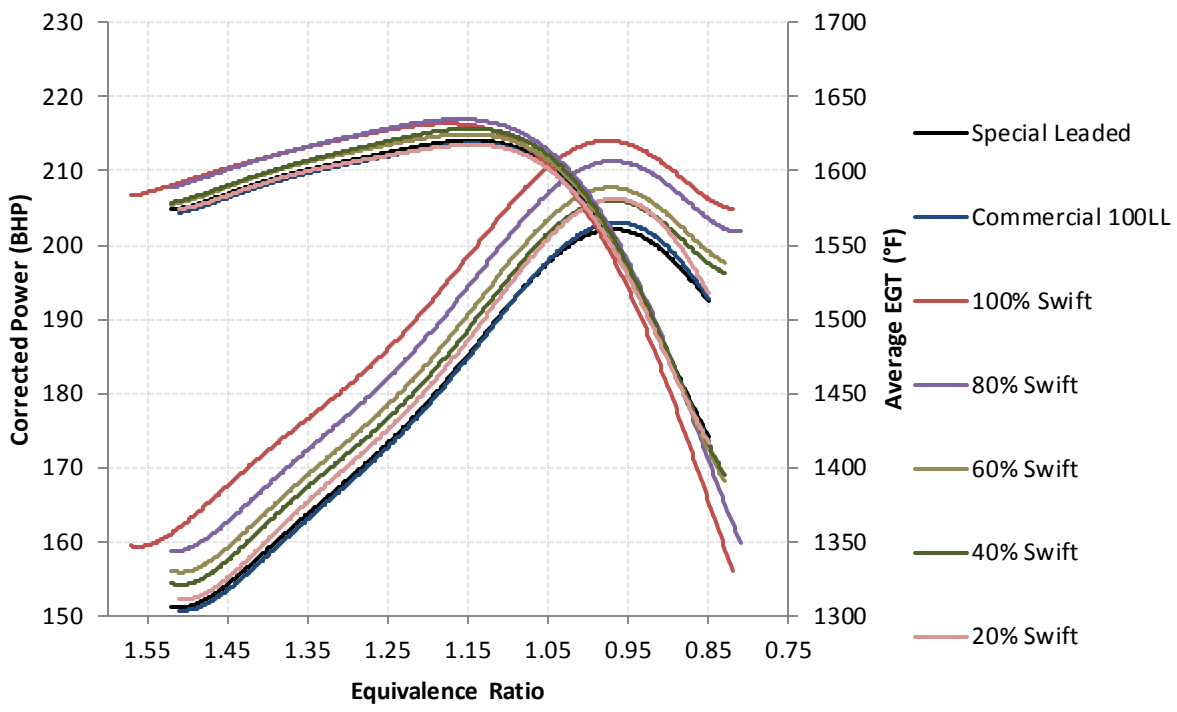

Figure 12. IO-540-K Engine Performance of All Blends at Cruise Power

The variation of MON, supercharge, and lead content with the percentage of Swift fuel in the blends is shown in figures 13 and 14. Blending in the high-octane aromatic content results in nonlinear MON and supercharge blend response. As the high-octane Swift fuel is blended into the 100LL the MON (per ASTM D2700) of the blend decreases and the SC PN (per ASTM D909) slowly increases until the Swift fuel concentration reached 40% mass/mass (m/m%) of the blend. Blending in an additional 20% by mass Swift fuel beyond the 40 m/m% value into the 100LL caused the MON to increase and the SC PN to spike. The SC PN measurement stops at 161 so those values were listed as >161 on the certificate of analysis. As the Swift fuel mass % was increased, the MON continually increased with a bigger proportional increase occurring between the 80%–100% Swift fuels than between the 60%–80% m/m Swift fuel blend.

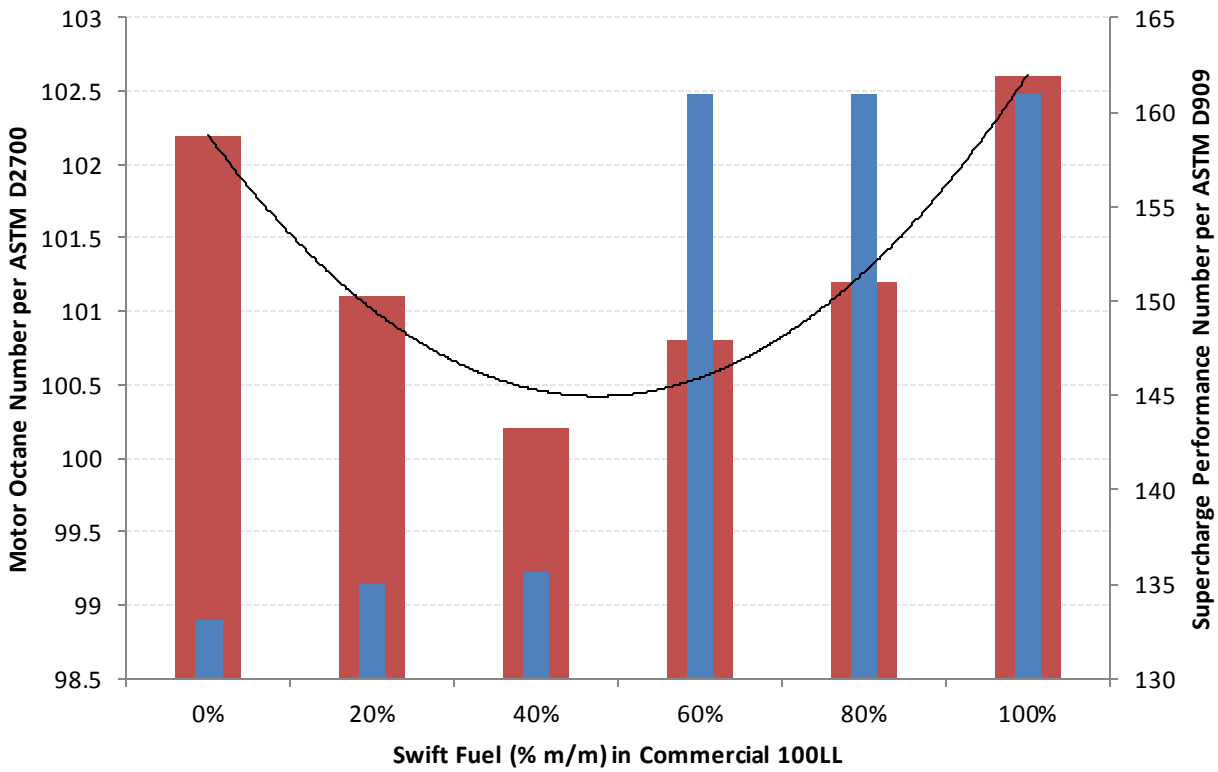

Figure 13. The MON per ASTM D2700 and SC PN per ASTM D909 for Fuels Tested

Previous FAA WJHTC POWER Laboratory testing, in coordination with the CRC, revealed that 100LL fuels of similar octane perform comparably in the full scale engine up to a condition in which the lead additive—tetraethyl lead—was below 0.55 ml TEL/gal. At lead concentrations below this level, a knee in the curve was determined where the full-scale engine detonation performance reduces considerably with reductions on lead concentration.

As figure 14 shows, this lead concentration level of 0.55 ml TEL/gal occurred between 60% and 80% m/m Swift fuel blends. Previous testing at the POWER Lab revealed that unleaded fuels typically underperform by approximately 2 MON [10] in the full-scale engine compared to leaded fuels of the same MON (per ASTM D2700). This relationship did not seem to hold in the case of 100% Swift fuel, for which more than 80% of the blend was 1,3,5 trimethylbenzene.

