DOT/FAA/TC-14/21

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Anti-Knock Performance of Unleaded 94 Aviation Gasoline in High-Octane Demand Full-Scale Engines

February 2015

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The U.S. Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

Technical Report Documentation Page

1. Report No. DOT/FAA/TC-14/21	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ANTI-KNOCK PERFORMANCE OF UNLEADED 94 AVIATION GASOLINE IN HIGH-OCTANE DEMAND FULL-SCALE ENGINES		5. Report Date February 2015
		6. Performing Organization Code ANG-E282
7. Author(s) David Atwood, Maryfaith Rodgers, and Cunping Huang		8. Performing Organization Report No.
9 Performing Organization Name and Address U.S. Department of Transportation Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division Propulsion and Fuels Section Atlantic City International Airport, NJ 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFAWA-10-A-00057
U.S. Department of Transportation Federal Aviation Administration New England Regional Office—Aircraft Certification Service Engine and Propeller Directorate 12 New England Executive Park Burlington, MA 01803		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency AIR-020

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was David Atwood.

16. Abstract

Removal of lead additive from 100 low lead (100LL) aviation gasoline would result in a fuel that has significantly reduced octane, with no changes to any of the other important fuel properties. This research evaluates the full-scale engine anti-knock performance of an unleaded 94 (UL94) laboratory motor octane number aviation fuel. The tests were performed by the Federal Aviation Administration (FAA) William J. Hughes Technical Center (WJHTC) Propulsion and Airpower Engineering Research (POWER) laboratories, using three high-compression engines approved for a minimum fuel grade of 100 low lead. The engines tested were a Continental IO-550-D, a Continental IO-360-DB, and a Lycoming IO-540-K. The Continental IO-550-D and the Lycoming IO-540-K engines were previously identified as representative high-octane-requirement engines in service. Under extreme hot- and dry-day sea-level test conditions, none of the engines could be operated without low levels of detonation at takeoff at the respective full-rich (F/R) mixture setting without either reducing the maximum cylinder head temperature, reducing the inlet air temperature, or retarding the engine ignition timing. Some of these operational changes were also performed at the 75% performance cruise setting to allow the engine to reach peak exhaust gas temperature, under lean mixture conditions, without exhibiting detonation. This research also investigated the effect of testing the cruise lean mixture condition at a low altitude, at the extreme hot- and dry-day standard conditions. This cruise condition at low altitude was tested in the high octane requirement IO-540-K engine, this engine was not able to be operated under a normal operating envelope, power and mixture settings, without light detonation under the low altitude temperature conditions of this test. This research suggests that under less extreme test conditions in combination, with reductions to maximum allowable engine temperatures, these engines could be operated without detonation on UL94 using F/R mixture schedules. It is outside the scope of this research to address the likely significant technical or financial challenges from seeking regulatory approval for any such operational changes.

17. Key Words Unleaded 94 aviation fuel, Aviation gasoline, Unleaded fuels, Piston engine, Aircraft, Alternative fuels, IO-550-D engine, IO-360-DB engine, IO-540-K engine, Environmental Protection Agency, Clean Air Act, 100 low lead, Detonation, Anti-Knock performance, Full-Scale engine, POWER lab	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 56	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors would like to thank the rest of the Federal Aviation Administration Propulsion and Airpower Engineering Research (POWER) laboratories' fuels team—Nick Sinclair, Jeff Warner, and Julian Canizales—and the contractors Ken Chann, Jerry Yu, and Anthony Dang for all of their efforts in supporting this research.

The authors would also like to thank the technical sponsor, Mark Rumizen, of AIR-020 for his continued support of this research.

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		xi
1.	INTRODUCTION	1
	1.1 Purpose	1
	1.2 Background	1
2.	TEST PROCEDURES	1
	2.1 Test Fuels	1
	2.2 Test Engines	5
	2.3 IO-550-D Engine Test Procedures	6
	2.4 IO-540-K Engine Test Procedures	7
	2.5 IO-360-DB Engine Test Procedures	8
3.	RESULTS AND DISCUSSION	9
	3.1 IO-550-D Engine Test Results	9
	3.2 IO-540-K Engine Test Results	35
	3.3 IO-360-DB Engine Test Results	40
4.	CONCLUSIONS	43
	4.1 Continental IO-550-D Engine	43
	4.2 Lycoming IO-540-K Engine	44
	4.3 Continental IO-360-DB Engine	44
5.	REFERENCES	45

LIST OF FIGURES

Figure		Page
1	The ASTM D910 Properties for the UL94 Fuel	2
2	GC-FID Chemical Analyses of the UL94 Fuel	3
3	The ASTM D910 Properties for the 100LL Fuel Used for the IO-550-D Test	4
4	The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and Standard 22° BTDC Ignition Timing	11
5	The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and 19° Ignition Timing	13
6	The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and 16° Ignition Timing	15
7	The IO-550-D Engine Power Performance of the UL94 and 100LL Fuels at Maximum CHT of 400 +5-0 °F and 460 +5-0 °F and 13° Ignition Timing	17
8	Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 19° BTDC Ignition Timing and at Maximum CHT of 460 +5-0 °F	19
9	Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 16° BTDC Ignition Timing and at Maximum CHT of 460 +5-0 °F	19
10	Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 13° BTDC Ignition Timing and at Maximum CHT of 460 +5-0 °F	20
11	Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 19° BTDC Ignition Timing and at a Maximum CHT of 400 +5-0 °F	20
12	Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 16° BTDC Ignition Timing and at a Maximum CHT of 400 +5-0 °F	21
13	Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 13° BTDC Ignition Timing and at a Maximum CHT of 400 +5-0 °F	21
14	The IO-550-D Engine Detonation Performance for UL94 and 100LL Fuels at Ignition Timing of 22° and 19° and CHT 460 +5-0 °F	22
15	The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 16° BTDC and CHT 460 +5-0 °F	23

16 The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 13° BTDC and CHT 460 +5-0 °F 24

17 The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 19° BTDC and CHT of 400 +5-0 °F 25

18 The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 16° BTDC and CHT 400 +5-0 °F 26

19 The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 13° and CHT 400 +5-0 °F 27

20 Light Detonation Equivalence Ratio for the UL94 Fuel at 460 +5-0 °F Maximum CHT and Standard 22° BTDC Ignition Timing, for IO-550-D 28

