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Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Anti-Knock Performance of Reduced Lead Aviation Gasoline in a Full-Scale Engine

June 2014

Final Report

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16. Abstract

The Federal Aviation Administration Aviation Fuel and Engine Test Facility (AFETF) in coordination with industry has undertaken a research program to investigate the use of reduced lead in current leaded aviation gasoline (AVGAS). The four fuels used in the testing were as follows: fuel 1—a minimum octane specification of 100 low-lead (100LL) AVGAS, blended to be close to the minimum ASTM International motor octane number (MON) per ASTM D2700 and D909 supercharge rich performance number (SC PN) specification limits, using commercial 100LL and containing approximately the maximum allowable tetraethyl lead level; fuel 2—the theoretical lowest leaded fuel, blended with pure isooctane, isopentane, and toluene to obtain a fuel meeting table 1 properties in ASTM D910 for 100LL with the least amount of lead needed; fuels 3 and 4—blended with commercial 95 MON and 92 MON alkylate, respectively, to meet the minimum ASDM D910 specification limits for MON and SC PN. A full-scale IO-540-K Lycoming engine was used for the study.

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 75% power, for which fuel mixture leaning is prohibited. At the 75% performance cruise power setting, under extreme hot- and dry-day conditions, approximating 3500-ft altitude for temperature and dry air, fuels 2 and 4 were below a 2% detonation intensity level. Fuels 1 and 3 approached a 2% detonation intensity level for two of the three repeat test runs.

For all of the extreme hot- and dry-day condition test points, fuel 2—the theoretical lowest lead fuel made from pure components—showed the worst anti-knock performance, whereas fuel 4—made from commercial 92 MON aviation alkylate—showed the best anti-knock performance. Both fuels 3 and 4, made using commercial alkylate and containing 45% and 28% of the maximum allowable lead level for 100LL, respectively, showed better anti-knock performance than the baseline laboratory 100LL fuel 1 containing the maximum allowable lead. Ultimately, these data may be used to establish a minimum value for lead content in the ASTM D910 specification for 100LL. In addition, a slight impact of toluene (aromatic) concentration on average exhaust gas temperature was noted during the study; however, these concentration levels fall within the experience of the existing fleet.

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LIST OF ACRONYMS

100LL	100 low-lead
AFETF	Aviation Fuels and Engine Test Facility
AVGAS	Aviation gasoline
BE	Best economy
BHP	Brake horsepower
CBHP	Corrected brake horsepower
CHT	Cylinder head temperature
EGT	Exhaust gas temperature
FAA	Federal Aviation Administration
F/R	Full-rich
IAT	Inlet air temperature
MAP	Manifold absolute pressure
MON	Motor octane number
RPM	Revolutions per minute
SC PN	Supercharge rich performance number
TEL	Tetraethyl lead
TEL-B	Mandatory TEL additive in 100LL
WJHTC	William J. Hughes Technical Center
WOT	Wide open throttle

EXECUTIVE SUMMARY

Extensive research done at the Federal Aviation Administration William J. Hughes Technical Center Aviation Fuel and Engine Test Facility (AFETF) and previous literature have shown that unleaded fuels of equivalent laboratory octane to leaded fuels typically do not perform as well in terms of full-scale engine anti-knock performance. This degradation of anti-knock performance is estimated to fall between 2 and 3 motor octane numbers (MONs) per ASTM International D2700. The current ASTM fuel specification covering types of leaded aviation gasoline (AVGAS), ASTM D910, contains a mandatory additive requirement for tetraethyl lead (TEL) and a maximum allowable lead level, but does not contain a minimum lead level. If there is a trend to reduce AVGAS lead content, a point may be reached at which the degradation in full-scale engine anti-knock performance observed for unleaded fuels may become apparent, either as a gradual erosion of detonation margin or as a sudden change. In cooperation with Industry, the AFETF has undertaken a research program to investigate this effect. This research covers engine and independent laboratory fuel tests that evaluated two different commercial alkylates with significantly reduced amounts of TEL added and compares that performance to a laboratory-made minimum specification of 100 low-lead (100LL) with close to maximum allowable lead content. In addition, a pure component AVGAS was included to represent a theoretical fuel of minimum TEL content.

The test fuels consisted of blends of commercial 100LL, commercial grade toluene, isopentane, isooctane, methyl-cyclohexane, 92 MON commercial alkylate, and a 95 MON commercial alkylate. The alkylate-blend components were provided by fuel refineries and the 100LL was procured from a local airport. The four fuels used in the testing were as follows:

- Fuel 1—A minimum octane specification of 100LL, blended to be close to the minimum MON and D909 supercharge rich performance number (SC PN) specification limits, using commercial 100LL, *n*-pentane, methyl cyclohexane, commercial toluene, and containing approximately the maximum allowable TEL level.

- Fuel 2—The theoretical lowest leaded fuel, blended with pure isooctane, isopentane, and toluene to obtain a fuel meeting table 1 properties in ASTM D910 for 100LL with the least amount of lead needed.

- Fuels 3 and 4—Blended with commercial 95 MON and 92 MON alkylate, respectively, with isopentane, commercial grade toluene, and TEL added to meet the minimum ASTM D910 specification limits for MON and SC PN.

Because the focus of the study was on laboratory octane quality versus full-scale engine anti-detonation performance, every effort was made to ensure the test fuels were of comparable MON, (range 100.1 to 100.8) and SC PN (range 130.0 – 130.9).

A full-scale IO-540-K Lycoming engine was used for this study, the engine previously determined to be a representative high octane requirement engine in the active general aviation fleet.

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 75% power, at which fuel mixture leaning is prohibited. At the 75% performance cruise power setting, under extreme hot- and dry-day conditions, approximating 3500-ft altitude for temperature and dry air, fuels 2 and 4 were below a 2% detonation intensity level. Fuels 1 and 3 approached a 2% detonation intensity level for two of the three repeat test runs, indicating the fuels were approaching detonation levels used for this testing.

For all of the extreme hot- and dry-day condition test points, fuel 2—the theoretical lowest lead fuel made from pure components—showed the worst anti-knock performance, whereas fuel 4—made from commercial 92 MON aviation alkylate—showed the best anti-knock performance. Both fuels 3 and 4, made using commercial alkylate and containing 45% and 28% of the maximum allowable lead level for 100LL, respectively, showed better anti-knock performance than the baseline laboratory 100LL fuel 1 containing the maximum allowable lead.

Under the conditions of the test:

Fuel 4 (0.90 ml TEL/gal) > Fuel 3 (0.55 ml TEL/gal) > Fuel 1 (2.00 ml TEL/gal) > Fuel 2 (0.35 ml TEL/gal)

→

Decreasing Full-Scale Engine Anti-Knock Performance

Ultimately, these data may be used to establish a minimum value for lead content in the ASTM D910 specification for 100LL.

In addition, a slight impact of toluene (aromatic) concentration on average exhaust gas temperature was noted during the study; however, these concentration levels fall within the experience of the existing fleet.

1. INTRODUCTION.

1.1 PURPOSE.

The purpose of this research was to compare the full-scale engine anti-knock performance of two commercial aviation alkylate 100 low-lead (100LL) blends containing reduced amounts of tetraethyl lead (TEL) against the anti-knock performance of a baseline laboratory 100LL of maximum lead content. In addition, a 100LL made from pure components was included to represent a theoretical minimum lead content fuel. These data may be used to assist in establishing a minimum lead content for ASTM International D910 [1] aviation gasoline (AVGAS) specifications.

1.2 BACKGROUND.

Researchers at the Federal Aviation Administration (FAA) Aviation Fuel and Engine Test Facility (AFETF) have many years of experience of testing unleaded and reduced lead aviation fuels in support of government, environmental, and industry initiatives. The current specification (ASTM D910) for leaded AVGAS, known as 100 low-lead (100LL), contains a mandatory requirement for the octane enhancement additive TEL-B, specifying a maximum allowable lead level, but without specifying a minimum lead level.

The FAA William J. Hughes Technical Center (WJHTC) and previous research have shown that unleaded and leaded fuels, with the same laboratory motor octane number (MON) per ASTM D2700 [2]), provide different levels of detonation protection in full-scale aviation engines. Further, leaded fuels typically provide better anti-knock performance in the full-scale engines than unleaded fuels of equivalent octane. This raises a significant concern that unleaded fuels may be produced that meet the ASTM D910 laboratory specification, but do not provide adequate detonation protection to the full-scale engine.

The objective of the research was to determine and compare the anti-knock performance of several variations of a reduced lead AVGAS to a minimum specification 100LL, which contains the maximum permissible amount of TEL. A pure component 100LL is also included to give a theoretical minimum lead content fuel. Testing multiple reduced leaded fuels may enable relevant parties to determine a minimum lead requirement for the ASTM D910 specification. This research addressed variations in commercial alkylate octane quality, but did not address changes in concentrations of the commercial grade toluene often found in AVGAS.

The engine used to evaluate the fuels was a Lycoming IO-540-K. This engine is a naturally aspirated, 540 cubic-inch, 6-cylinder engine that was previously determined by the engine manufacturer to be a representative high-octane sensitivity engine.

2. TEST PREPARATION.

2.1 REDUCED LEAD FUELS.

Four fuels, that were made using commercial 100LL, commercial grade toluene, n/isopentane, isooctane, methyl cyclohexane, commercial 92 MON per ASTM International D2700 alkylate, commercial 95 MON alkylate, and TEL-B, were tested for this research. These components were provided to an independent laboratory for manufacture of the four test fuels and analyses.

Fuel 1 was a baseline comparison laboratory 100LL blended to be close to the minimum MON and supercharge rich performance number (SC PN) per ASTM D910. The blend was made by using commercial 100LL with the MON and SC PN reduced through the use of n-pentane and methyl cyclohexane and the SC PN was attained by using commercial toluene. The TEL was added to a level close to the maximum allowed lead concentration for 100LL per ASTM D910. This blend served as the comparison to the other reduced leaded blends.

Fuel 2 was made to represent the theoretical lowest lead fuel, blended using the best pure chemicals typically found in conventional AVGAS—namely pure isooctane, isopentane, and toluene—to obtain a fuel meeting ASTM D910 SC PN and MON using the least amount of lead possible.

Fuels 3 and 4 were blended using commercial grade aviation alkylate of approximately 95 and 92 MON per ASTM D2700, respectively, and represented the typical range in refinery production. Isopentane, commercial grade toluene, and TEL were added to approach the minimum ASTM D910 MON and SC PN specification limits.

All MON values reported were determined by the standard test ASTM D2700 and all SC PN values reported were determined by the standard test ASTM D909 [3]. For other fuel properties, the following ASTM tests were used: lead content was determined by D5059 [4], heat of combustion was determined by D4809 [5], hydrocarbon types were determined by D1319 [6], distillation properties were determined by D86 [7], and freeze point was determined by D2386 [8]. The fuels were also characterized by their vapor pressure, density, and gas chromatography flame ionization detection for mass percent of toluene, isooctane, and isopentane. Table 1 shows the fuel property results and table 2 shows the compositions.