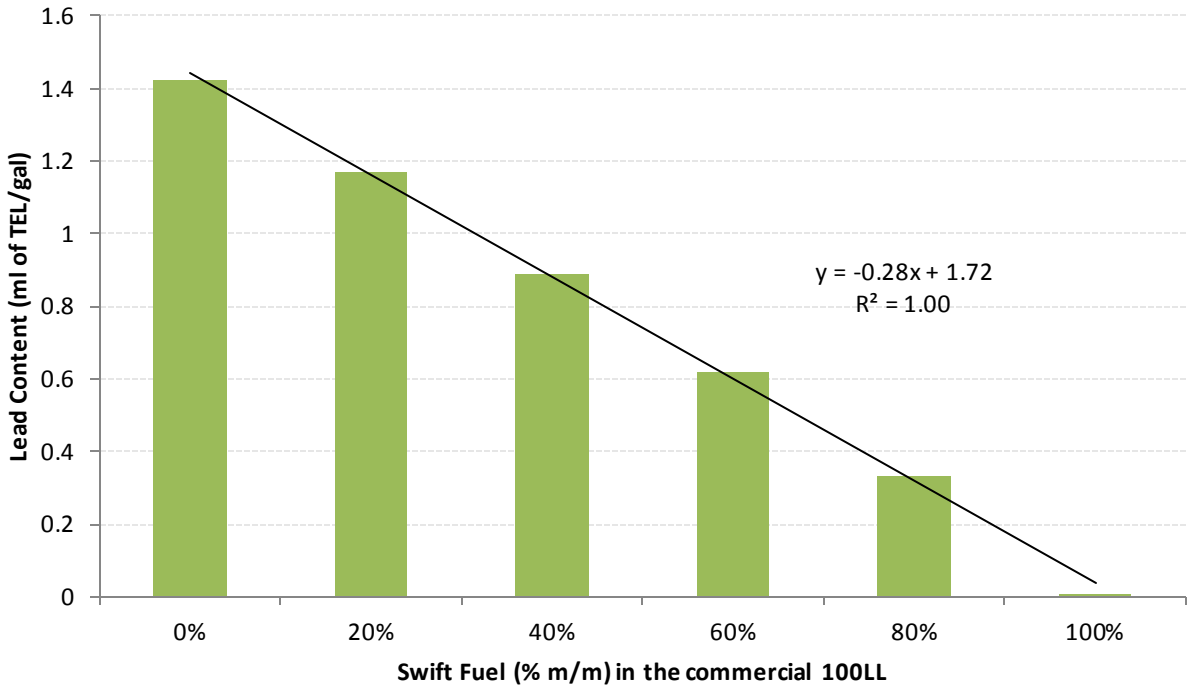

Figure 14. Lead Content Variation With Swift Fuel Content

The detonation onset of the fuels tested in the IO-540-K engine is shown in figure 15. The detonation onsets for the 0% Swift fuel blend and the special leaded fuel occur, as expected, based on the respective MON (per ASTM D2700) and supercharge laboratory test results.

As shown in figure 15, 0% Swift fuel (100% commercial 100LL) performs, as expected, based on the fuel's moderate MON and supercharge test results. The detonation response of the 20% Swift blend decreases at all power settings. This corresponds to the decrease in MON and lead content due to the increase in aromatic content. The detonation response of the 40% Swift blend improves at take-off power and decreases at climb and cruise. This tracks with an increase in the supercharge, which has the greatest impact on the take-off power setting and a further decrease in the lead content and the MON, which has a greater impact than the supercharge and the most impact at the low power settings. With the additional 20 m/m% of Swift fuel from 40% to 60%, the detonation response continues to improve at take-off, begins to improve at climb, and stabilizes at cruise power settings. This corresponds to the spike in the SC PN and the increase in the MON. At the 60% m/m Swift concentration, the lead concentration is above the 0.55 ml TEL/gal level. The detonation response of the 80 m/m% Swift blend degrades from the 60 m/m% response at take-off and climb and stays the same at cruise. Between the 60% and 80% Swift blends, the lead concentration of the fuel decreases below the 0.55 ml TEL/gal level for this engine even though there was a slight increase in the blend MON. The 100% Swift fuel detonation response improves, with the aromatic concentration overwhelming the blend, for all fuels and behaves as suggested given the fuels MON and supercharge characteristics.

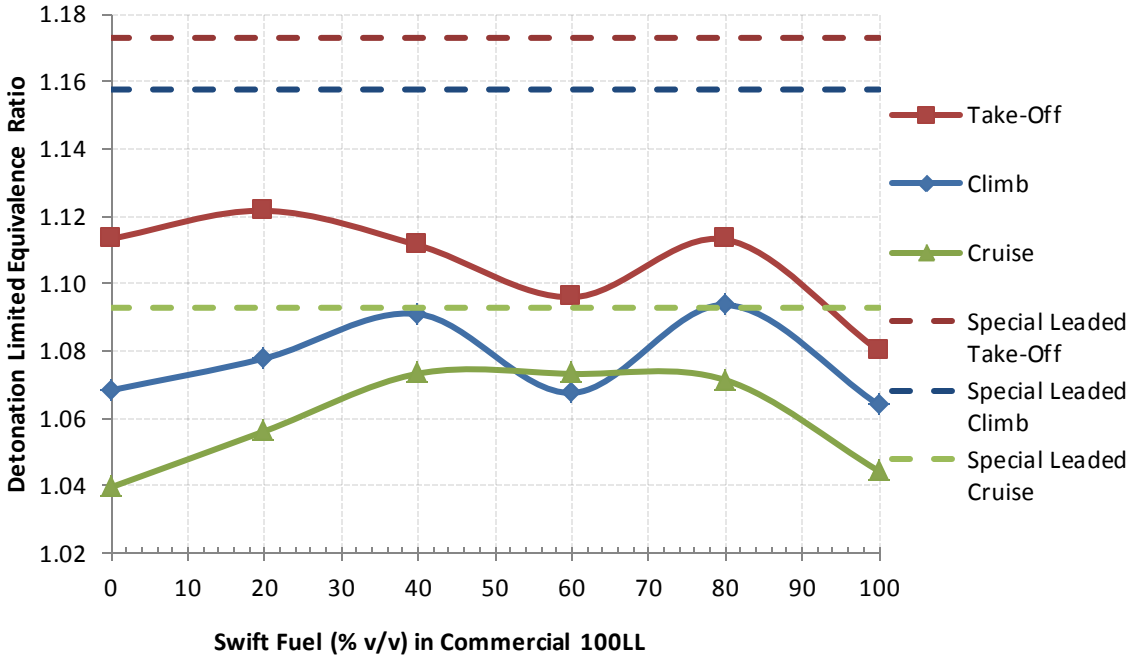

Figure 15. Full-Scale Engine Detonation Performance of Swift Fuel Blended With 102.2 MON 100LL, From 0% to 100% in Increments of 20% m/m

To demonstrate the non-linear impacts, the detonation onset equivalence ratio is compared to the fuel MON (per ASTM D2700), as shown in figure 16. Note that the 100.8 MON blend has a higher supercharge than the 101.1 MON fuel, so the inversion of the trends at high and low power makes sense. This is the same with the 102.6 MON Swift fuel in which the zero lead content increases detonation onset at cruise compared to the 100% commercial 100LL.