21 Light Detonation Equivalence Ratio for the UL94 Fuel at 400 +5-0 °F Maximum CHT and Standard 22° BTDC Ignition Timing, for IO-550-D 28

22 Light Detonation Equivalence Ratio for the UL94 Fuel at 460 +5-0 °F Maximum CHT and 19° BTDC Ignition Timing, for IO-550-D 29

23 Light Detonation Equivalence Ratio for the UL94 Fuel at 400 +5-0 °F Maximum CHT and 19° BTDC Ignition Timing, for IO-550-D 30

24 Light Detonation Equivalence Ratio for the UL94 Fuel at 460 +5-0 °F Maximum CHT and 16° BTDC Ignition Timing, for IO-550-D 31

25 Light Detonation Equivalence Ratio for the UL94 Fuel at 400 +5-0 °F Maximum CHT and 16° BTDC Ignition Timing, for IO-550-D 32

26 Light Detonation Equivalence Ratios for the UL94 Fuel at 460 +5-0 °F Maximum CHT and 13° BTDC Ignition Timing, for IO-550-D 33

27 Effect of Ignition Timing on Average EGT With 460 +5-0 °F CHT at 2700 RPM and Takeoff Power Setting, for IO-550-D 34

28 Effect of Ignition Timing on Average EGT With 400 +5-0 °F CHT at 2700 RPM and Takeoff Power Setting, for IO-550-D 34

29 The IO-540-K Engine Light Detonation Power and EGT as Functions of Fuel-to-Air Equivalence Ratio on the Extreme Hot- and Dry-Day and at Sea Level Conditions (475 +5-0 °F Maximum CHT) 38

30 The IO-540-K Engine Light Detonation Power and EGT as Functions of Fuel-to-Air Equivalence Ratio on the Extreme Hot- and Dry-Day and at Sea Level Conditions (425 +5-0 °F Maximum CHT) 39

31 The IO-540-K Engine Light Detonation Power and EGT as Functions of Fuel-to-Air Equivalence Ratio on the Extreme Hot- and Dry-Day and at 3500 ft Altitude Conditions 39

32 The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (460 +5-0 °F maximum CHT and standard 20° ignition timing) 40

33 The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (400 +5-0 °F maximum CHT and standard 20° ignition timing) 41

34 The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (460 +5-0 °F maximum CHT and retarded 17° ignition timing) 42

35 The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (400 +5-0 °F maximum CHT and retarded 17° ignition timing) 42

LIST OF TABLES

Table		Page
1	Test Engine Parameters	5
2	Maximum CHT and Engine Ignition for the IO-550-D Engine	7
3	Test Parameters for the IO-540-K Engine	8
4	Engine Power Settings for the IO-360-DB Engine Testing	9
5	Summary of the Anti-Knock Performance of the UL94 Fuel at Various Engine Ignition Timing and Maximum CHTs in the IO-550-D Engine	35
6	Repeatability of IO-540-K Engine Testing Data for UL94 Fuel at 2% Detonation Intensity Onset	36
7	Repeatability of IO-540-K Engine Testing Data for 100LL Fuel at 2% Detonation Intensity Onset	36

LIST OF ACRONYMS

100LL	100 low lead
AVGAS	Aviation gasoline
BHP	Brake horsepower
BTDC	Before top dead center
CHT	Cylinder head temperature
EGT	Exhaust gas temperature
FAA	Federal Aviation Administration
F/R	Full rich
GC-FID	Gas Chromatography-Flame Ionization Detector
HP	Horsepower
BHP	Brake Horsepower
IAT	Inlet air temperature
MAP	Manifold absolute pressure
MON	Motor octane number per ASTM D2700
OilT	Oil temperature
POWER	Propulsion and Airpower Engineering Research
RPM	Revolutions per minute
TEL	Tetraethyl lead
UL94	Unleaded 94
WJHTC	William J. Hughes Technical Center
WOT	Wide open throttle

EXECUTIVE SUMMARY

Removal of lead additive from aviation gasoline results in a fuel that meets all of the important fuel-specification properties per ASTM International Specification D910, except for both ASTM International D2700 motor octane number (MON) and ASTM D909 supercharge rich performance number. Typical commercial unleaded aviation alkylate, the base product of the widely used 100 low-lead (100LL) fuel, is estimated to have an unleaded fuel MON typically falling between 91 and 94, per ASTM International standard test method D2700. So UL94 would be representative of a high octane quality unleaded aviation alkylate. This research evaluated the anti-knock performance of an unleaded 94 (UL94) MON aviation gasoline at the Federal Aviation Administration (FAA)William J. Hughes Technical Center's (WJHTC) Propulsion and Airpower Engineering Research (POWER) laboratories, in multiple high-compression, full-scale engines approved for a minimum fuel grade of 100LL. For these tests, the engines were operated under extreme hot- and dry-day conditions. The following engines were tested: a 6-cylinder, Continental Motors IO-550-D engine with a compression ratio of 8.5:1 and rated power of 300 brake horsepower (BHP); a 6-cylinder, Continental Motors IO-360-DB engine with a compression ratio of 8.5:1 and a rated power of 210 BHP, and a 6-cylinder, Lycoming IO-540-K engine with a compression ratio of 8.7:1, and a rated power of 300 BHP. The UL94 full-scale, detonation free operational window was compared to that of a 100LL fuel purchased from a local airport. Additionally, the engine ignition timing, engine air inlet temperature, and maximum allowable cylinder head temperature (CHT) were varied in an attempt to investigate the full-scale, anti-knock performance differences between UL94 and 100LL fuels. At a 75% rated cruise power setting, the highest power that IO-540-K and IO-360-DB engines allow for fuel mixture leaning, these tests evaluated the fuel performance under both sea-level and 3500 ft altitude extreme hot- and dry-day inlet air temperature (IAT) conditions. The 80% power setting is the highest power that the IO-550-D engine allows for fuel mixture leaning.