Given the focus of the study was on AVGAS laboratory octane versus full-scale anti-detonation performance, every effort was made to ensure the final test fuels were of similar MON and SC. As can be seen in table 1, all test fuels were equivalent within ASTM D909 repeatability of ± 1.8 to 2.0 SC PN. No precision data are available for the ASTM D2700 range in question; however, in the range 102 to 103 MON, a repeatability of ± 0.6 MON is reported. This suggests the test fuel spread of 0.7 MON is reasonable.

Table 1. Laboratory Test Results for Reduced Leaded Test Fuels

Property	Specification Limit	Fuel 1	Fuel 2	Fuel 3	Fuel 4
MON (ASTM D2700)	99.6 Minimum	100.1	100.5	100.2	100.8
SC PN (ASTM D909)	130.0 Minimum	130.8	130.9	130.0	130.8
TEL Content (ml/gal) (ASTM D5059)	2.01 Maximum	2.00	0.35	0.55	0.90
Net Heat of Combustion (MJ/kg) (ASTM D4529 [9])	43.5 Minimum	43.73	43.64	43.69	43.71
Distillation (ASTM D86)					
Initial Boiling Point (°C)	Report	39.0	39.0	38.5	37.5
10% evaporated (°C)	75 Maximum	69.5	69.5	70.5	68.0
40% evaporated (°C)	75 Minimum	97.5	97.0	101.5	97.5
50% evaporated (°C)	105 Maximum	101.0	98.5	104.0	100.5
90% evaporated (°C)	135 Maximum	108.5	100.0	110.0	107.5
Final Boiling Point (°C)	170 Maximum	138.0	110.5	168.5	128.5
Sum of 10% and 50% (°C)	135 Minimum	170.5	168.0	174.5	168.5
Percent Recovery	97 Minimum	98.0	99.0	98.0	99.0
Percent Residue	1.5 Maximum	1.2	0.7	1.2	0.8
Percent Loss	1.5 Maximum	0.8	0.3	0.8	0.2
Vapor Pressure (kPa) (ASTM D5191 [10])	38.0 Minimum 49.0 Maximum	40.6	38.0	38.4	41.4
Density (kg/m^3) (ASTM D4052 [11])	Report	723.9	724.5	725.3	721.0

Table 2. Compositions of Test Fuel Blends

	Fuel 1		Fuel 2		Fuel 3		Fuel 4	
	Mass	Volume	Mass	Volume	Mass	Volume	Mass	Volume
Aviation gasoline*	0.6360	0.6602						
Alkylate-95†					0.6472	0.6599		
Alkylate-92‡							0.6837	0.7100
Iso-octane			0.5771	0.5998				
i-Pentane			0.1419	0.1650	0.1422	0.1650	0.867	0.1001
n-Pentane	0.0871	0.0999						
n-Butane	0.0031	0.0039	0.0041	0.0051				
Toluene	0.1873	0.1552	0.2769	0.2301	0.2106	0.1751	0.2296	0.1899
Methyl cyclohexane	0.0864	0.0809						
TEL, ml/gal		2.0		0.35		0.55		0.90

* AVGAS from local airport. Contains 6.9 mass % iso-pentane; contains no toluene
† Alkylate-95 contains 1.05 mass % iso-pentane; contains no toluene
‡ Alkylate-92 contains 10.85 mass % iso-pentane; contains no toluene

Multiple laboratory scale blends of each fuel were blended for testing before the recipe of the two drums of fuel for the engine testing was determined. Twenty-one test blends were made for fuel 1; ten test blends were made for fuel 2; seven test blends were made for fuel 3; and five test blends were made for fuel 4. One replicate blend was made and tested. The difference in MON, SC PN, and vapor pressure between blends was 0.1 MON, 0.3 SC PN, and 0.25 kPa, respectively. The composition of these laboratory test blends and their critical ASTM D910 properties can be found in appendix A.

2.2 TEST ENGINE.

A Lycoming IO-540-K was used for this test with standard ignition timing settings (20/20 degrees before top-dead-center) selected. Table 3 shows the Lycoming 10-540-K engine specifications. This engine was previously determined to be representative of a high octane requirement engine for the active general aviation fleet and of known performance based on past detonation testing.

Table 3. Lycoming IO-540-K Engine Specifications

Engine	Manufacturer	Rated Power (CBHP)	Rated Engine Speed (RPM)	No. of Cylinders	Cylinder Compression Ratio	Induction	Magneto Static Ignition Timing (° BTDC)
IO-540-K	Lycoming	300	2700	6	8.7:1	Natural	20/20

CBHP = corrected brake horsepower; RPM = revolutions per minute

The engine was originally broken in using Phillips 66® Type M nondispersant, 20W-50 mineral oil, and previously operated mostly on unleaded fuels, except for brief comparison detonation testing with leaded 100LL fuels. Following any short duration comparison testing with 100LL and, prior to any subsequent unleaded fuel testing, engine operations with unleaded fuels were performed for 30 to 45 minutes to purge the engine of lead deposits. Such an engine purge period with unleaded fuels is important because lead combustion chamber deposits have been shown to significantly affect unleaded fuel anti-knock performance [12].

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

In previous testing, the engine cylinder assemblies had been removed and drilled in the fin area to install high-temperature, water-cooled piezoelectric pressure transducers flush with the internal combustion chamber. One transducer was installed in the cylinder head of each cylinder with the transducer face as flush as possible with the cylinder cavity. The transducers were connected to charge-to-voltage amplifiers, which were connected to a data acquisition system. Analog cylinder pressure signals from each channel were digitized at the rate of 50 kHz.

The engine was also instrumented with the following sensors:

- Cylinder head temperatures (CHTs) 1-6
- Exhaust gas temperatures (EGTs) 1-6
- Inlet air temperature (IAT) and inlet air pressure
- Mass air flow rate
- Air-to-fuel ratio for both banks of cylinders
- Manifold absolute pressure (MAP) and air temperature
- Engine speed (revolutions per minute (RPM)) and shaft torque
- Brake horsepower (BHP)
- Fuel mass and volume flow rates
- Engine cowling air temperature and pressure
- Fuel temperature and mass density
- Metered fuel pressure and fuel pump outlet pressure
- Oil temperature and pressure

The engine parameter data were 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 test. After the instrumentation was calibrated, a series of maintenance runs were performed to verify the engine system's integrity and instrumentation accuracy. Prior to any engine operation, the mixture cutoff and full-rich (F/R) settings and the throttle stop and throw positions were verified. The fuel delivery system was designed to isolate multiple fuel sources and the integrity of the fuel system was checked prior to and after each run to ensure that cross-contamination did not occur.

2.3 TEST PROCEDURES.

For this test, the throttle position was set and the mixture was leaned from the F/R stop position to lean of best economy (BE) or heavy detonation, whichever occurred first. The desired engine speed was set and the MAP was then adjusted to obtain the desired corrected brake horsepower (CBHP). Table 4 shows the engine test points.

Table 4. Test Conditions

Engine Speed (RPM)	Throttle	Power	Mixture Setting	Engine Inlet Conditions
2700	Wide open	100%	F/R to detonation or BE	Extreme hot- and dry-day sea-level conditions (IAT 103 ± 3°F) with maximum allowable CHT at 475 -0 + 5 °F
2600	Adjust to obtain power	85% of CBHP of 2700 RPM point	F/R to detonation or BE	Extreme hot- and dry-day sea-level conditions (IAT 103 ± 3°F) with maximum allowable CHT at 475 -0 + 5 °F
2450	Adjust to obtain power	75% of CBHP of 2700 RPM point	F/R to detonation or BE	Extreme hot- and dry-day sea-level conditions (IAT 103 ± 3°F) with maximum allowable CHT at 475 -0 + 5 °F
2450	Adjust to obtain power	75% of CBHP of 2700 RPM point	F/R to detonation or BE	Extreme hot- and dry-day at 3500-ft altitude temperature conditions (IAT 90 ± 3°F), with maximum allowable CHT at 425 -0 +5 °F

Initial tests were performed using extreme hot- and dry-day conditions at sea-level altitude pressure and temperature engine inlet conditions. This was to promote detonation and allow differentiation between the fuel types. Test points where detonation was detected were repeated using the extreme hot- and dry-day standard ambient temperature at 3500-ft altitude and the reduced maximum allowable CHT of 425 -0+5°F. Sea-level altitude engine inlet and exhaust back pressure were used for all of these tests.

The maximum CHT was set to the desired test condition, -0 + 5°F, with all other CHTs controlled to within 50°F of the maximum CHT. The oil temperature was adjusted to maintain maximum allowable inlet temperature of 245 ± 10°F oil temperature. The engine inlet air relative humidity was maintained below 2%.

The fuel mixture was leaned from a richer, non-knocking setting until heavy detonation, maximum allowable EGT, 50ºF past peak EGT, or lean of BE was reached. Careful attention was given to the individual EGT and CHT spreads and two exhaust gas Lambda sensors were used, one for each bank of cylinders. It was ensured that the CHT and EGT spreads and air-to-

fuel reading differentials were minimal to prevent gross mixture imbalances between cylinders and cylinder banks. Mixture adjustments were automated by a computer algorithm to ensure fuel flow changes were slow and repeatable with fuel mixture changes less than 1 lb/hr/s. The 2450 RPM, 75% power point was repeated at reduced temperature inlet air with reduced maximum CHT. For this colder condition, the inlet air was set to the extreme hot- and dry-day standard for 3500 ft (90 ± 3 °F) with a maximum CHT of 425 -0 + 5 °F. The reduced temperature test condition offers a closer approximation to actual in-flight engine cruise conditions for a naturally aspirated engine.

3. RESULTS AND DISCUSSION.

Equivalence ratio is calculated by dividing the blend's stoichiometric air-to-fuel ratio at any given moment in time by the actual air-to-fuel ratio. Operating the engine at cruise power with fuel mixture strength near an equivalence ratio of 1.0 typically results in the highest EGTs and slightly rich of BE performance. Mixture strengths rich of this setting result in equivalence ratios greater than one, and leaning past peak EGT results in equivalence ratio values below 1. Table 5 shows the detonation onset fuel mass flow and equivalence ratio data, along with the repeatability of the test results for the hot condition data, with the sea-level extreme hot- and dry-day IAT of 103 ± 3 °F and the maximum CHT of 475 -0+5 °F. The table shows the minimum, maximum, and average detonation limited fuel flows and equivalence ratios. For all data points collected under these temperature conditions, a detonation intensity percentage of 2% was used, and the data show very good repeatability.