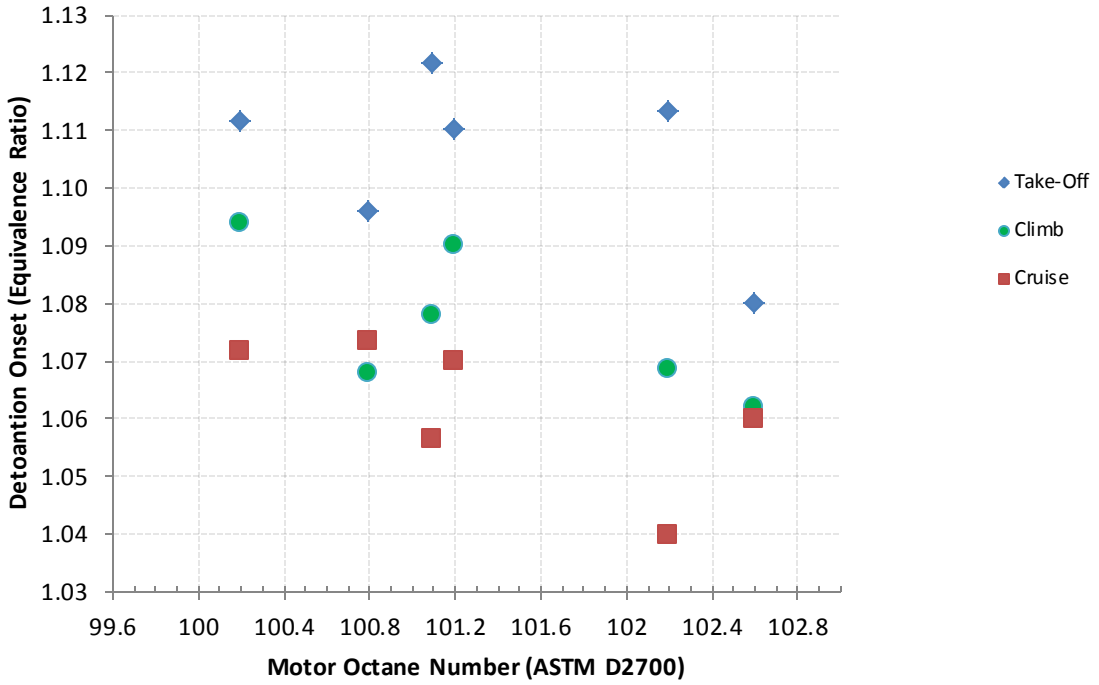

Figure 16. Detonation Performance of Swift Fuel Blends Relative to ASTM D2700 MON

Direct comparisons of the special leaded fuel detonation onset and the onset with the other test fuels are shown in figures 17 through 28. The differences in fuel behavior are more apparent using an equivalence ratio than with fuel mass flow. This is the expected behavior because Swift fuel is approximately 1 lb/gal denser than the average AVGAS. This increase in density means that, at the same fuel mass flow rate, the engine is running chemically leaner on Swift fuel than on 100LL.

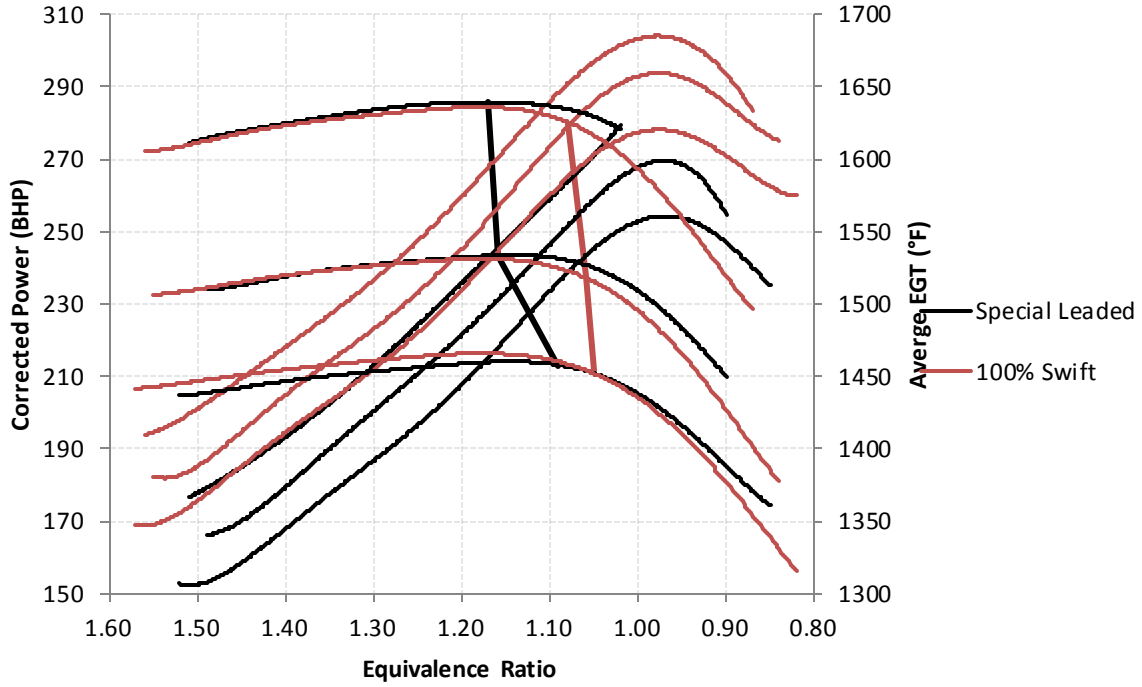

Figure 17. Direct Comparison of Special Leaded Detonation Onset and 100% Swift Fuel vs. Equivalence Ratio

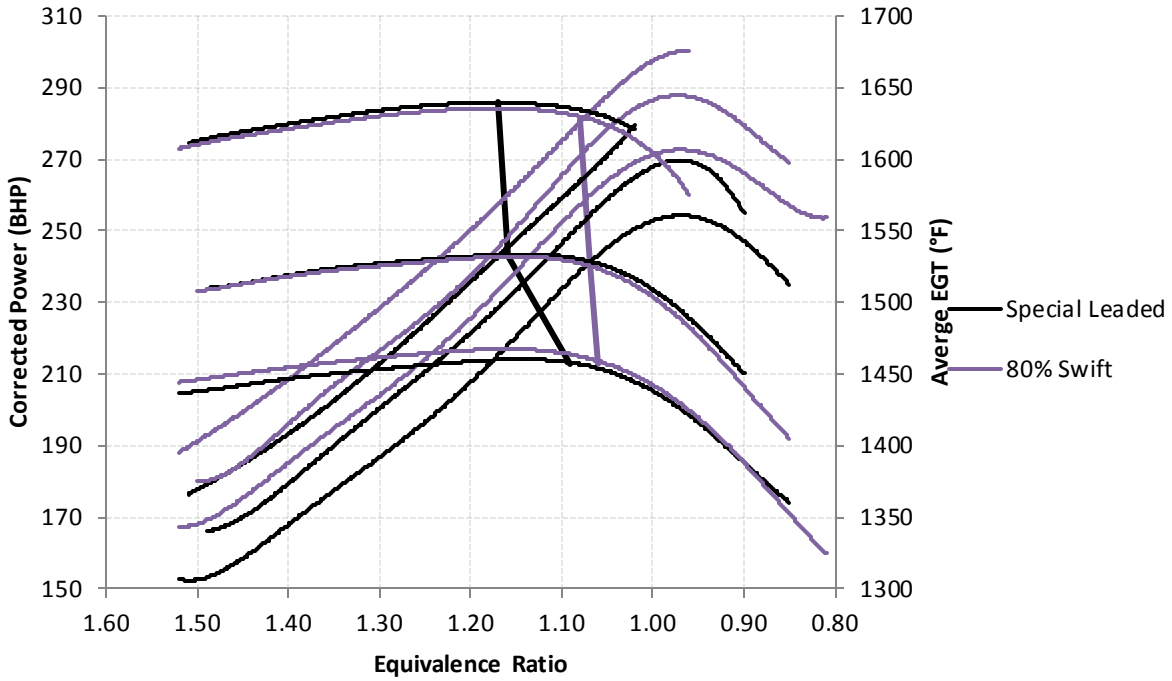

Figure 18. Direct Comparison of Special Leaded Detonation Onset and 80% Swift Fuel vs. Equivalence Ratio