Under the extreme hot- and dry-day at sea-level test conditions used in this research, the UL94 produced low levels of detonation at takeoff power for all three test engines at the full-rich mixture setting. Results also indicated that reducing IAT, and maximum CHT, or retarding ignition timing allow the engine to reach peak exhaust gas temperature without detonation at a 75% cruise power setting. Recent research performed at the FAA WJHTC POWER laboratories indicated that even small amounts of intake air humidity improve fuel anti-knock performance. Additional testing under a different set of extreme conditions, such as engine operational changes, reduced IAT simulating conditions at a low cruise altitude, and slightly increased intake air humidity levels was performed.

1. INTRODUCTION.

1.1 PURPOSE.

The goal of this research was to quantify anti-knock performance of an unleaded aviation gasoline (AVGAS) with a motor octane number (MON) of unleaded 94 (UL94). This fuel was tested in multiple full-scale high-octane demand engines under extreme hot- and dry-day test conditions. The test conditions were also varied to determine the effects of fuel anti-knock performance.

1.2 BACKGROUND.

Researchers at the Federal Aviation Administration (FAA) William J. Hughes Technical Center's (WJHTC) Propulsion and Airpower Engineering Research (POWER) laboratories have extensive experience testing unleaded and reduced-lead aviation fuels. Research has focused on safety in regard to the performance and use of unleaded aviation fuels on a fleet that was designed and certificated largely on high-octane, leaded AVGAS. Removing the additive tetraethyl lead (TEL) from 100 low-lead (100LL) AVGAS results in a fuel with a motor octane number (MON) typically falling between 91 to 94, per ASTM International test method D2700 [1]. However, whereas the resulting unleaded aviation gasoline is much lower in octane than 100LL, all of the other very important fuel specification property limits, for which the fleet was designed, do not change. Replacing the octane provided by small amounts of TEL additive requires use of larger amounts of less effective organometallic additives or use of relatively large amounts of novel and specialty chemicals, not found in conventional AVGAS at appreciable levels. As documented in the Unleaded Aviation Gasoline Transition Aviation Rulemaking Committee final report [2], fuel complexity typically increases with increasing unleaded fuel target octane. The use of large amounts of chemicals to obtain the desired octane levels results in fuel blends having fuel properties that often fall outside the experience of the legacy fleet on 100LL and that can result in new fit-for-purpose issues.

The purpose of the research was to determine and compare the anti-knock performance of a UL94 fuel, made from traditional aviation gasoline components, in three high-octane demand engines. The fuel approximates high-octane quality unleaded aviation alkylate currently in production. The anti-knock performance of UL94 was compared with that of a locally procured 100LL AVGAS. Engine test conditions were varied from the extreme hot- and dry-day test conditions to assess the impact of test condition changes on UL94 anti-knock performance.

2. TEST PROCEDURES.

2.1 TEST FUELS.

Both the UL94 and the 100LL were tested for the specification properties shown in table 1 of ASTM D910 [3]. The UL94 fuel was also analyzed using gas chromatography-flame ionization detection (GC-FID) for its chemical composition. The laboratory testing results can be found in figures 1 through 3. Figure 1 shows that the specification properties of UL94 fuel meet the requirements for 100LL fuel based on ASTM D910, except for the MON per ASTM D2700, supercharge rich performance number per ASTM D909, and mandatory blue colored dye [1 and

4]. Figure 2 also lists the chemical compositions of the UL94 fuel. Figure 3 shows the certificate of analysis of the 100LL used for the IO-550-D testing. The 100LL fuel used for both the IO-360-DB and IO-540-K tests contained 1.87 ml TEL/gal, with a MON of 103.4 and a supercharge performance number of 132.5.

CERTIFICATE OF ANALYSIS

Number: 134269

Client: FAA WJH Technical Center
Propulsion and Fuel Systems Team, AJP-6340
Atlantic City International Airport, NJ 08405

Date: March 12, 2010

Sample: UL 94

D2700	Motor octane number (BRE/29.8in/300F)	94.4
D909	ASTM Supercharge rating	
	Octane number	98
D5059A	Lead, mL/L	< 0.01
D2392	Color	Unacceptable
D4052	Density at 15 °C, kg/m^3	696.2
D86	Distillation	
	Initial boiling point, °C	37.5
	Fuel evaporated, °C	
	10 volume %	64.5
	40 volume %	92.0
	50 volume %	95.5
	90 volume %	99.5
	Final boiling point, °C	115.0
	Sum of 10 % + 50 %	160.0
	Recovery, volume %	98.0
	Residue, volume %	0.7
	Loss, volume %	1.3
	(Barometric pressure, 758.8 mm Hg; Procedure arithmetical)	
D5191	Vapor pressure, DVPE (250 mL), kPa	48.7
D2386	Freezing point, °C	< -70.0
D2622	Total sulfur content, mass %	< 0.0001
D4809	Net heat of combustion, MJ/kg	44.008
D130	Corrosion copper strip (2 h/100 °C)	1a
D873	Oxidation stability (5 h aging)	
	Potential gum, mg/100 mL	< 1
	Precipitate, mg/100 mL	< 0.1
D1094	Water reaction	
	Volume change, mL	0.0
	Interface condition	1
	Degree of separation	1

Figure 1. The ASTM D910 Properties for the UL94 Fuel

Certificate of Analysis 134269
March 12, 2010

GC-FID*	Composition, mass %	
	Propane	0.05
	Isobutane	0.90
	n-Butane	0.60
	Isopentane	14.15
	n-Pentane	0.36
	2-Methyl-2-Butene	0.02
	2,2-Dimethylbutane	1.18
	Cyclopentane	0.33
	2,3-Dimethylbutane	0.51
	2-Methylpentane	1.50
	3-Methylpentane	0.90
	n-Hexane	0.04
	Methylcyclopentane	1.33
	2,4-Dimethylpentane	0.09
	Cyclohexane	1.19
	2,3-Dimethylpentane	0.23
	3-Methylhexane	0.09
	2,2,4-Trimethylpentane	64.13
	n-Heptane	0.03
	Methylcyclohexane	0.34
	2,2,3,3-Tetramethylbutane	1.51
	2,5-Dimethylhexane	0.69
	2,4-Dimethylhexane	0.04
	2,3,4-Timethylpentane	0.95
	Toluene	8.59
	3-Methylpentane	0.06
	trans-1,4-Dimethylcyclohexane	0.03
	Unidentified	0.16