Table 5. Repeatability Data for Hot- and Dry-Day Condition Detonation Testing

Fuel	Targeted Power (% CBHP)	Minimum Fuel Flow (lb/hr at 2% detonation intensity)	Maximum Fuel Flow (lb/hr at 2% detonation intensity)	Limited Fuel Flow Spread (maximum-minimum at 2% detonation intensity)	Minimum Equivalence Ratio (at 2% detonation intensity)	Maximum Equivalence Ratio (at 2% detonation intensity)	Equivalence Ratio Spread (maximum-minimum at 2% detonation intensity)
1	100	131.3	134.5	3.2	1.22	1.25	0.03
	85	117.5	118.1	0.6	1.20	1.21	0.01
	75	99.5	100.9	1.4	1.16	1.17	0.01
2	100	134.3	136.1	1.8	1.21	1.23	0.02
	85	118.0	119.0	1.0	1.16	1.19	0.03
	75	101.7	105.3	3.6	1.14	1.18	0.04
3	100	130.4	133.7	3.3	1.19	1.22	0.03
	85	114.2	117.8	3.6	1.16	1.18	0.02
	75	99.5	100.3	0.8	1.15	1.16	0.01
4	100	127.4	128.4	1.0	1.20	1.22	0.02
	85	110.8	113.1	2.3	1.14	1.19	0.05
	75	96.4	99.5	3.1	1.14	1.18	0.04

It should be noted that the testing in this section was performed under extreme conditions with dry inlet air containing less than 2% relative humidity. Recent tests performed at the FAA WJHTC AFETF determined that inlet air humidity plays a significant role in engine detonation testing, with more humid inlet air resulting in reduced engine detonation. For a naturally aspirated engine, as altitude is increased from sea level, output power reduces proportionately to outside air pressure and the engine IAT decreases with altitude. As the aircraft is leveled off at cruise altitude, the engine experiences colder air flowing into the cowling for engine cooling along with colder engine inlet air. Both of these conditions result in a relatively lower detonation propensity. Because of this, the use of extreme hot- and dry-day sea-level inlet air and maximum allowable CHTs for cruise power testing for naturally aspirated engines is extreme. Seeing the detonation response at the cruise-lean condition at a low altitude condition was desired. Therefore, the cruise condition was repeated using reduced temperatures approximating what an engine would experience at 3500-ft altitude on an extreme hot- and dry-day. Sea-level inlet air and exhaust back pressure were used for this testing and only the IAT was adjusted to 90 ± 3°F to approximate the extreme hot- and dry-day at altitude. The maximum CHT was reduced to 425 -0+5°F at this setting to better approximate realistic conditions for a naturally aspirated engine.

Samples of the detonation intensity, corrected power, and average EGT versus equivalence ratio for both the extreme hot conditions and the reduced temperature test condition are shown in figures 1 through 4. All three replicates are shown for one fuel at each test point and are typical results for these data. For the reduced temperature condition at 75% power, figure 4 shows good repeatability of the detonation intensity data. It should be noted that, because only one of the three repeats approached a 2% detonation intensity level, this condition would not be considered as limiting detonation. Under the reduced temperature conditions, the detonation response peaked between 1% and 2% detonation intensity. As such, the detonation intensity repeatability at 2% detonation intensity could not be determined for the reduced temperature test.

It should also be noted that at the end of the mixture leaning on each plot, there is an appearance that the peak detonation occurs at different mixture settings. This is an illusion caused by the software programmed automated fuel mixture enrichment that occurs when individual cycle detonation index values reach a predetermined level. This automatic fuel mixture enrichment is performed to protect the engine from damage. As the fuel mixture is enriched the detonation intensity typically reduces. At these high levels of detonation, repeated iterations stop at slightly different mixture strengths, resulting in the false appearance of peaks at different mixture strengths.

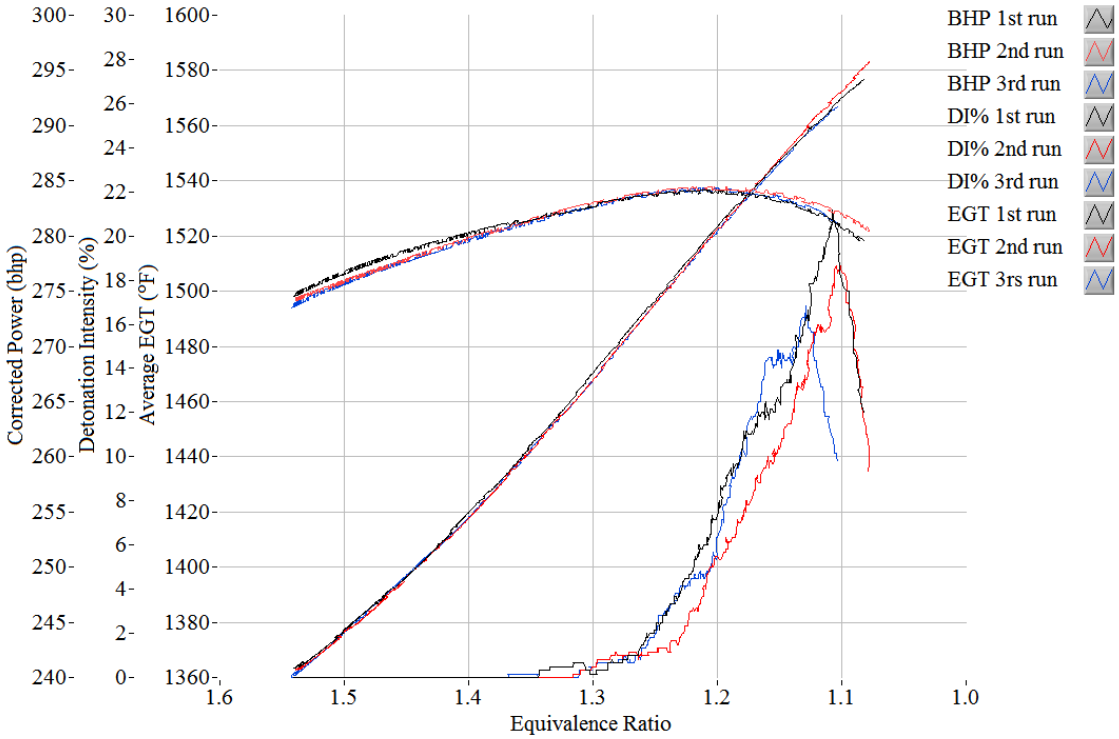

Figure 1. Repeatability Data for Fuel 1 at Wide Open Throttle, Full Power, Sea-Level Extreme Hot- and Dry-Day Conditions

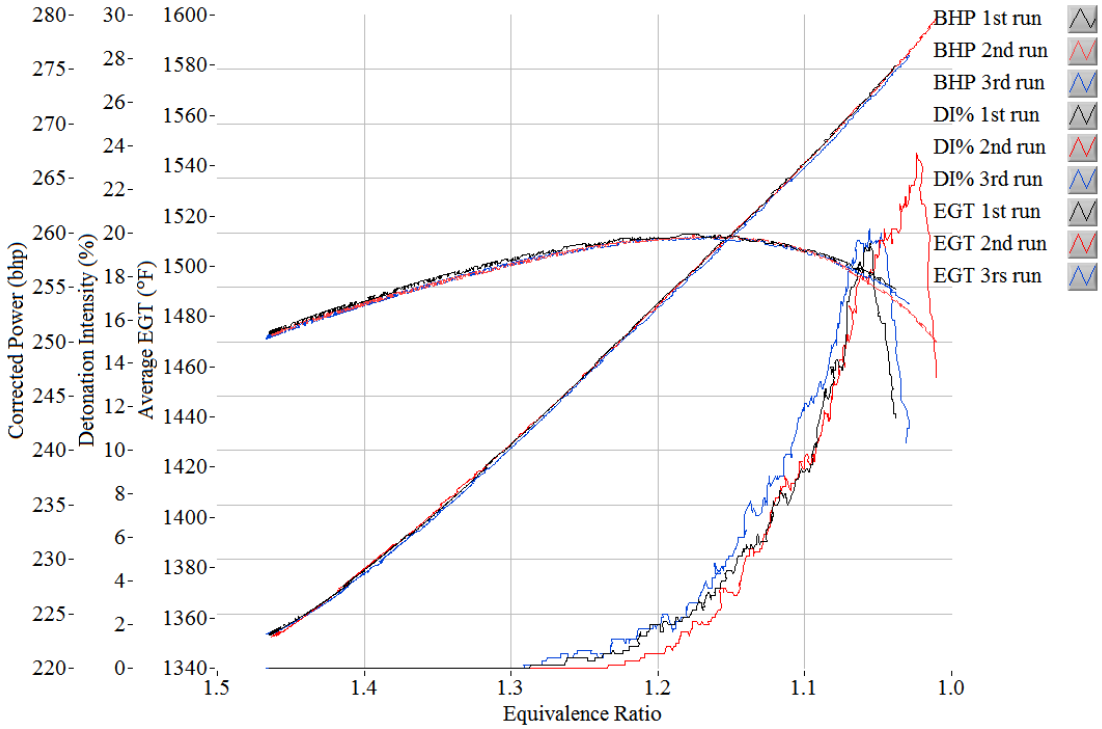

Figure 2. Repeatability Data for Fuel 2 at 85% Power, Sea-Level Extreme Hot- and Dry-Day Conditions

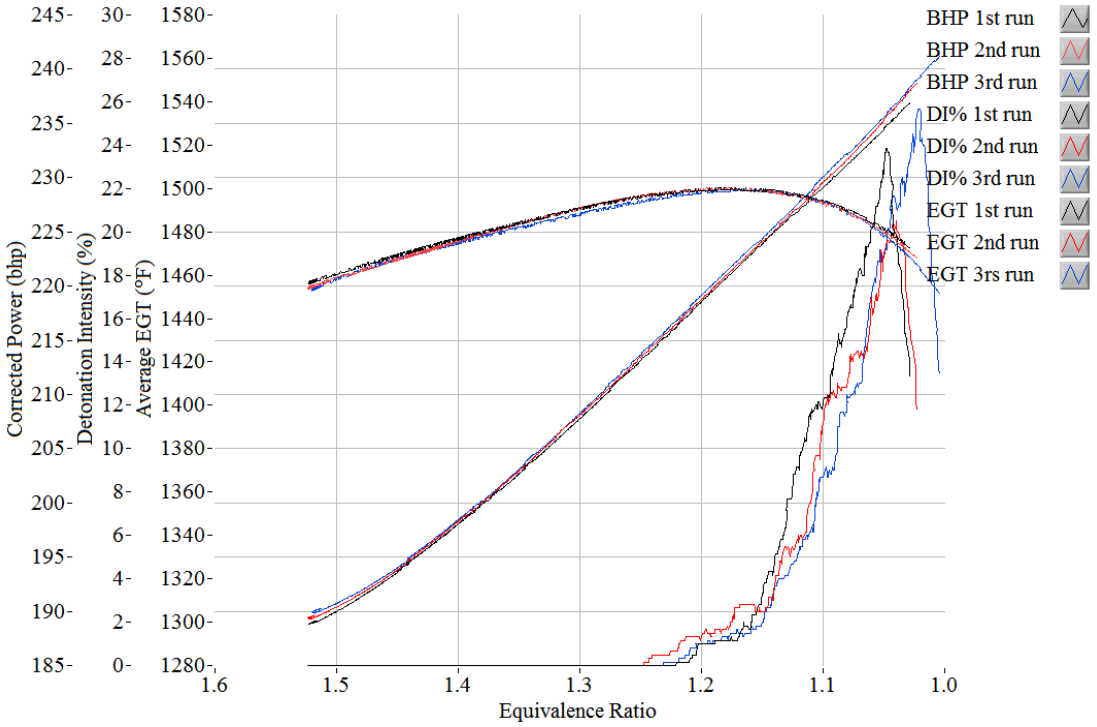

Figure 3. Repeatability Data for Fuel 3 at 75% Power, Sea-Level Extreme Hot- and Dry-Day Conditions