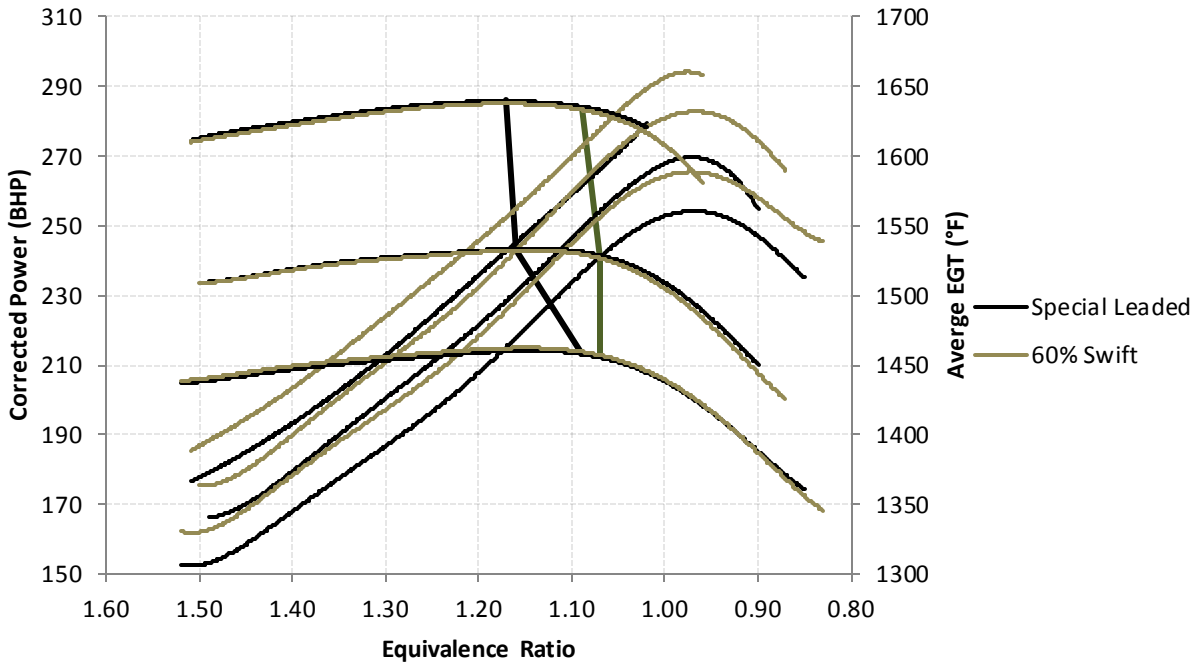

Figure 19. Direct Comparison of Special Leaded Detonation Onset and 60% Swift Fuel vs. Equivalence Ratio

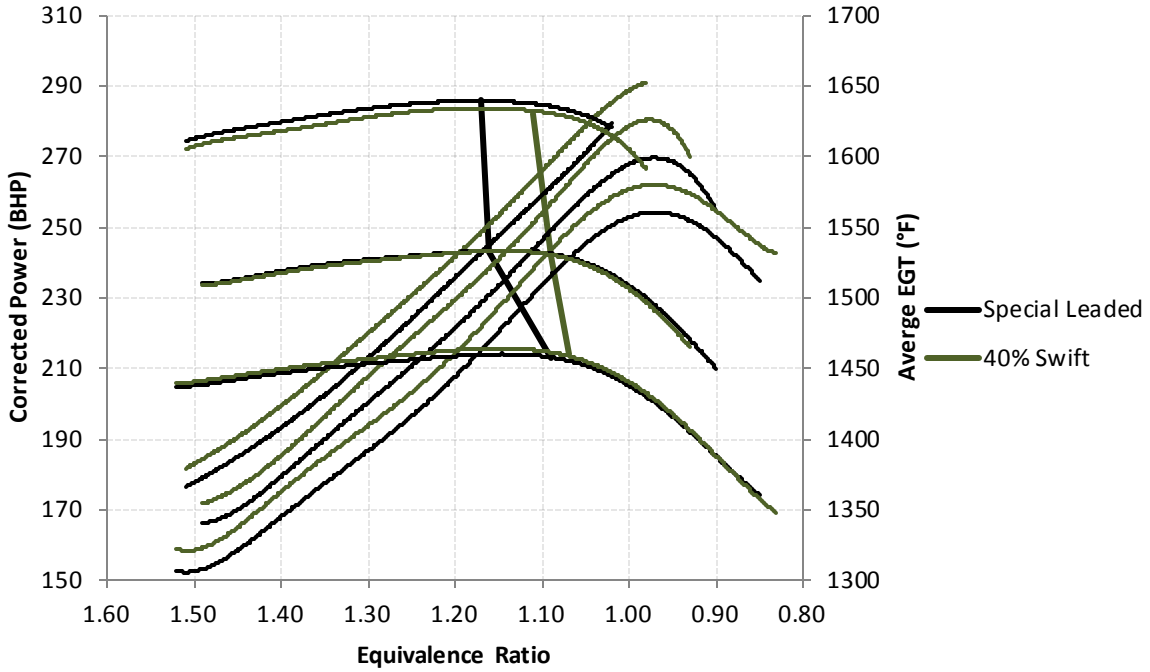

Figure 20. Direct Comparison of Special Leaded Detonation Onset and 40% Swift Fuel vs. Equivalence Ratio

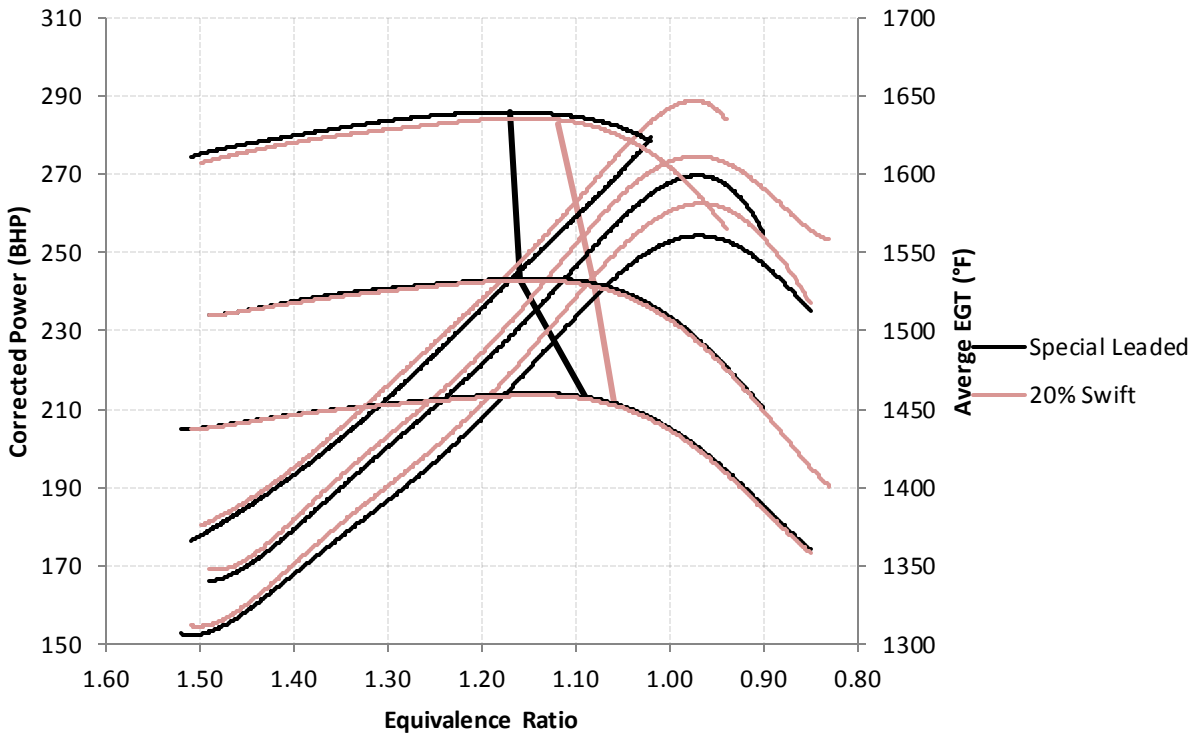

Figure 21. Direct Comparison of Special Leaded Detonation Onset and 20% Swift Fuel vs. Equivalence Ratio