Figure 2. GC-FID Chemical Analyses of the UL94 Fuel

CERTIFICATE OF ANALYSIS

Number: 134270

Client: FAA WJH Technical Center
Propulsion and Fuel Systems Team, AJP-6340
Atlantic City International Airport, NJ 08405

Date: March 11, 2010

Sample: 100LL

			D 910-07a Grade 100LL
D2700	Motor octane number (BRE/30.0in/300F)	104.3	99.6 min
D909	ASTM Supercharge rating, mL TEL/gal	1.39	
	Performance number	131.5	130.0 min
D5059A	Lead, mL/L	0.51	0.53 max
D2392	Color	Acceptable	Blue
			All Grades
D4052	Density at 15 °C, kg/m^3	693.6	Report
D86	Distillation		
	Initial boiling point, °C	41.0	Report
	Fuel evaporated, °C		
	10 volume %	73.0	75 max
	40 volume %	95.0	75 min
	50 volume %	98.5	105 max
	90 volume %	109.0	135 max
	Final boiling point, °C	137.5	170 max
	Sum of 10 % + 50 %	171.5	135 min
	Recovery, volume %	98.0	97 min
	Residue, volume %	1.1	1.5 max
	Loss, volume %	0.9	1.5 max
	(Barometric pressure, 758.8 mm Hg; Procedure arithmetical)		
D5191	Vapor pressure, DVPE (250 mL), kPa	41.4	38.0 min-49.0max
D2386	Freezing point, °C	< -70.0	- 58 max
D2622	Total sulfur content, mass %	0.0008	0.05 max
D4809	Net heat of combustion, MJ/kg	44.068	43.5 min
D130	Corrosion copper strip (2 h/100 °C)	1a	No. 1 max
D873	Oxidation stability (5 h aging)		
	Potential gum, mg/100 mL	1	6 max
	Precipitate, mg/100 mL	0.7	3 max
D 1094	Water reaction		
	Volume change, mL	0.0	± 2 max
	Interface condition	1	-
	Degree of separation	1	-

Figure 3. The ASTM D910 Properties for the 100LL Fuel Used for the IO-550-D Test

2.2 TEST ENGINES.

Three naturally aspirated, fuel-injected engines were used in this research. Table 1 provides a detailed summary of the test engine parameters. The first engine was a Continental IO-550-D—a 6-cylinder horizontally opposed engine—with a rated maximum 300 brake horsepower (BHP) at 2700 revolutions per minute (RPM). The second Continental engine was a 6-cylinder horizontally opposed IO-360-DB engine, with a rated maximum power of 210 BHP at 2800 RPM. The third engine evaluated was a Lycoming IO-540-K, also a 6-cylinder horizontally opposed engine, with a rated maximum power of 300 BHP at 2700 RPM. The minimum permitted fuel grade for all these engines is 100LL fuel.

Table 1. Test Engine Parameters

Engine	Rated Power (HP)	Rated Engine Speed (RPM)	No. of Cylinders	Compress Ratio	Cylinder Bore (in.)	Magneto Static Ignition Timing	Fuel Servo
Continental IO-550-D	300	2700	6	8.5:1	5.25	22°	Continental Continuous Flow Fuel Injection System
Lycoming IO-540-K	300	2700	6	8.7:1	5.125	20°	AvStar model RSA-10ED1
Continental IO-360-DB	210	2800	6	8.5:1	4.438	50°	Continental Continuous Flow Fuel Injection System

The Continental engines were originally broken-in following the Continental Motors break-in procedure (service bulletin M89-7R1 [5]) using an unleaded isooctane primary reference grade fuel and AeroShell 100 straight mineral aviation oil meeting the MIL-L-6082E standard. The Lycoming engine was originally broken-in using Phillips 66® Type M nondispersant 20W-50 mineral oil and isooctane primary reference grade fuel.

As matter of best practice, 100LL fuel tests were always performed after all unleaded fuels had been tested. To eliminate the lead memory concerns, a 30- to 45-minute lead deposit purge run using the unleaded fuel was performed after short duration testing with leaded fuel, prior to additional unleaded fuel tests.

An eddy-current dynamometer was used for power absorption; only the engine accessories that were required for engine operation were installed. An Aeroshell Type W 15W-50 ashless dispersant oil was used for all engine testing and operation after the break-in period.

As part of the previous tests with the IO-550-D and IO-540-K engines, the cylinder assemblies had been removed, drilled, and tapped into the fin area to install high-temperature, water-cooled piezoelectric pressure transducers. The detonation data for the IO-360-DB engine were collected using accelerometers. The FAA WJHTC POWER laboratories have considerable experience comparing full-scale engine detonation test results between flush-mounted pressure transducers and Kistler piezoelectric accelerometers.

For the in-cylinder and flush-mounted transducers, one transducer was installed in each cylinder head with the transducer face flush with the surface of 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 D6424 [6]. The engines were instrumented to record many other engine parameters, which were measured 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 instruments were calibrated, a series of maintenance runs was carried out to verify the integrity of engine systems and the accuracy of instruments. Prior to any engine operation, the mixture cutoff, the mixture full-rich (F/R) settings, the throttle stop, and the throttle throw positions were verified.

The engines were instrumented with the following minimum set of sensors:

- Cylinder head temperatures (CHT) 1 to 6
- Exhaust gas temperatures (EGT) 1 to 6
- Inlet air temperature (IAT) and inlet air pressure
- (IAP)_Air mass flow rate
- Air-to-fuel ratios for both banks of cylinders
- Manifold Absolute Pressure (MAP) and Manifold Air Temperature (MAT)
- Engine speed (RPM) and shaft torque
- Corrected (calculated) brake horsepower (BHP)
- Fuel mass and volume flow rates
- Engine cowling air temperature and pressure
- Fuel temperature and fuel mass density
- Metered and unmetered fuel pressures
- Oil temperature (OilT) and oil pressure (OilP)
- Kistler piezoelectric in-cylinder pressure transducers/Kistler piezoelectric accelerometers

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

2.3 IO-550-D ENGINE TEST PROCEDURES.

The objective of this test was to compare the anti-knock performance of the UL94 fuel against the 100LL fuel across the engine operating range. Two maximum CHTs and multiple ignition timings were tested to determine the impacts of lowering the maximum CHT or of retarding the ignition timing on the anti-knock performance of the UL94 fuel. Table 2 lists the maximum

CHT and ignition timing settings that were used in the test. These tests were carried out with an inlet air temperature (IAT) of 103 ± 3 °F and a targeted OilT of 245 ± 10 °F.