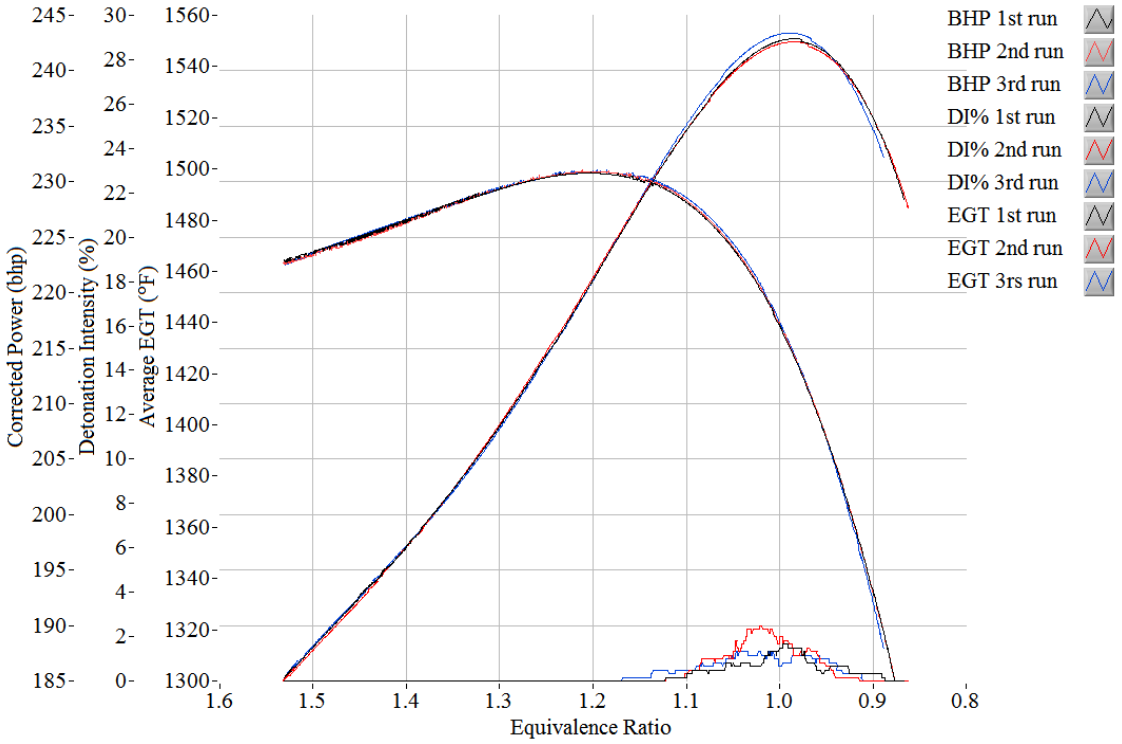

Figure 4. Repeatability Data for Fuel 4 at 75% Power, 3500-ft Altitude Extreme Hot- and Dry-Day Conditions

Figure 5 shows the average corrected power and detonation lines for the sea-level extreme hot- and dry-day conditions plotted versus equivalence ratio. It can be observed that richer fuel mixtures are on the left with the mixture leaning along the curves to the right. Thus, higher equivalence ratios are for relatively richer air-to-fuel mixture settings. Table 6 shows the same data in tabular format.

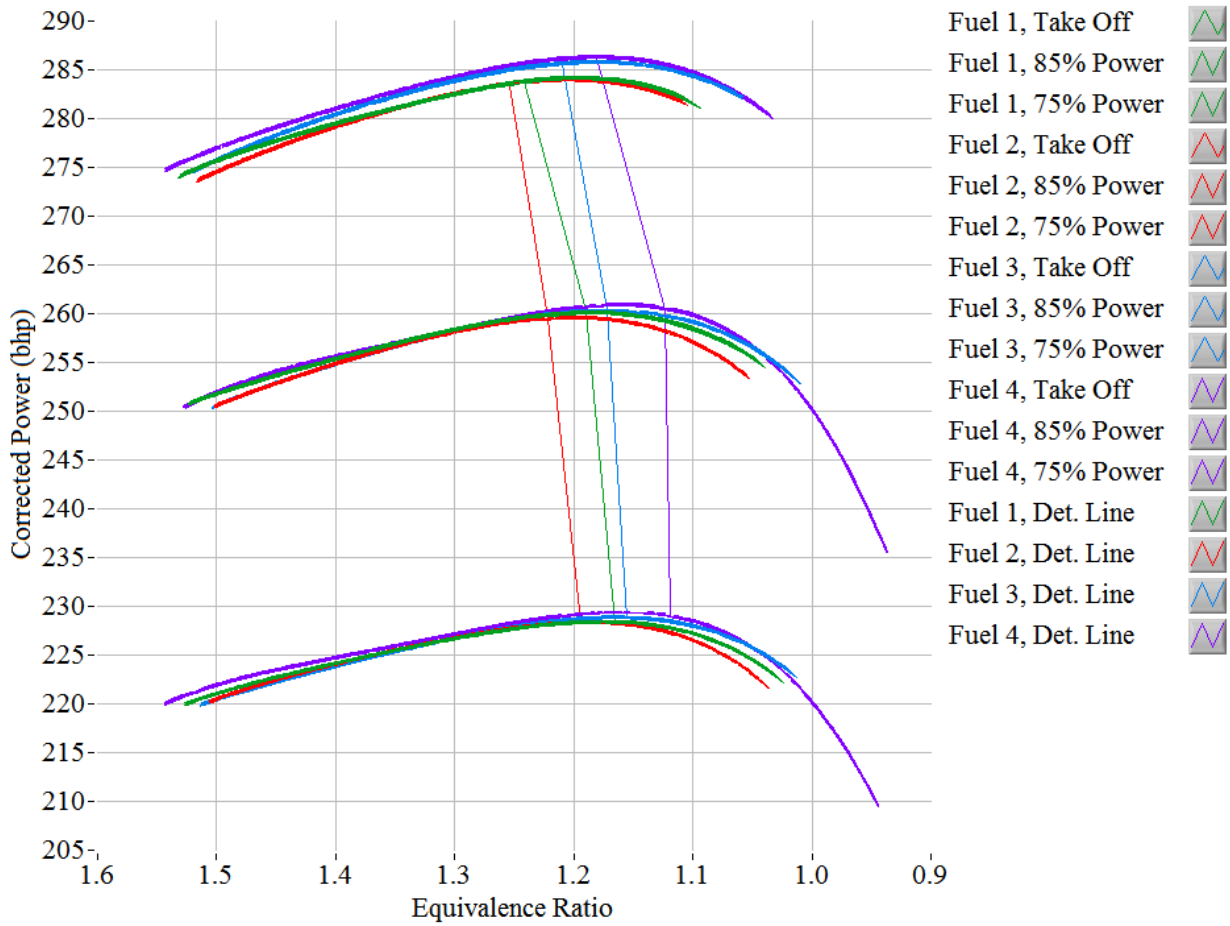

Figure 5. Power and Detonation Lines vs. Fuel Equivalence Ratio for All Test Fuels at 2% Detonation Intensity, Sea-Level Extreme Hot- and Dry-Day Conditions

Table 6. Detonation Results for the Extreme Hot- and Dry-Day Test Conditions

Test Fuel	MON (ASTM D2700)	SC PN (ASTM D909)	TEL Content (ml/gal)	Targeted Engine Speed (RPM)	Targeted Power (% CBHP)	Mean Fuel Flow (lb/hr, at 2% detonation intensity)	Mean Equivalence Ratio (at 2% detonation intensity)
1	100.1	130.8	2.00	2700	100	133.4	1.24
1				2600	85	117.7	1.20
1				2450	75	100.3	1.16
2	100.5	130.9	0.35	2700	100	135.2	1.22
2				2600	85	118.6	1.17
2				2450	75	103.0	1.15
3	100.2	130.0	0.55	2700	100	131.7	1.20
3				2600	85	116.0	1.17
3				2450	75	99.9	1.16
4	100.8	130.8	0.90	2700	100	128.0	1.21
4				2600	85	111.7	1.16
4				2450	75	98.0	1.16

With all power settings under sea-level extreme hot- and dry-day conditions, fuel 2, made from pure components with the lowest lead content, exhibited the poorest detonation performance and, therefore, exhibited detonation at the richest mixtures. Fuel 4, made using the 92 MON alkylate and containing 45% of the maximum allowable lead level, showed the best detonation performance. Fuel 4 also showed much better anti-knock performance than the minimum specification, maximum lead content fuel. Both fuels 3 and 4—made using the 95 and 92 MON alkylates and containing 45% and 28% of the lead content, respectively—as the minimum specification, maximum lead content fuels showed better anti-knock performance than the minimum-specification, maximum-lead-content fuel.

The data show that, even under extreme hot- and dry-day sea-level test conditions, the engine with all four test fuels was easily satisfied at the F/R takeoff and 85% climb power settings, for which manual fuel mixture leaning is prohibited. At the extreme hot sea-level conditions at 75% power, the mixture was able to be leaned to approximately best power mixture or leaner before the 2% detonation intensity was reached.

At wide open throttle (WOT), the 2% detonation intensity power was approximately 4 BHP less with fuel 2 as compared to fuel 4. At the 85% power setting, the 2% detonation intensity was approximately 3 BHP less with fuel 2 compared to fuel 3. At approximately 75% power, there was only an approximate 1 BHP difference. However, at 75% power, the 2% detonation intensity equivalence ratio for fuel 4 was 0.08 leaner than fuel 2; the 2% detonation intensity equivalence ratio for fuel 3 was 0.05 leaner than fuel 2; and the 2% detonation intensity equivalence ratio for fuel 1 was 0.04 leaner than fuel 2. At approximately 85% power, the 2% detonation intensity equivalence ratio for fuel 4 was 0.1 leaner than fuel 2; the 2% detonation

intensity equivalence ratio for fuel 3 was 0.06 leaner than fuel 2; and the 2% detonation intensity equivalence ratio for fuel 1 was 0.04 leaner than fuel 2. At WOT, the 2% detonation intensity equivalence ratio for fuel 4 was 0.09 leaner than fuel 2; the 2% detonation intensity equivalence ratio for fuel 3 was 0.06 leaner than fuel 2; and the 2% detonation intensity equivalence ratio for fuel 1 was 0.02 leaner than fuel 2. Additionally, fuel 4 was the only test fuel able to be leaned past stoichiometric air-to-fuel ratios at 75% and 85% power under the extreme hot- and dry-day sea-level conditions. Table 7 shows the detonation results for the extreme hot- and dry-day test conditions.