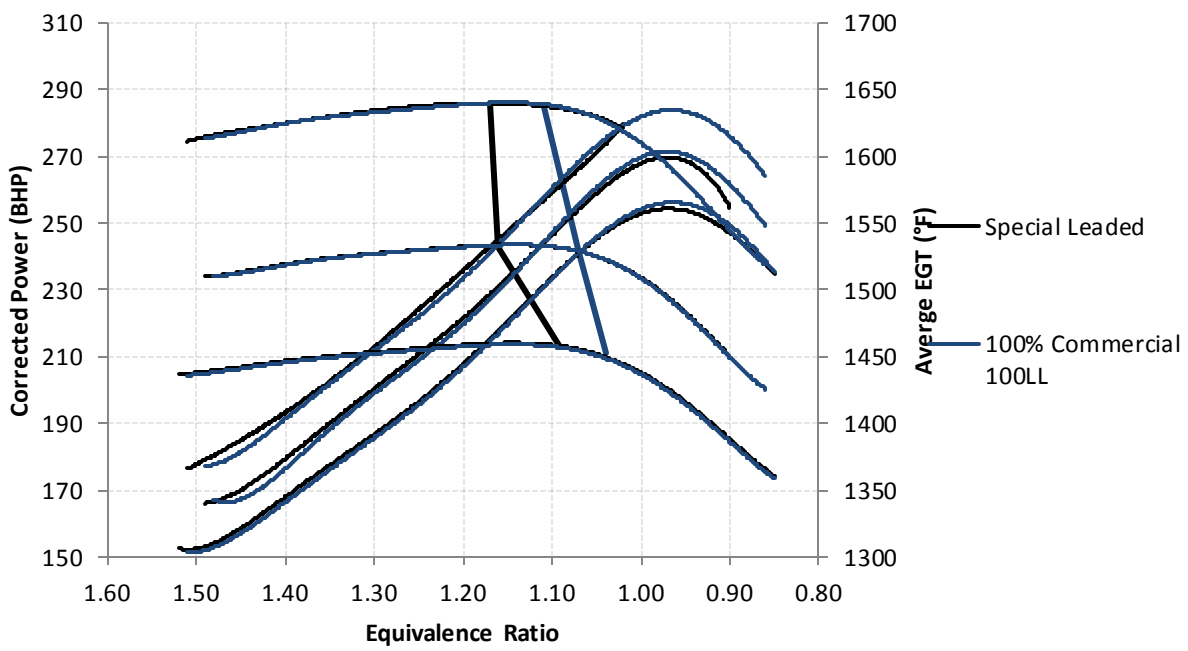

Figure 22. Direct Comparison of Special Leaded Detonation Onset and 100% Commercial 100LL vs. Equivalence Ratio

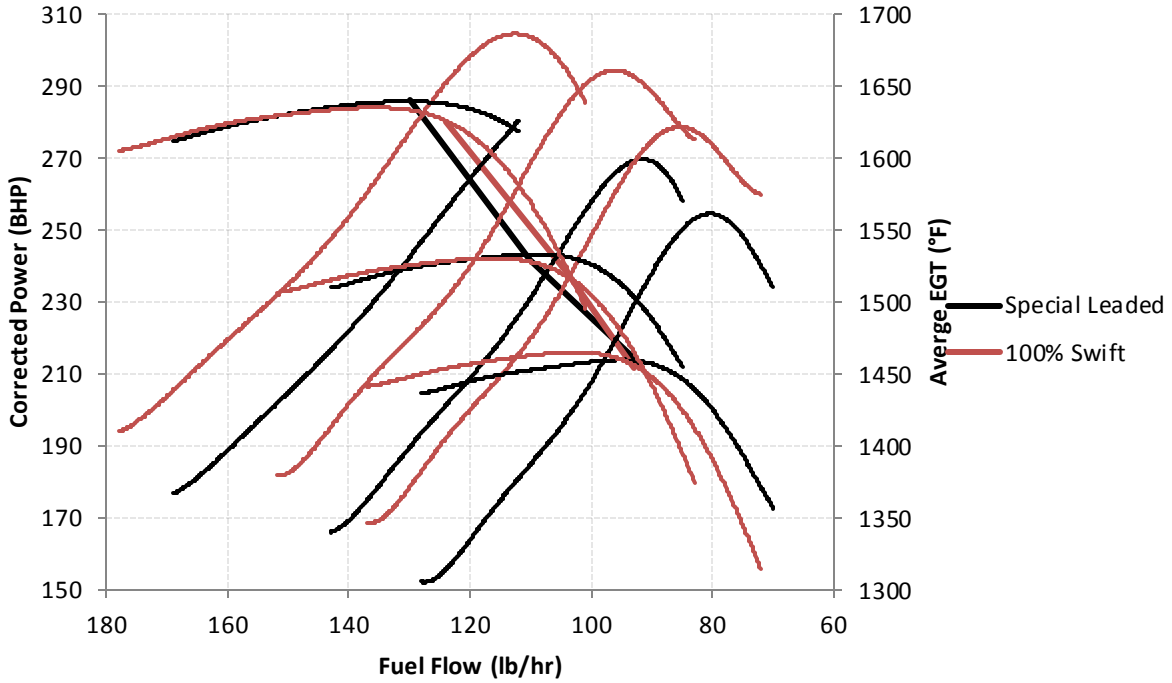

Figure 23. Direct Comparison of Special Leaded Detonation Onset and 100% Swift Fuel vs. Fuel Flow

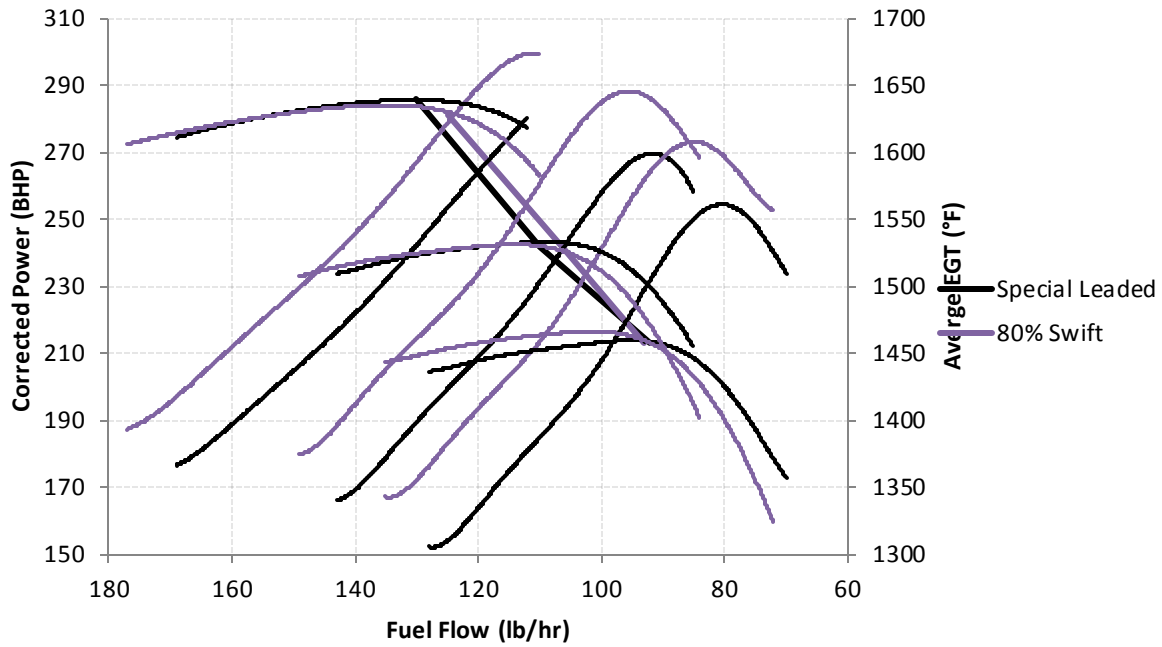

Figure 24. Direct Comparison of Special Leaded Detonation Onset and 80% Swift Fuel vs. Fuel Flow