Table 2. Maximum CHT and Engine Ignition for the IO-550-D Engine (103 ± 3 °F IAT, 245 ± 10 °F OilT)

Targeted Maximum CHT (°F)	Ignition Timing (Before Top-Dead-Center)			
460 + 5-0	22°/22°, standard	19°/19°	16°/16°	13°/13°
400 + 5-0	22°/22°, standard	19°/19°	16°/16°	13°/13°

The F/R, best power, and best economy power curves for the 100LL fuel were created by performing mixture sweeps from the F/R setting to the best economy setting. Each curve was derived based on combinatory conditions of RPM, MAP, maximum CHT, and ignition timing. In this test, engine speeds ranged from 2300 to 2700 RPM in 100 RPM increments, and engine MAPs ranged from 22 inHg to wide open throttle (WOT) pressure in 2 inHg increments. It was noted that detonation was not detected on the 100LL fuel at any of the power settings.

Because the heat content of the UL94 fuel is close to that of the 100LL fuel, the power produced via combustion of these two fuels was the same. Mixture leaning on the UL94 fuel started from the F/R fuel mixture setting to the occurrence of engine detonation. The test was carried out for each of the RPM and MAP combination to identify the leanest mixture at which detonation-free engine operation can be obtained. These test conditions were also used for the 100LL fuel tests. The mixture leaning was stopped when either heavy detonation occurred or the peak EGT was attained. The results are described as critical fuel mass flow at light detonation, set at each power point for the UL94 fuel.

2.4 IO-540-K ENGINE TEST PROCEDURES.

Two maximum CHTs, along with two IATs at the cruise power settings, were used to evaluate the fuel anti-knock performance. The IAT was varied at the cruise power setting to determine fuel anti-knock performance at extreme hot- and dry-day standard temperatures, both at 3500 ft altitude and sea level. Both the 100LL and UL94 fuels were used in this testing.

Table 3 summarizes the test parameters for the IO-540-K engine. Under all testing conditions, the engine was adjusted to the power specified in the targeted MAP section and then leaned toward the targeted power percentage. This process accounted for the power increase as fuel mixture setting was leaned, while the fuel-mixture setting is rich at the best power.

Table 3. Test Parameters for the IO-540-K Engine

Engine Speed (RPM)	Targeted Power Percentage/ (peak corrected BHP)	Targeted Throttle	Targeted Maximum CHT (°F)	Targeted IAT (°F)	Mixture Setting
2700	Full Throttle	Record	475 +5-0	103 ± 3	F/R to heavy detonation
2600	85% (255)	Adjust to 252 corrected BHP at F/R	475 +5-0	103 ± 3	F/R to heavy detonation
2450	75% (225)	Adjust to 218 corrected BHP at F/R	475 +5-0	103 ± 3	F/R to best economy or heavy detonation
2350	65% (195)	Adjust to 188 corrected BHP at F/R	475 +5-0	103 ± 3	F/R to best economy or heavy detonation
2700	Full Throttle	Record	425 +5-0	103 ± 3	F/R to heavy detonation
2600	85% (255)	Adjust to 252 corrected BHP at F/R	425 +5-0	103 ± 3	F/R to heavy detonation
2450	75% (225)	Adjust to 218 corrected BHP at F/R	400 +5-0	90 ± 3	F/R to best economy or heavy detonation
2350	65% (195)	Adjust to 188 corrected BHP at F/R	400 +5-0	90 ± 3	F/R to best economy or heavy detonation

2.5 IO-360-DB ENGINE TEST PROCEDURES.

Mixture lean-outs were performed by starting at the F/R fuel mixture stop setting and then leaning the mixture until the engine either reached heavy detonation or was past peak EGT. Mixture adjustments were carried out at a variety of engine power settings throughout the engine's operating envelope, including takeoff, climb, and two cruise power settings, as shown in table 4. The fuel performances were evaluated at maximum CHT settings of 460 +5-0 °F and 400 +5-0 °F and at standard 20°/20° before top dead center (BTDC) ignition timing, as well as at retarded ignition timing of 17°/17° BTDC. The IAT was controlled to the range of 103 ± 3 °F, OilT was maintained at 245 ± 10 °F, and the relative humidity of the inlet air was adjusted between 5% and 10% throughout any test process for all testing conditions.

Table 4. Engine Power Settings for the IO-360-DB Engine Testing

Engine Power Setting	Rated Engine Speed (RPM)	CMI Corrected Power (BHP) at F/R	MAP	Fuel Mixture
Maximum continuous power	2800	Full Throttle (210 ± 2.5%) (205 to 215)	Full Throttle (Record)	Lean from F/R to heavy knock or 50 °F past peak EGT
Climb power (85% Rated Power)	2600	178.5 ± 1.0	Adjust to the power setting	Lean from F/R to heavy knock or 50 °F past peak EGT
Maximum cruise power (75% rated power)	2500	157.5 ± 1.0	Adjust to the power setting	Lean from F/R to heavy knock or 150 °F past peak EGT
Low cruise power (65% rated power)	2300	136.5 ± 1.0	Adjust to the power setting	Lean from F/R to heavy knock or 150 °F past peak EGT

3. RESULTS AND DISCUSSION.

3.1 IO-550-D ENGINE TEST RESULTS.

The engine power performance and anti-knock performance of the UL94 fuel is compared to that of the 100LL fuel in figures 4 through 26. Figure 4 depicts the power performance of 100LL and UL94 fuels at the maximum CHT of 400 °F and 460 °F. The performance curves for the 100LL and UL94 fuels are shown in solid and dotted lines, respectively. The blue and red lines represent the fuel performance curves at CHT 400 +5-0 °F and 460 +5-0 °F, respectively. A pair of blue and red lines on the top of the figure shows the engine power performance of the 100LL fuel at the F/R mixture settings at CHT 400 +5-0 °F and 460 +5-0 °F, respectively. The middle set of the solid lines depicts the engine performance at the best power settings, and the performance at the best economy mixture settings are depicted with the bottom set of solid lines. It is noted that at all power and fuel mixture settings, detonation was not detected when the engine was operated on the locally purchased 100LL fuel. Because the IO-550-D engine did not experience detonation on 100LL, the solid lines in figures 4 to 26 are provided as a reference to engine power at F/R, best power, and best economy, not depicting the light detonation line. The dotted lines in figures 4 to 26 are plotted along the fuel mass flow and corrected power points where the IO-550-D engine entered a light detonation condition on UL94.