Table 7. Summary of Detonation Results for the Extreme Hot- and Dry-Day Test Conditions

	Fuel 1	Fuel 2	Fuel 3	Fuel 4
Targeted Percent Power	Mean Fuel Flow (lb/hr, at 2% detonation intensity)			
100	133.4	135.2	131.7	128.0
85	117.7	118.6	116.0	111.7
75	100.3	103.0	99.9	98.0
	Mean Equivalence Ratio (at 2% detonation intensity)			
100	1.24	1.22	1.20	1.21
85	1.20	1.17	1.17	1.16
75	1.16	1.15	1.16	1.16

Figure 6 shows the detonation results and power for all of the test points. For these data, 2% detonation intensity was used for comparison. The lines are drawn through the mean value at each power setting. In terms of fuel mass flow, under the extreme hot- and dry-day sea-level temperature conditions, fuel 2 was again the worst and fuel 4 the best in terms of anti-knock performance. At WOT, fuel 1 was knock limited at a fuel mass flow of approximately 2 lb/hr less than fuel 2, whereas fuel 3 and fuel 4 were at 3.5 lb/hr less and 7 lb/hr less than fuel 2, respectively. At 85% power, fuel 1 reached 2% detonation intensity at a fuel mass flow of approximately 1 lb/hr less than fuel 2, whereas fuel 3 and fuel 4 were at 2.5 lb/hr less and 7 lb/hr less than fuel 2, respectively. At 75% power, fuel 1 reached 2% detonation intensity at a fuel mass flow of approximately 2.5 lb/hr less than fuel 2, whereas fuel 3 and fuel 4 were at 3 lb/hr less and 5 lb/hr less, respectively.

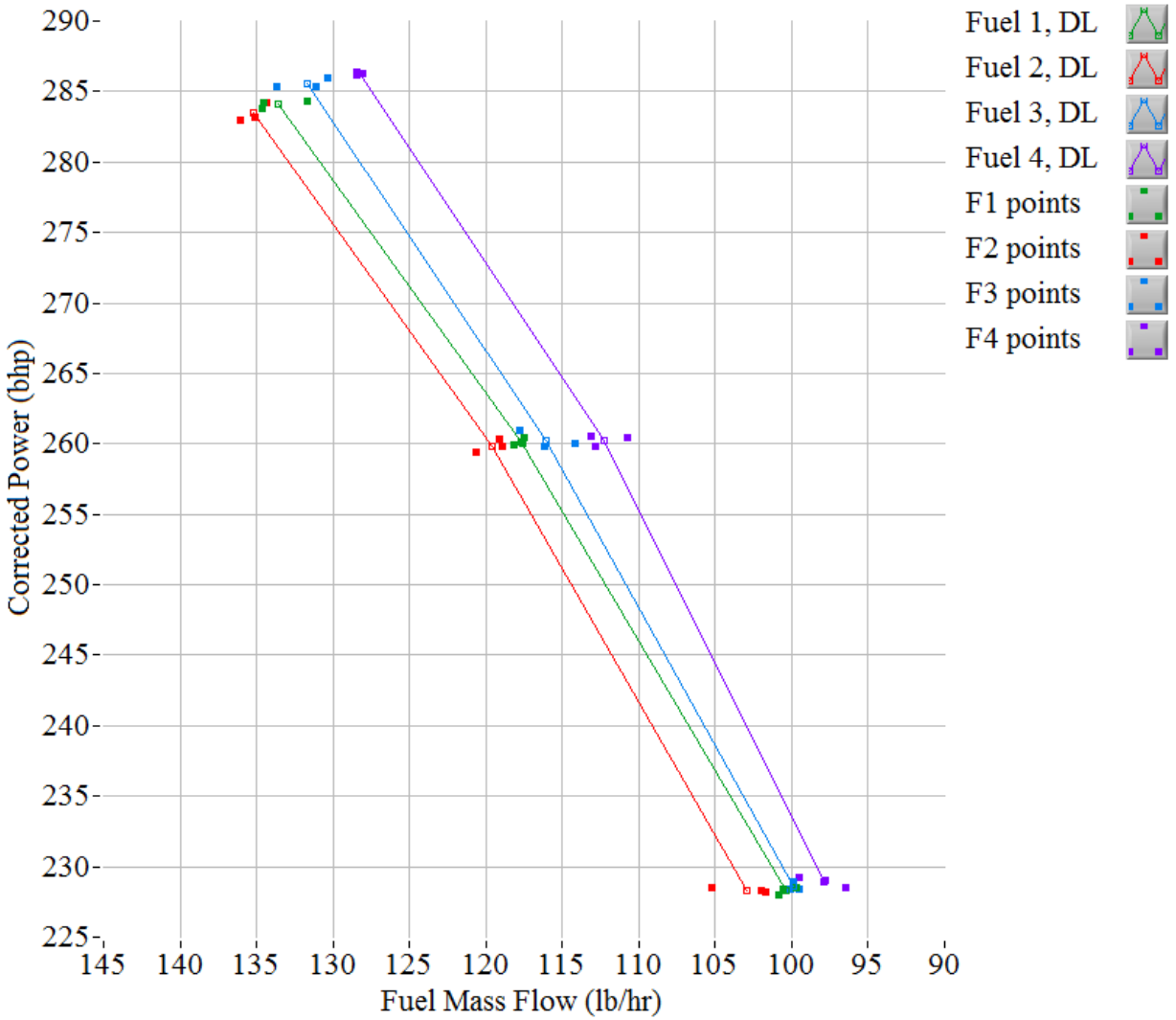

Figure 6. Detonation Points and Power Relative to Fuel Mass Flow, Sea-Level Extreme Hot- and Dry-Day Conditions

Figure 7 shows the 2% detonation intensity for the reduced temperature conditions at 75% power for all fuels and all test runs. Note that fuel 1 only slightly approached the 2% limit for two out of the three test points, whereas fuel 3 approached the 2% detonation intensity for three test points and reached a maximum detonation intensity of 3%. When comparing figure 7 to figure 6, the data show that the requirement to test naturally aspirated engines at sea-level, extreme hot- and dry-day test conditions with dry air at maximum allowable CHTs for cruise power settings may be overly extreme and should be further investigated. The FAA Advisory Circular 33.47 for detonation testing does not specify an inlet air humidity. Dry air was chosen to obtain detonation on these fuels. Testing at higher relative humidity levels would have resulted in considerably lower detonation levels. Repeating the testing at the extreme hot- and dry-day standard at low altitude with perhaps a more realistic set of boundary condition temperatures results in greatly improved anti-knock fuel results. This observation highlights the importance of investigating the impact of test conditions for naturally aspirated engines on the anti-knock fuel performance. This observation also highlights the importance of understanding the test objective

to either set severe conditions to promote detonation for differentiating between fuel types or to set severe but realistic conditions to determine if an engine octane requirement can be met by the fuels available.

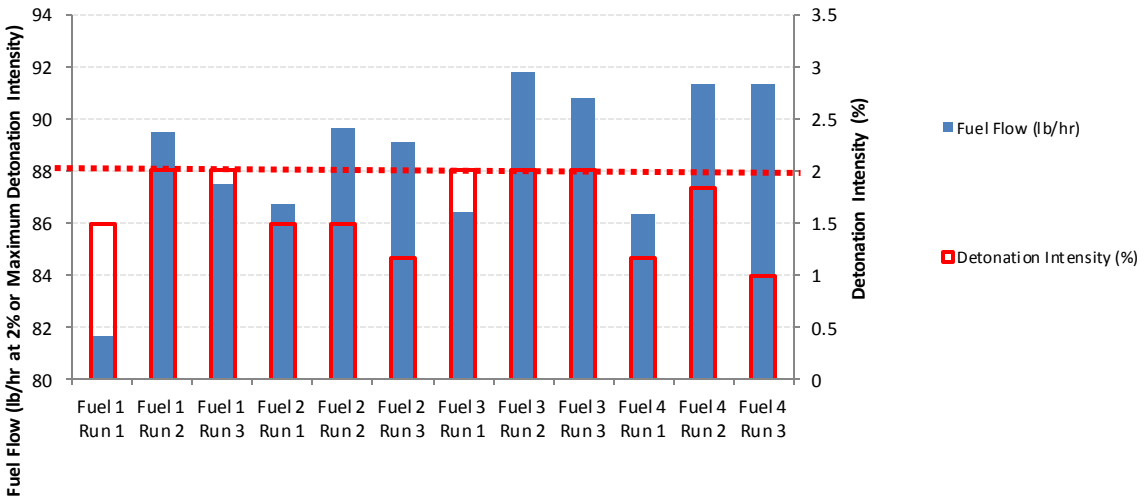

Figure 7. Detonation Intensity Fuel Flow and Maximum Detonation Intensity at 75% Power for the 3500-ft Altitude Extreme Hot- and Dry-Day Conditions for All Test Runs and All Fuels

Figure 8 shows the average EGT at sea-level extreme hot- and dry-day conditions. In all cases for all fuels, the automatic mixture leaning program has a cutoff that automatically richens the mixture back to the F/R setting when consistent heavy knock is detected. This is why the mixture curves do not go to peak EGT for many of the fuels. The 2% detonation intensity for fuel 2 was reached before best power at WOT and 85% power and at best power for the 75% power at sea-level extreme hot- and dry-day conditions. The 2% detonation intensity for fuel 1 was reached before best power at WOT, at best power for the 85% power, and just past best power for the 75% power at sea-level extreme hot- and dry-day conditions. The 2% detonation intensity for fuel 3 was reached at best power at WOT and 85% power and just past best power for the 75% power at sea-level extreme hot- and dry-day conditions. The 2% detonation intensity occurred just past best power under all power settings with fuel 4.

The EGT data show that fuel 2 had consistently higher average EGTs. This fuel also had higher toluene content than the other blends with a mass of 28% as compared to 19% and 23%, respectively. Such an observation may be important if aromatics concentrations increase in AVGAS for octane enhancement or other reasons. However, this concentration of 28% mass (23% volume) is at the high end of the fuel fleet experience.