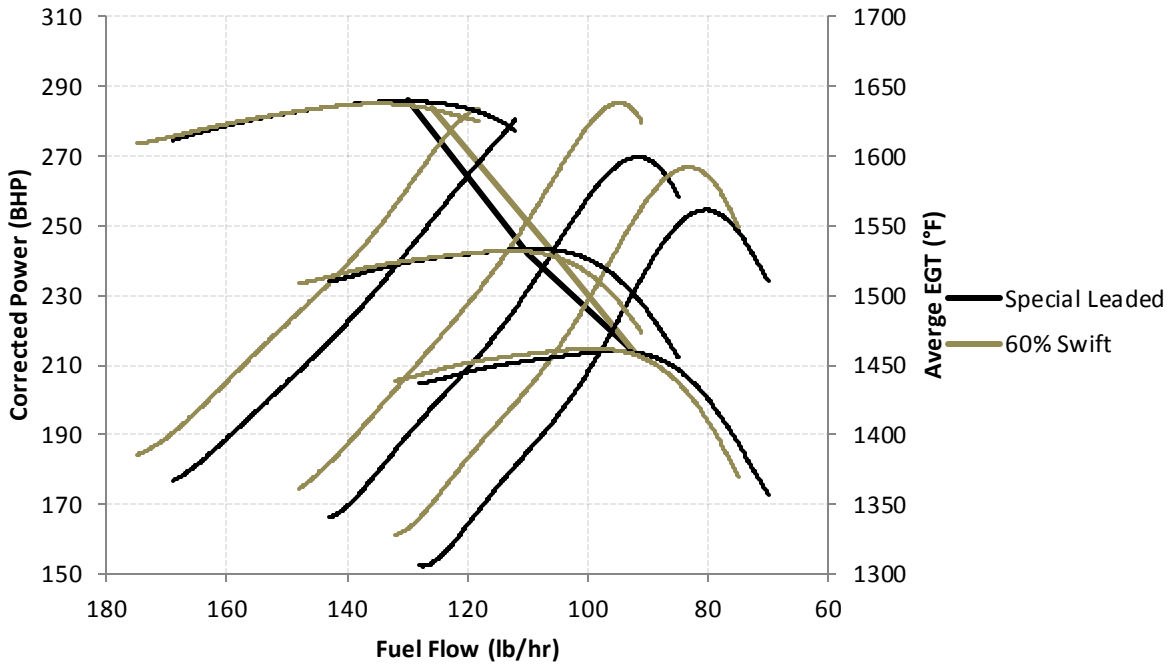

Figure 25. Direct Comparison of Special Leaded Detonation Onset and 60% Swift Fuel vs. Fuel Flow

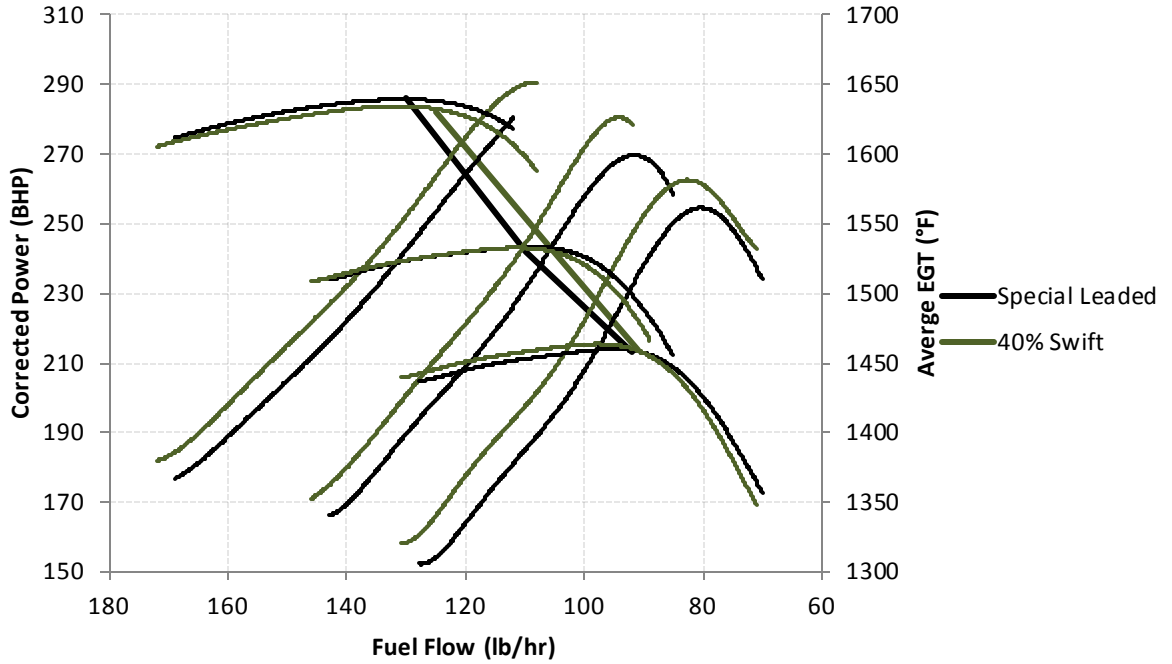

Figure 26. Direct Comparison of Special Leaded Detonation Onset and 40% Swift Fuel vs. Fuel Flow

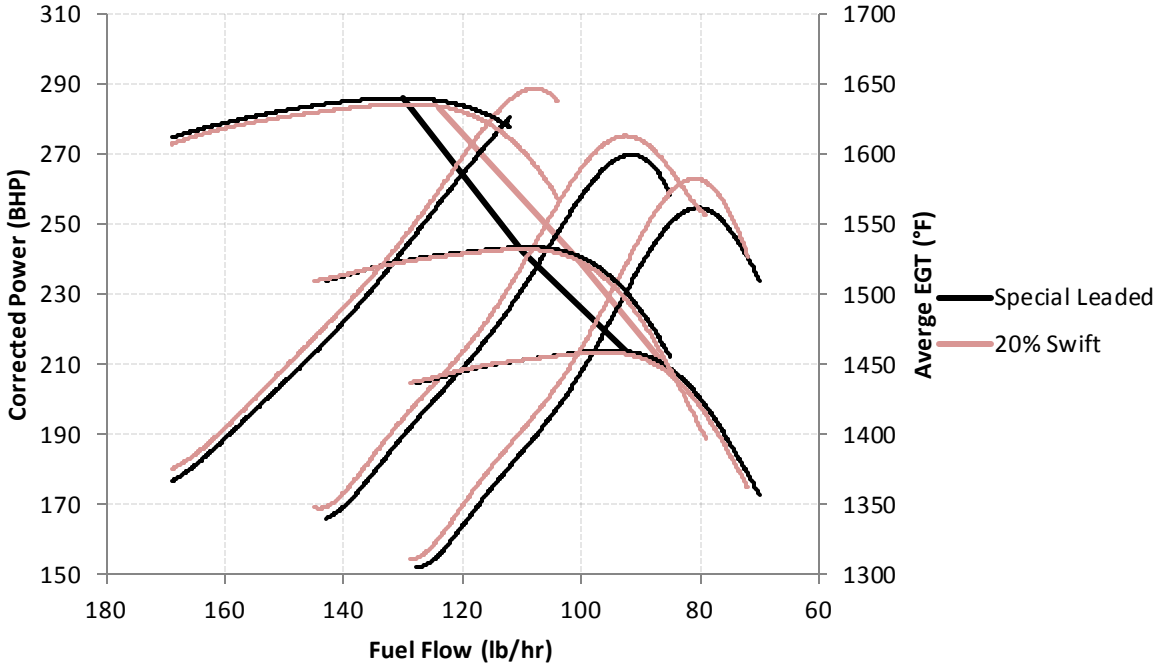

Figure 27. Direct Comparison of Special Leaded Detonation Onset and 20% Swift Fuel vs. Fuel Flow