The red lines are for the 460 +5-0 °F maximum CHT and blue for 400 +5-0 °F maximum CHT. This means that the richer mixtures or reduced power settings above and to the left of this light detonation curve represent the detonation free region. The area below and to the right of the red dotted light detonation line for the UL94 fuel is the heavier detonation region with leaner

mixtures and increased power. In addition to the two maximum CHTs discussed (460 +5-0 °F and 400 +5-0 °F), the engine power performance tests were carried out under extreme hot- and dry-day conditions at sea level with an IAT of 103 ± 3 °F and an inlet air relative humidity < 2%.

The effect of reducing maximum allowable CHT on the anti-knock performance of the UL94 fuel in the IO-550-D high-compression engine is shown in figures 4 through 7. As expected, under all ignition timing conditions, decreasing the maximum CHT increased the fuel anti-knock performance both in terms of engine power output and the capability for the engine to be operated at leaner fuel mixture. In all cases, the detonation free region for the UL94 fuel was smaller than that of the 100LL fuel. It should be noted that light detonation was not detected on the 100LL fuel at any power setting, fuel mixture, or test conditions.

As shown in figure 4, when the IO-550-D engine was tested under conditions of standard ignition timing—a maximum CHT of 460 +5-0 °F and F/R fuel mixture—the engine BHP for the UL94 fuel at light detonation was found to be 70 BHP less than that of the 100LL fuel performed under the same conditions. In other words, for the engine to not exhibit light detonation on UL94, when tested at extreme hot and dry sea-level test conditions with the maximum allowable CHT (460 + 5-0 °F), the engine could be operated only below 75% rated power with F/R mixture. Additionally, under standard engine ignition timing, the maximum allowable CHT, and extreme hot- and dry-day conditions, the UL94 fuel could not be leaned to the best power setting at any engine power output without generating light engine knock. At the reduced CHT of 400 °F, the engine could be leaned only to the best power setting below 205 BHP while remaining below light detonation. Above 205 BHP, the fuel would exhibit detonation if one attempted to follow along the best power curve (i.e., the dotted blue line in figure 4 that transitions above the solid-blue line of the best power curve at this point).

When the engine was operated at a maximum CHT of 460 °F for the UL94 fuel, the detonation-free zone shown in figure 4 is between one solid and one dotted red line. This narrow region indicates that the UL94 fuel has a limited region of detonation free operation at specified maximum of 460 °F CHT. At this temperature, when the fuel is operated at power setting greater than 75% of rated power (225 BHP), the engine was operating in a detonation status. However, if the maximum CHT is reduced to 400 °F, the detonation free zone for the UL94 fuel can be expanded to the area between one solid and one dotted blue line (see figure 4), which is much wider than that for 460 °F maximum CHT. This indicates that UL94 fuel, at reduced maximum CHT of 400 °F, can perform detonation free at F/R fuel mixture settings at power settings above 75% rated power.