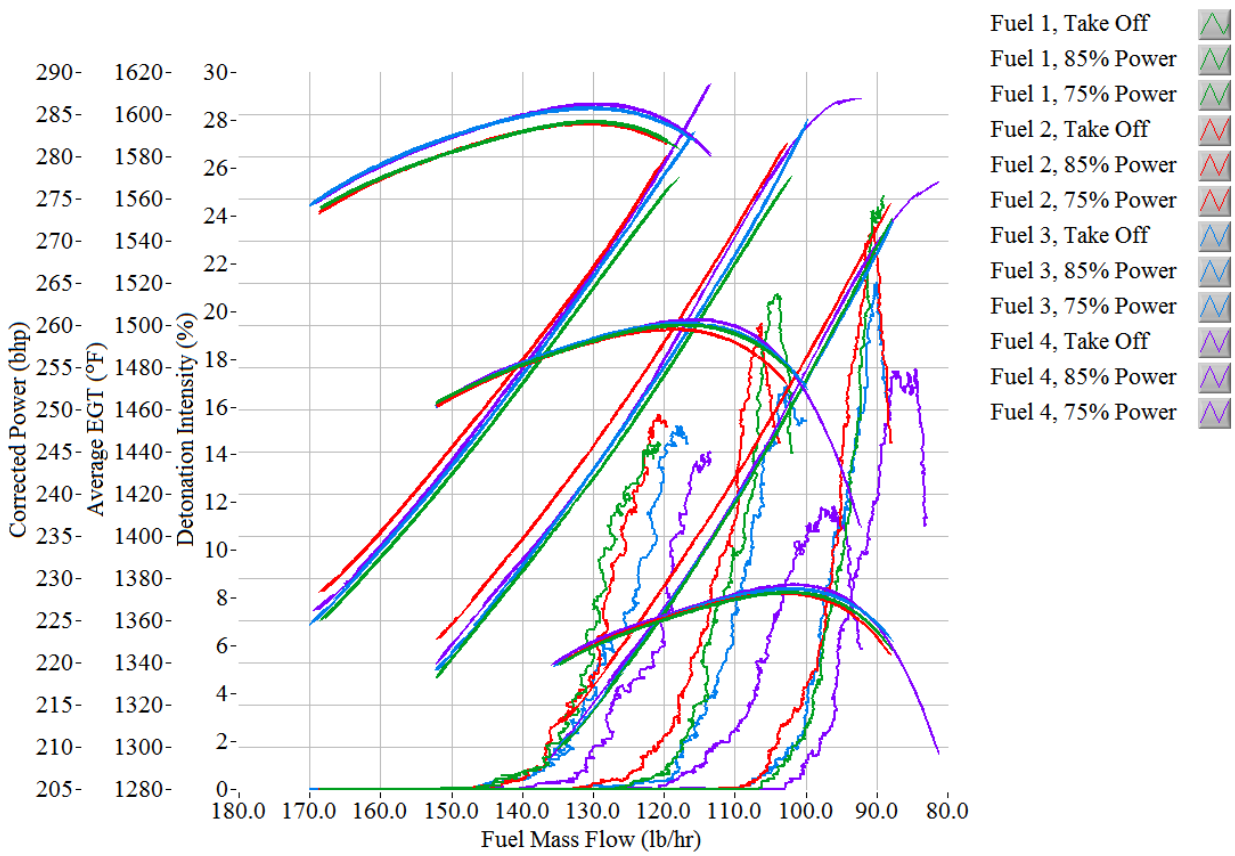

Figure 8. Average EGT at Sea-Level Extreme Hot- and Dry-Day Conditions Compared to Fuel Mass Flow and Power

Extreme hot- and dry-day temperature conditions of 475 -0+5°F maximum CHT and sea-level extreme hot- and dry-day standard IAT of 103 ± 3 °F were used to compare the performance of the test fuels at WOT, 85%, and 75% power. The 75% power setting was repeated at reduced temperature conditions of 425 -0+5°F maximum CHT and the 3500-ft extreme hot- and dry-day standard IAT of 90 ± 3 °F.

Figure 9 shows the average EGT data at the 3500-ft altitude extreme hot- and dry-day temperature conditions. Fuels 1, 2, and 4 were all leaned through peak EGT without consistently reaching an average of 2% detonation intensity. In summary, fuels 1, 2, and 4 did not show an average detonation intensity greater than 2% when leaned through peak EGT. Fuel 3 reached the average 2% detonation intensity level when leaned to peak EGT.

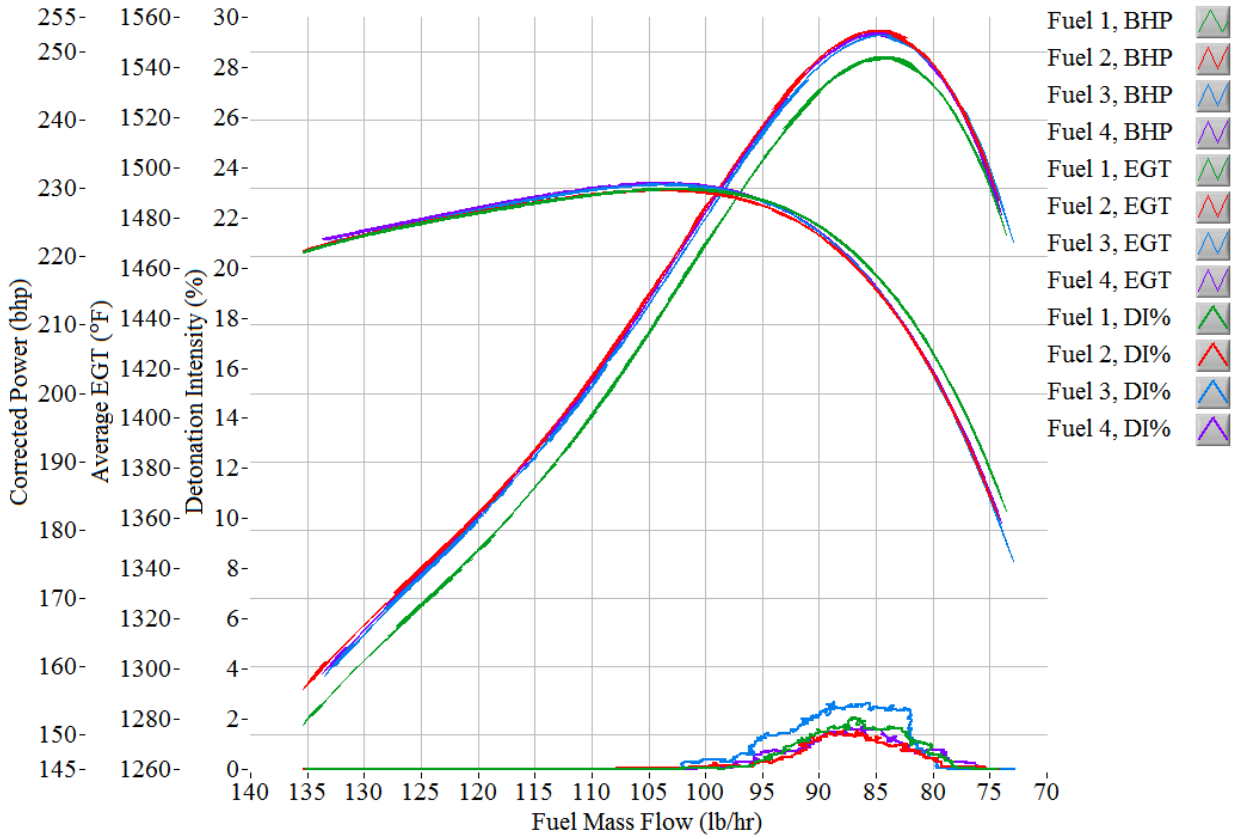

Figure 9. 75% Power at the 3500-ft Altitude Extreme Hot- and Dry-Day Temperature Conditions

One of the purposes of this testing was to evaluate the effect of lead concentration on the anti-knock performance of commercial fuel in a full-scale engine. Fuel 1 is the baseline fuel for this characterization because it was blended from commercial 100LL to be close to the minimum octane requirements of ASTM D910 while containing near the maximum allowable concentration of lead. When comparing test fuels 2, 3, and 4, there is an increase in detonation protection, as quantified with both 2% detonation intensity power and equivalence ratio, with an increase in lead concentration. This trend is observed under all engine power settings, with the performance of the baseline fuel falling between test fuels 2 and 3, as shown in figures 10 through 12. Figure 13 shows the 2% detonation intensity fuel flow as a function of TEL content.

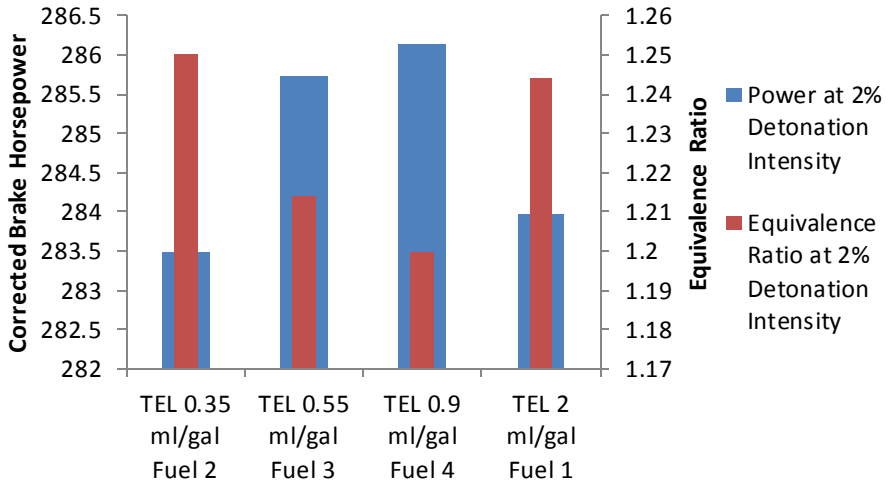

Figure 10. Lead Concentration and Anti-Knock Performance, Take-Off Power, Sea-Level Extreme Hot- and Dry-Day Conditions

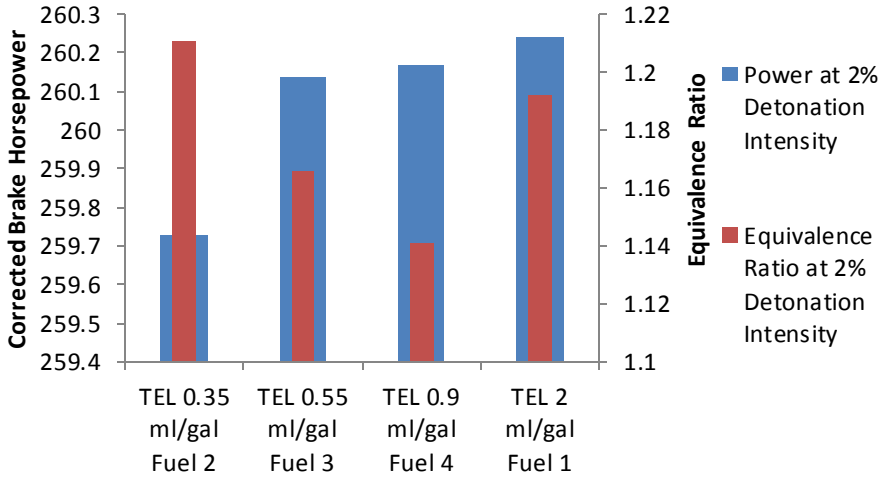

Figure 11. Lead Concentration and Anti-Knock Performance, 85% Power, Sea-Level Extreme Hot- and Dry-Day Conditions