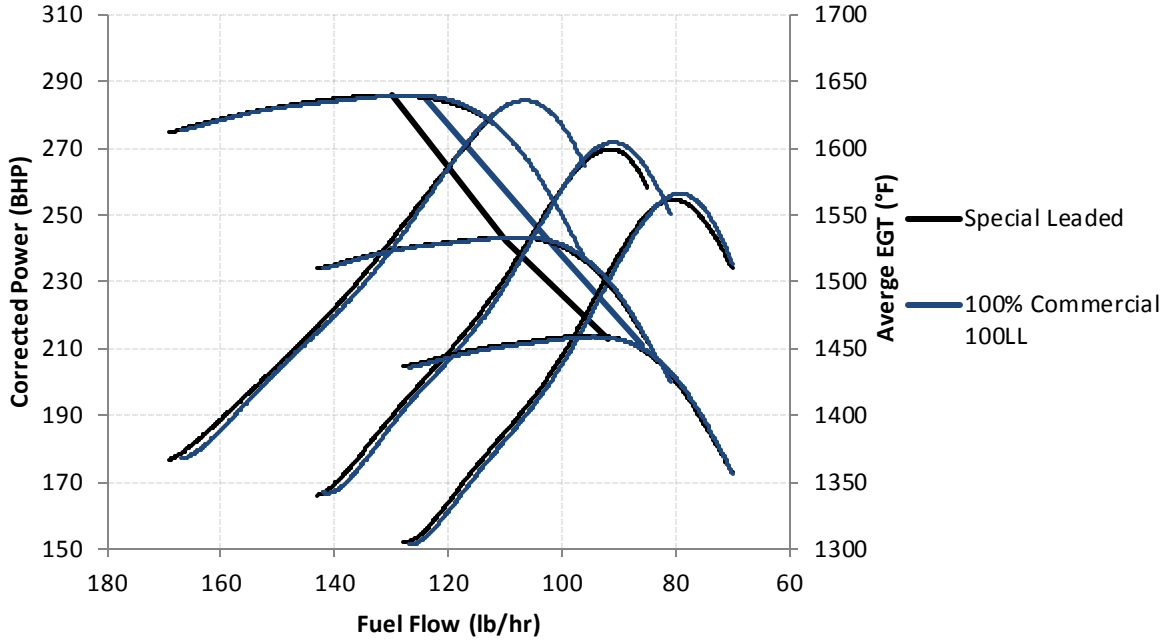

Figure 28. Direct Comparison of Special Leaded Detonation Onset and 100% Commercial 100LL vs. Fuel Flow

3.2 CONTINENTAL IO-360-DB

Figures 29 through 31 provide a general overview of the overall performance of the fuels tested. At the full-rich condition, Swift fuel produced 9 BHP or 4% of rated powers less than the 100% commercial 100LL at take-off. As the fuel mixture was leaned, the Swift fuel experienced a slightly increased loss of power compared to the 100% commercial 100LL. With Swift fuel, there was approximately a 40°–70°F increase in average peak EGT compared to the 100LL fuels, depending on the power setting. The blends of Swift fuel and 100% commercial 100LL show the same trend with EGT, such that the higher the percentage of Swift fuel, the higher the average EGT.

Only individual, isolated, and random minor detonation events occurred during this testing. The POWER Laboratory has experienced these random light detonation events even when operating on commercial 100LL. Advisory Circular 33.47 also acknowledges the potential for individual detonation events during normal operation with up to 9 flashes or events allowed per minute [11].