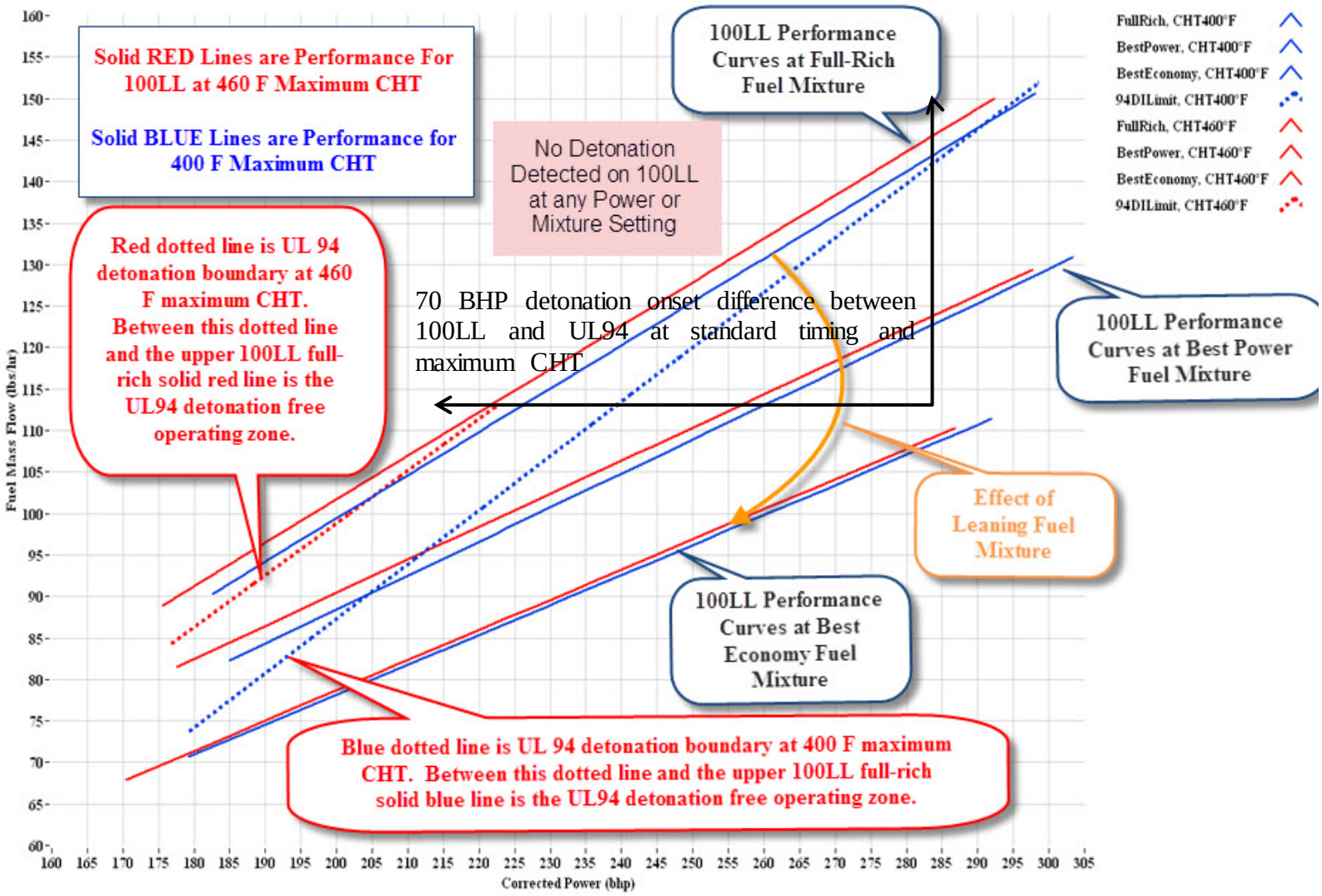

Figure 4. The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and Standard 22° BTDC Ignition Timing

As shown in figure 5, when engine ignition timing changes from standard 22° to retarded 19° BTDC ignition timing, the UL94 fuel light detonation line (dotted red line) is below the F/R solid red line for the 100LL fuel across the entire engine operating power range. This indicates that the UL94 fuel is capable of producing the same power as the 100LL fuel while operating detonation free at a maximum CHT of 460 +5-0 °F and at all power settings using F/R mixture settings. However, the fuel cannot be leaned at best power settings above approximately 217 corrected BHP without entering detonation. This is indicated by the red dotted line, which rises above the best power line (red solid line) at 217 CBHP. With 19° BTDC retarded ignition timing and at a reduced 400 +5-0 °F maximum CHT, the UL94 and 100LL fuels generate approximately the same power. The UL94 at the 19° BTDC retarded ignition timing, cannot be leaned to best power setting above 282 BHP; further mixture leaning may be carried out below this power.

Summarizing figure 5, retarding the ignition timing by 3° to 19° BTDC allows the IO-550-D engine to operate detonation free at any power setting, provided the mixture setting is maintained at F/R. Lowering the maximum allowable CHT to 400 +5-0°F increases the engine power output by approximately 3 BHP (1% of rated power) and would allow detonation free operation at takeoff and climb power settings at F/R fuel mixture. Additionally, the UL94 fuel mixture may be leaned below best power at less than 270 BHP if maximum CHT can be maintained below 400 °F.

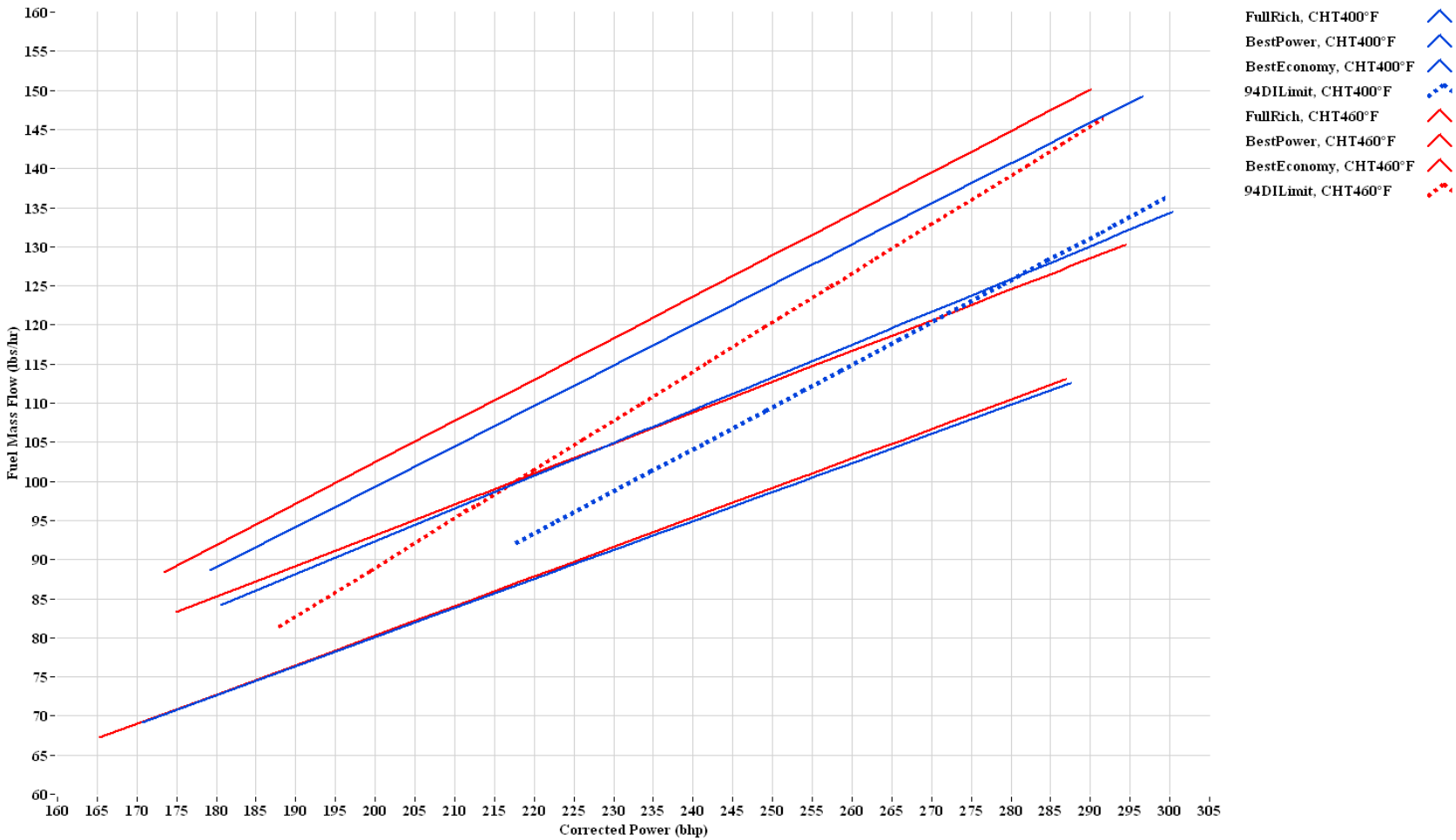

Figure 5. The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and 19° Ignition Timing