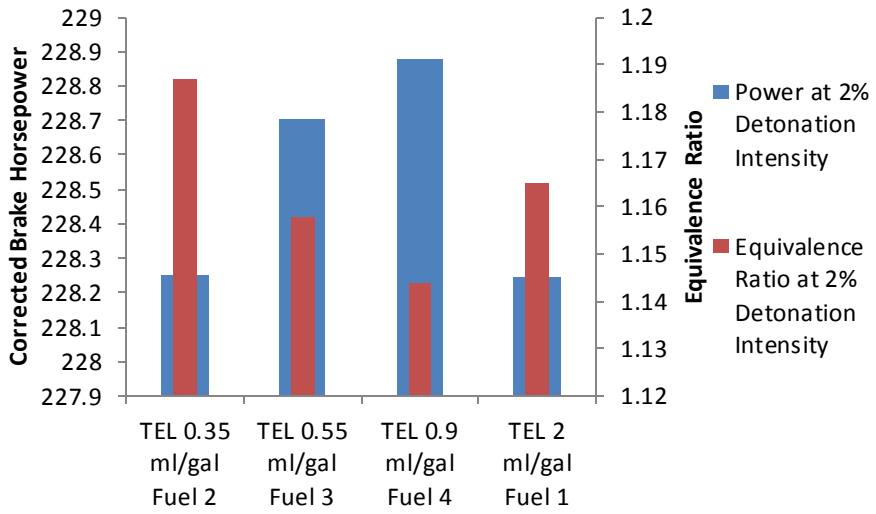

Figure 12. Lead Concentration and Anti-Knock Performance, 75% Power, Sea-Level Extreme Hot- and Dry-Day Conditions

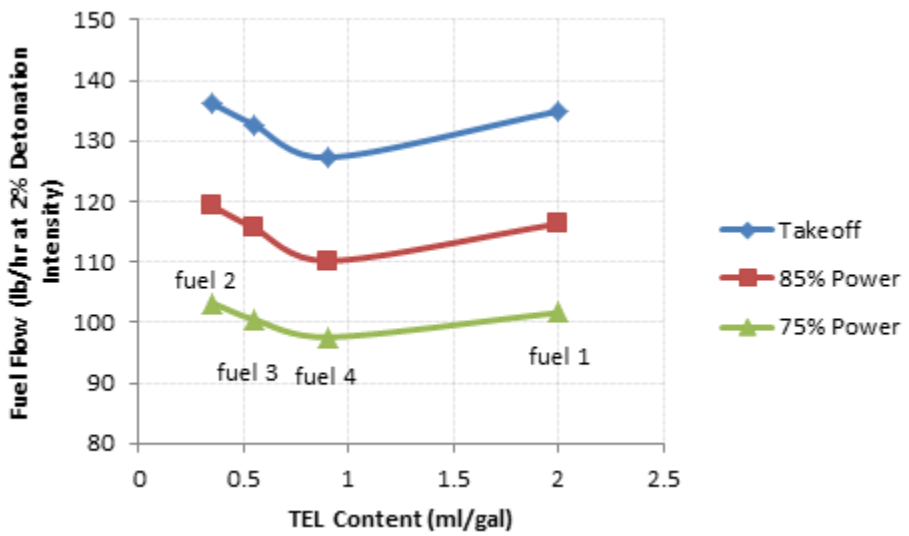

Figure 13. A 2% Detonation Intensity Fuel Flow vs. TEL Content, Sea-Level Extreme Hot- and Dry-Day Conditions

The effect of the slight laboratory MON variations between the test fuels was considered and is presented in figures 14 through 16. The MON of the fuels tested varied from 100.1 to 100.8 and did not appear to have a significant effect on the trends for both detonation limited power and equivalence ratio. Figure 17 shows all power settings on one graph. The possibility of an effect on 2% detonation intensity fuel flow due to the SC PN was considered and graphically presented in figure 18. There does not seem to be a significant effect due to the variation in the SC PN used in this study; however, the variation between all four fuels' SC PN is less than the standard deviation of the ASTM D909 test, as shown in figure 18.

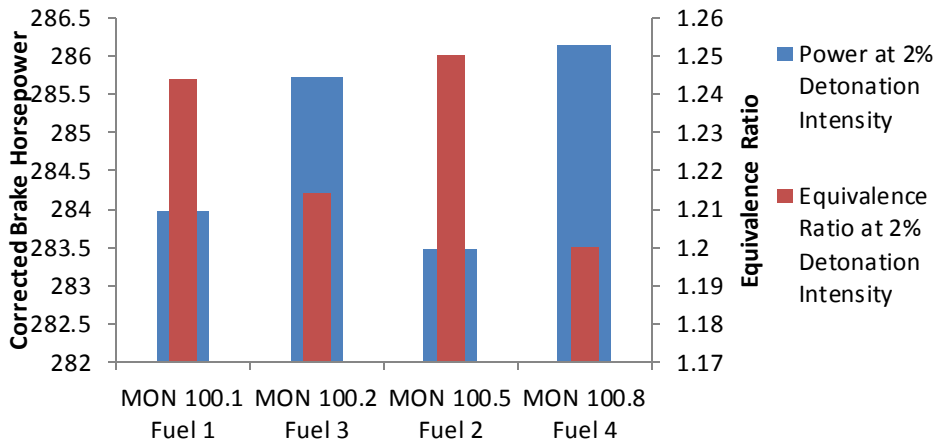

Figure 14. The MON and Anti-Knock Performance, Take-Off, Sea-Level Extreme Hot- and Dry-Day Conditions

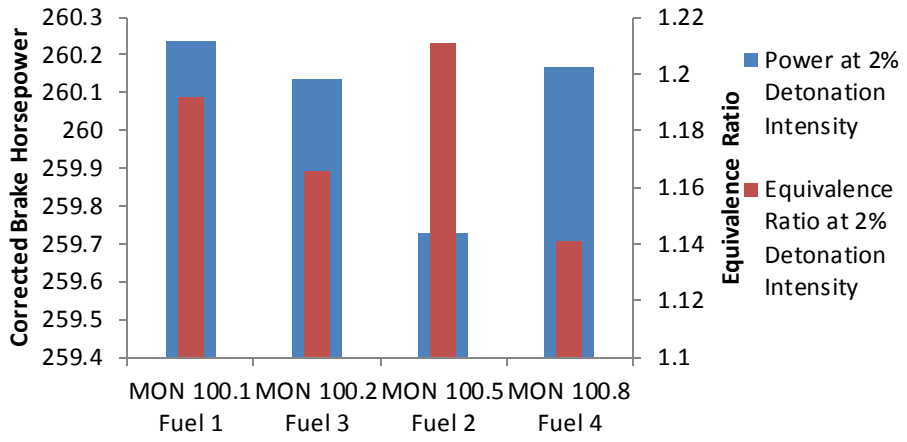

Figure 15. The MON and Anti-Knock Performance, 85% Power, Sea-Level Extreme Hot- and Dry-Day Conditions

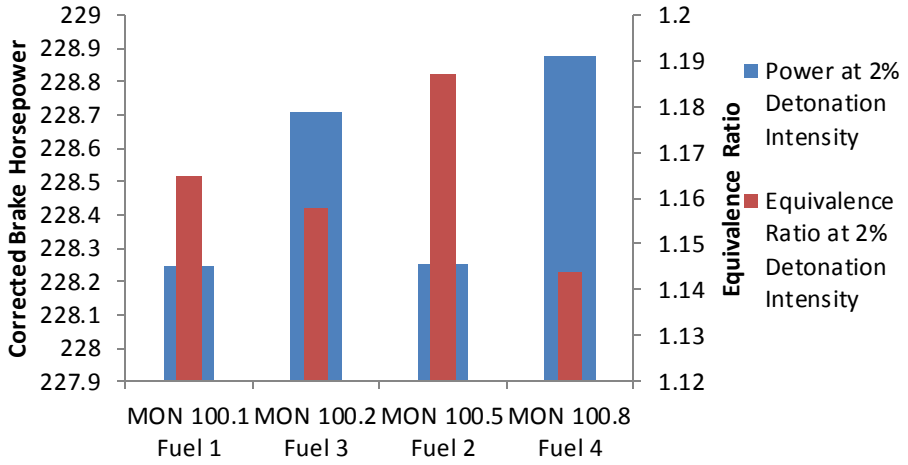

Figure 16. The MON and Anti-Knock Fuel Performance, 75% Power, Sea-Level Extreme Hot- and Dry-Day Conditions

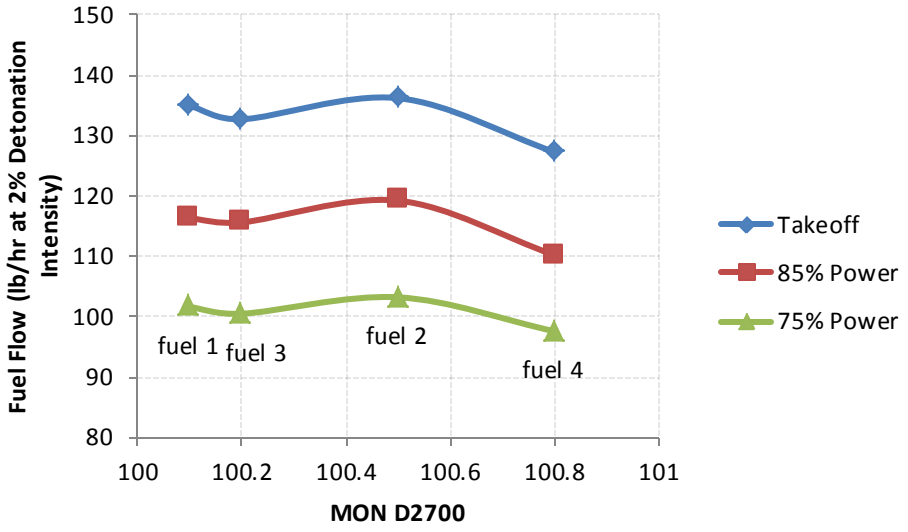

Figure 17. A 2% Detonation Intensity Fuel Flow vs. MON, Sea-Level Extreme Hot- and Dry-Day Conditions