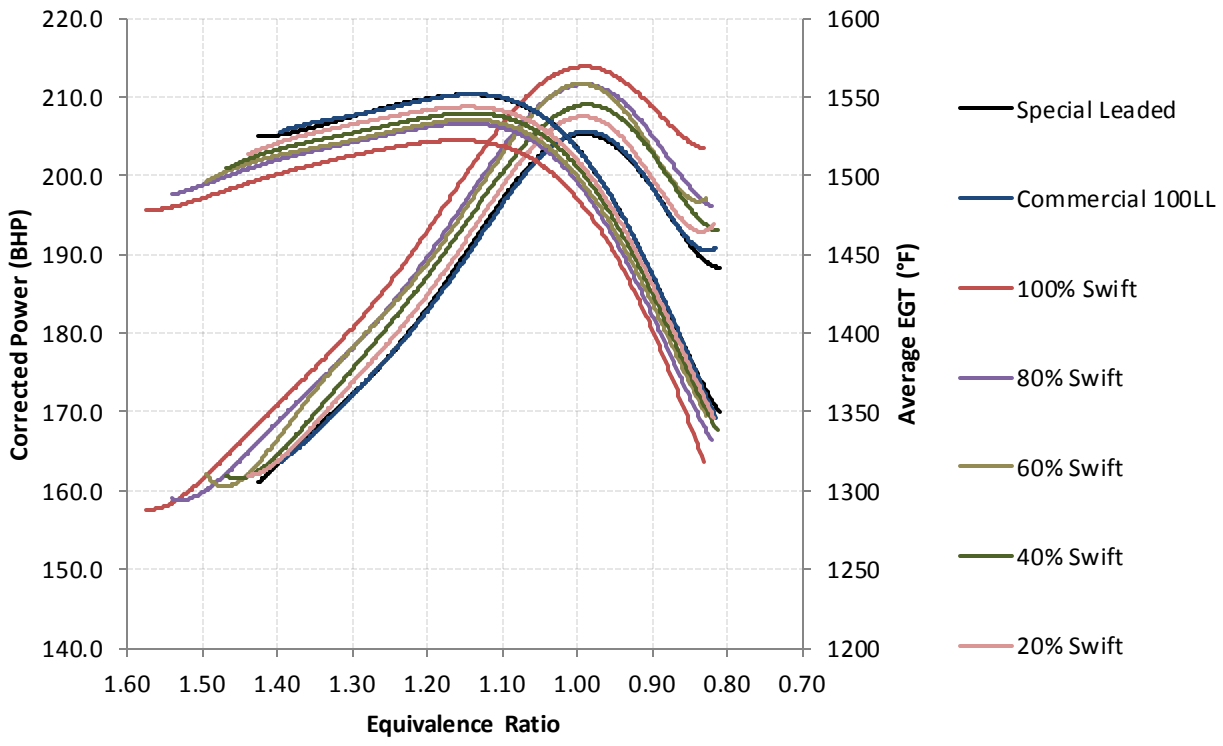

Figure 29. Engine Performance of All Blends at Take-off Power in the IO-360-DB

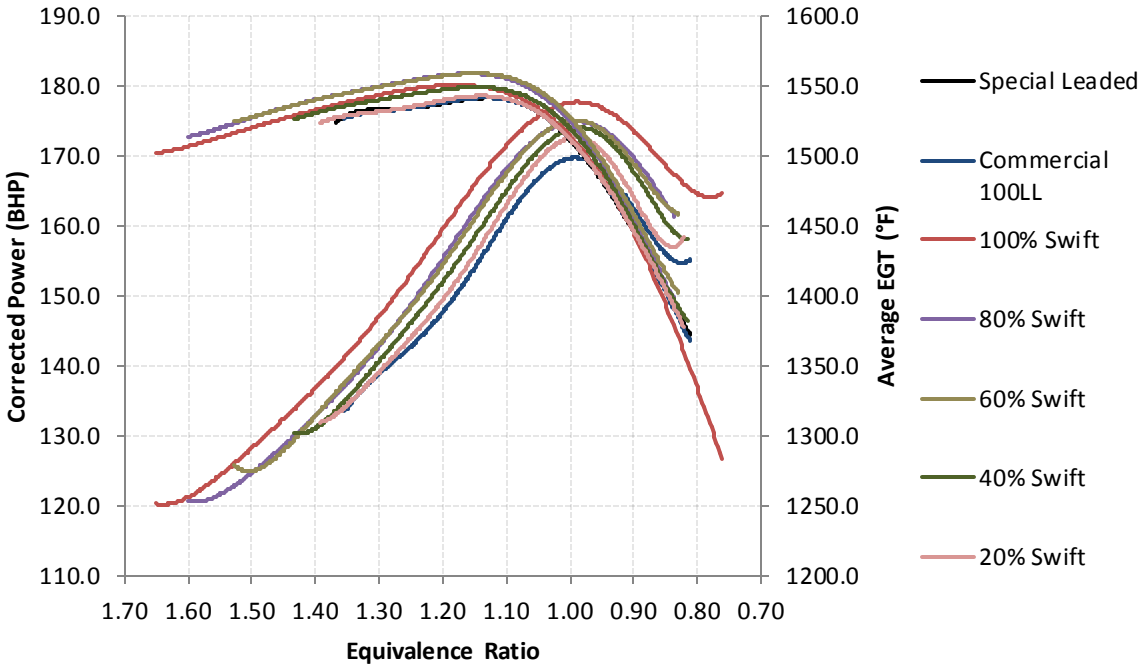

Figure 30. Engine Performance of All Blends at Climb Power in the IO-360-DB

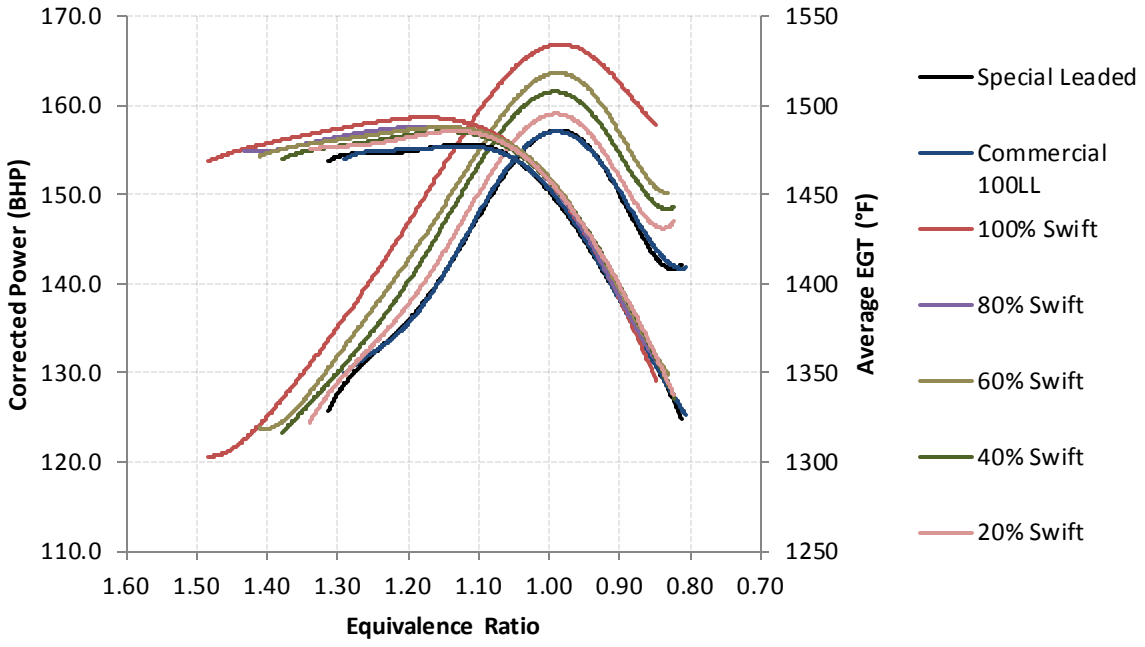

Figure 31. Engine Performance of All Blends at Cruise Power in the IO-360-DB

4. CONCLUSIONS

This report is an evaluation of the tested blends detonation performance; other impacts of these blends on the engine and airframe combination were not evaluated in this testing. At the request of the applicant, detonation testing of Swift fuel and 100 low-lead (100LL) blends to determine backwards and forwards compatibility of Swift fuel in a high-octane demand engine was performed. A Lycoming IO-540-K and a Continental IO-360-DB were used for this testing. The IO-540-K was previously tested with Swift fuel and is accepted as a high-octane demand engine. The blends tested ranged from 100% Swift fuel to 100% commercial 100LL in increments of 20% mass Swift fuel. A special leaded test fuel, which met ASTM D910 and was laboratory manufactured to be near the minimum motor octane number (MON) and supercharge rich performance number (SC PN) limits, was also tested in the engines; this fuel also contained near-maximum allowable lead content.

Research performed at the Federal Aviation Administration William J. Hughes Technical Center POWER has shown nonlinear MON (per ASTM D2700) and SC PN (per ASTM D909) behavior of blends of high-aromatic unleaded fuel and 100LL. This previous research has also shown that full boiling range unleaded fuels of equivalent laboratory octane to leaded fuels do not perform as well in terms of full-scale engine antiknock performance, suggesting that the type of testing performed and documented in this report is needed to verify sufficient detonation protection. However, with the 100% Swift fuel, this relationship did not seem to hold.

The addition of as little as 20% Swift fuel to 100LL resulted in a fuel that no longer met the D910 specification. Specifically, for the blends used in this testing, the heat of combustion and 50% and 90% distillation limits will no longer meet specification limits of D910. This blend also did not meet the Swift D7719 specification for lead content or density. The impact of the blending and mixing of fuels on these specification limits needs to be considered. As shown in this testing, two fuels meeting their respective specifications were combined and the resulting blends did not meet all of the limits for either specification.

In the IO-540-K, under extreme hot- and dry-day sea-level test temperatures with dry inlet air, all of the fuels provided detonation-free operation at the full-rich requirement for this engine above the cruise power setting, where fuel mixture leaning is prohibited. At all power settings, all blends provided an increase in detonation protection compared to the special leaded fuel, when evaluated using the equivalence ratio and at take-off and climb power for fuel mass flow. None of the blends offer the same detonation protection as the best fuel for a given power setting. The 40%, 60%, and 80% Swift fuels offer more detonation protection than the commercial 100LL at take-off, and the 40% Swift fuel also offers more detonation protection at climb. All of the blends perform worse than both the 100% Swift fuel and the 100% commercial 100LL at cruise. Analysis with fuel mass flow fails to account for the significant density difference between 100LL and Swift fuel. The 100% Swift fuel offers the most detonation protection at both take-off and climb power settings; the 100% commercial 100LL, used in this testing, is better at cruise. At the cruise power setting, equivalent detonation protection to the special leaded fuel was found even when evaluating the use of fuel mass flow. Swift fuel produces approximately 3 BHP less in the IO-540-K as the 100% commercial 100LL or 1% of rated power, and produces a 50°–70°F increase in average exhaust gas temperatures (EGTs).

For the IO-360-DB, under extreme hot-day sea-level test temperatures with 10% relative humidity in the intake air, all of the fuels provided detonation-free operation throughout the entire window of operation tested. This includes the lean of peak EGT operation at take-off power. Swift fuel produced 9 BHP less during operation at take-off power and full-rich operation; this is 4% of the rated power for this engine. The use of Swift fuel also increased the average EGT 40°–70°F.

5. REFERENCES

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