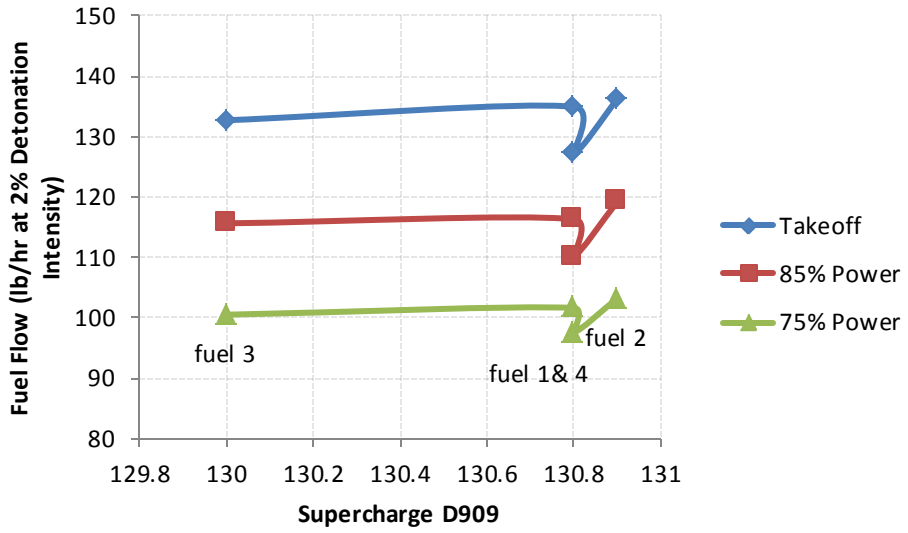

Figure 18. A 2% Detonation Intensity Fuel Flow vs. SC PN, Sea-Level Extreme Hot- and Dry-Day Conditions

4. CONCLUSIONS.

The objective of this research was to determine and compare the anti-knock performance of several variations of reduced lead aviation gasoline (AVGAS) versus a baseline 100 low-lead (100LL) of minimum octane and maximum lead content. Ultimately, these data may be used to establish a minimum value for lead content in the ASTM D910 specifications for 100LL and similar grades. The engine used in this testing was a Lycoming IO-540-K, which had previously been determined to be a representative high octane, naturally aspirated engine.

Four test fuels were evaluated:

- Fuel 1—A minimum octane specification 100LL, blended to be close to the minimum motor octane number (MON) per ASTM D2700 and supercharge performance number (SC PN) per ASTM D909 specification limits using commercial 100LL, *n*-pentane, methyl cyclohexane, commercial toluene, and containing approximately the maximum allowable tetraethyl lead (TEL)-B level, 2.00 ml/gal.

- Fuel 2—Pure components blend containing the lowest lead level. Fuel 2 was blended using pure isooctane, isopentane, and toluene to obtain a fuel meeting table 1 properties in ASTM D910 for 100LL, while containing the least amount of TEL- B needed, 0.35 ml/gal.

- Fuels 3 and 4—Commercial 95 MON and 92 MON alkylate blends, respectively, with isopentane, commercial grade toluene, and TEL-B added to meet the minimum ASTM D910 specification limits for MON and SC PN: 95 MON alkylate 0.55 ml TEL/gal and 92 MON alkylate 0.90 ml TEL/gal.

Full-scale engine detonation tests were conducted under extreme hot- and dry-day temperatures with dry air at sea-level conditions to promote detonation and allow differentiation between fuel types. The lean cruise condition was also evaluated at an extreme hot- and dry-day temperature condition approximating the temperature at 3500-ft altitude with dry air.

A 2% detonation intensity was used for comparison of all the data points collected under the hot-temperature conditions, and the data showed very good reproducibility. At the 3500-ft altitude extreme hot- and dry-day temperature conditions, the data were less repeatable, partially because all of the points tested reached a maximum detonation intensity level between 1% and 2%, and, therefore, data were not available at the 2% condition.

At the extreme hot- and dry-day sea-level test conditions with dry inlet air, all of the fuels provided detonation levels less than 2% detonation intensity operation at the full-rich requirement for the test engine above 75% power, for which fuel mixture leaning is prohibited. At the 75% performance cruise power setting, under extreme hot- and dry-day altitude conditions approximating 3500-ft altitude temperature and dry air, fuels 2 and 4 were below the 2% detonation intensity level. Fuel 1 reached the 2% detonation intensity level for two of the three repeat test runs. Fuel 3 slightly reached the 2% detonation intensity level for all three repeat runs and reached a maximum intensity of 3%.

For all of the extreme hot- and dry-day sea-level test conditions' test points, fuel 2, the theoretical lowest lead fuel made from pure components and containing 0.35 ml TEL/gal, showed the worst anti-knock performance, whereas fuel 4, made from commercial 92 MON aviation alkylate and containing 0.90 ml TEL/gal showed the best anti-knock performance. Thus, both fuels made with commercial alkylate and containing 28% and 45% of the maximum allowable lead level for 100LL, respectively, showed better anti-knock performance than the baseline 100LL fuel 1 containing maximum allowable lead and the lowest lead content blend made from pure components.

Under the conditions of the test:

Fuel 4 (0.9 ml TEL/gal) > Fuel 3 (0.55 ml TEL/gal) > Fuel 1 (2.00 ml TEL/gal) > Fuel 2 (0.35 ml TEL/gal)

→

Decreasing Full-Scale Engine Anti-Knock Performance

These tests addressed the use of two different octane quality commercial alkylates with varying lead levels and compared that performance against a baseline minimum specification 100LL with maximum allowable lead and a pure component blend with significantly reduced lead. These tests did not address the impact of varying the composition of toluene on the full-scale engine anti-knock performance, which was observed to impact average exhaust gas temperatures.

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APPENDIX A—LABORATORY ANALYSES OF TEST FUELS

Exhibit 1-B

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 A-1. Laboratory Test Blends 1 Through 11 for Fuel 1

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 A-2. Laboratory Test Blends 12 Through 21 for Fuel 1

Exhibit 2-B

Fuel 2 Laboratory Blends

Blend No.:	1	2	3	4	5	6	7	8	9	10
Composition, vol-%										
Toluene	25	25	20	20	20	20	25	24	24	23
i-Octane	53	53	63	62	62	62	56	56	59	60
i-Pentane	22	20	17	18	18	18	19	20	16.5	16.5
n-Butane	0	2	0	0	0	0	0	0	0.5	0.5
Volume, L	0.900	0.900	8.000	7.570	7.570	7.570	7.570	7.570	7.570	7.570
TEL, mL/gal				0.6	0.5	0.3	0.3	0.3	0.3	0.35
TEL for MON			1.11							
MON+TEL			103.5							
MON	95.0	94.8	96.0	101.9	101.5	100.5	100.4	100.1	100.2	100.7
D909 mL			0.122	1.36	1.37	0.82	1.20	0.79	1.09	1.28
D909 PN			104.7	131.1	131.2	122.6	128.8	122.0	127.2	130.0
Vapor Pres.	44.13	49.61	37.34	38.47	38.13	38.40	34.85	40.75	38.4	38.9
IBP	37.5	35.0	43.0	42.0	38.0	39.0	40.0	38.0	38.5	38.5
10	63.4	62.0	71.6	70.7	70.3	68.6	69.5	67.0	71.5	71.4
40	95.2	96.0	96.1	96.8	96.8	95.7	97.5	96.0	97.5	96.9
50	98.25	98.8	98.3	98.9	98.9	98.2	99.5	98.5	99.0	98.8
90	101.4	101.4	100.4	100.5	100.0	99.9	102.0	101.5	101.0	100.9
End	106.0	106.0	107.0	103.0	103.5	105.5	106.0	109.0	105.0	106.5
10 + 50	161.65	160.8	169.9	169.6	169.2	166.8	169.0	165.5	170.5	170.2
Recovery	98.0	98.5	98.5	99.0	99.0	97.9	98.5	97.9	98.5	98
Residue	1.0	0.9	0.6	0.6	0.6	0.6	0.7	0.6	0.6	6
Loss	1.0	0.6	0.9	0.4	0.4	1.5	0.8	1.5	0.9	1.4
TEL, mL/gal				0.51	0.50	0.30	0.30	0.3	0.28	0.36
D3338 Heat of Combustion										44.0

Figure A-3. Laboratory Test Blends 1 Through 10 for Fuel 2

Exhibit 3-B

Fuel 3 Laboratory Blends

Blend No.:	1	2	3	4	5	6	7
Composition, vol-%							
Alkylate-E	100	80	70	60	65	65.5	66.0
i-Pentane		20	20	20	15	16.5	16.5
Toluene-E			10	20	20	18.0	17.5
Volume, L	0.800	0.800	0.800	0.800	7.570	7.570	7.570
TEL, mL/gal		0.8	0.8	0.8	0.7	0.5	0.55
MON	94.9	101.7	101.0	100.9	100.7	100.1	100.1
D909 mL					1.51	1.28	1.43
D909 PN					133.0	130.0	132.0
Vapor Pres.	15.93	46.3	43.71	44.89	35.91	38.64	38.13
IBP					39.5	40.0	39.0
10					72.5	71.5	71.0
40					102.0	101.5	101.5
50					104.5	104.0	104.0
90					110.5	111.0	110.5
End					174.0	171.0	169.0
10 + 50					177.0	175.5	175.0
Recovery					98.0	98.0	98.0
Residue					1.1	1.4	1.4
Loss					0.9	0.6	0.6
TEL, mL/gal					0.66	0.44	0.57
D3338 Heat of Combustion						43.41	43.43
Density, 15 C						725.93	725.36
Aniline Pt.							53.25
D4529 Heat of Combustion							43.70
D4809 Heat of Combustion							43.74

Figure A-4. Laboratory Test Blends 1 Through 7 for Fuel 3

Exhibit 4-B

Fuel 4 Laboratory Blends

Blend No.:	1	2-1	2-2	3	4	5
Composition, vol-%						
Alkylate-P	65.0 *	66.0	66.0	71.0	71.0	71.0
i-Pentane	15.0		16.0	11.0	10.5	10.0
n-Pentane		16.0				
Toluene-E	20.0	18.0	18.0	18.0	18.5	19.0
Volume, L	7.570	7.570	7.570	7.570	7.57	7.57
TEL, mL/gal	0.7	0.5	0.5	0.7	0.9	0.95
MON	100.6	94.5	98.6	100.2	100.8	100.7
D909 mL	1.54		<0.05	0.79	1.24	1.36
D909 PN	133.3			122.0	129.4	131.1
Vapor Pres.	36.16	41.99	47.78	41.82	41.06	40.40
IBP			40.5	37.5	37.5	
10			65.5	66.0	65.5	
40			93.5	97.0	96.5	
50			99.5	100.5	101.0	
90			107.5	107.5	107.5	
End			127.0	127.5	127.5	
10 + 50			165.0	166.5	166.5	
Recovery			98.5	98.5	98.5	
Residue			0.9	0.8	1.0	
Loss			0.6	0.7	0.5	
TEL, mL/gal		0.44	0.44		0.96	
D3338 Heat of Combustion			43.48	43.45		
Density, 15 C			716.5	719.2	720.1	721.2
Aniline Pt.					52.8	52.4
D4529 Heat					43.72	43.70
D4809 Heat			43.74			

* Alkylate-E was used by mistake when peparing this blend.

Figure A-5. Laboratory Test Blends 1 Through 5 for Fuel 4