Figure 6 shows that, at 16° BTDC retarded ignition timing and a maximum CHT of 460 +5-0 °F, the UL94 fuel produces approximately 5 BHP less power than that of the 100LL fuel at standard ignition timing when measured at the same maximum power setting. This is approximately equivalent to 1.5% of rated power. In addition, the UL94 fuel can be leaned to the best power fuel mixture setting below approximately 255 BHP (85% of rated power) without light detonation. However, it cannot be leaned to the best economy fuel mixture at any power setting without exhibiting light detonation. When reducing the maximum CHT from 460 +5-0 °F to 400 +5-0 °F at the 16° retarded ignition timing, the UL94 fuel was able to reach best economy power settings below 215 BHP. It is important to note that this test was carried out at sea level and under extreme hot- and dry-day conditions. Low altitude and extreme hot- and dry-day conditions are less severe and would further increase the power at which the engine could be leaned to best power and best economy. Retarding 6° BTDC ignition timing would reduce engine detonation, but it would lead to increased EGT. However, the impacts of engine durability resulting from elevated EGT remains unknown.

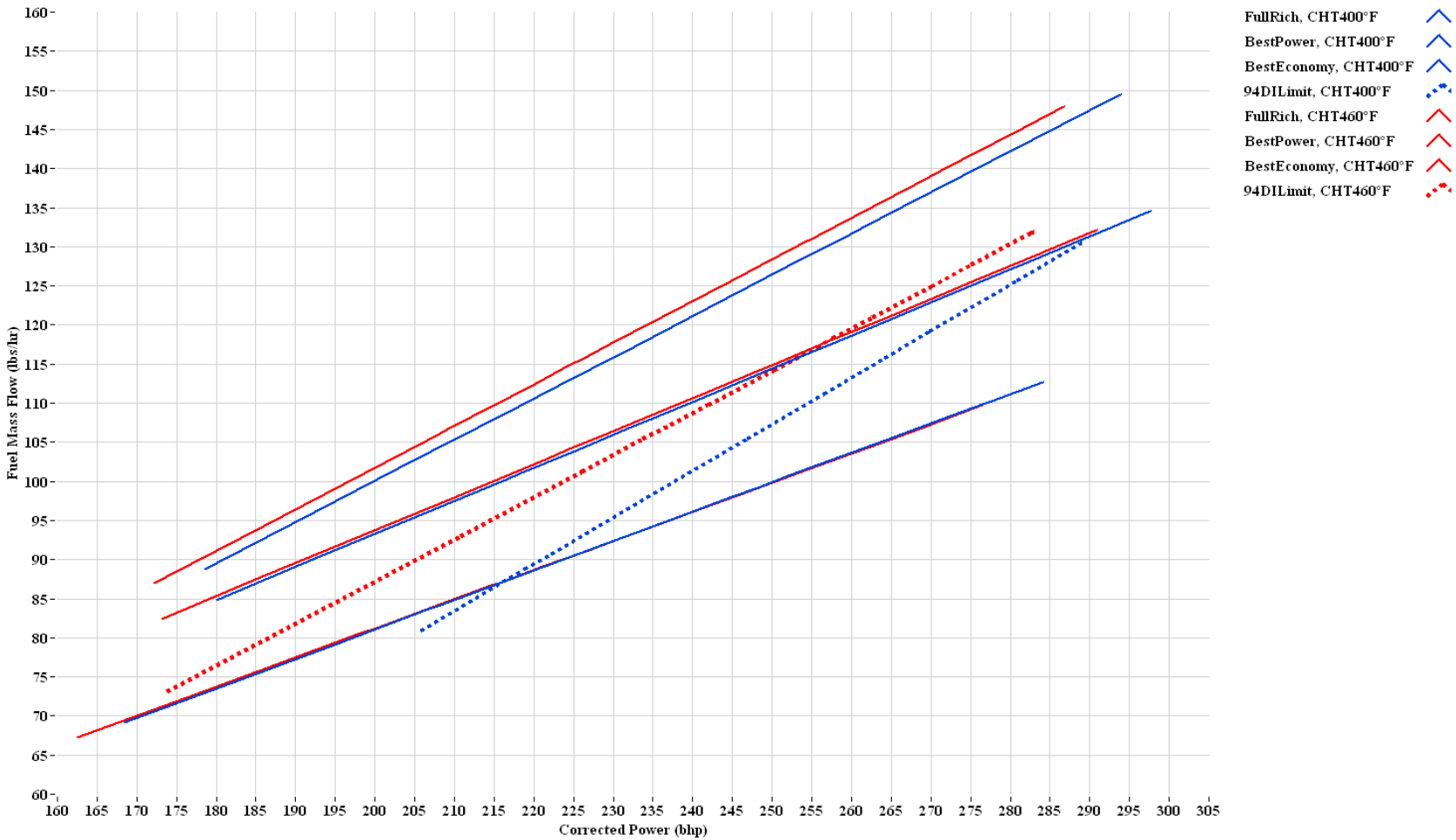

Figure 6. The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and 16° BTDC Ignition Timing

Figure 7 shows that, with 13° BTDC retarded ignition timing and at a maximum CHT of 460 +5-0 °F, the UL94 fuel is unable to be leaned to the best economy power setting (approximately 221 BHP) without reaching light detonation. This is very close to the best economy fuel mixture at 75% performance cruise power setting (225 BHP). Also, with 13° ignition timing and at a reduced maximum CHT of 400 +5-0 °F, the UL94 fuel can be leaned to the best economy mixture at any power setting lower than 250 BHP. Retarding ignition timing from the standard 22° to 13° BTDC decreases the best power by approximately 10 BHP at 460 +5-0 °F CHT and 8 BHP at 400 +5-0 °F CHT, respectively. It is important to note that the impact of changing engine ignition timing and increased EGT on the engine durability is beyond the scope of this research. In addition the impact of the power reduction with the timing change is not addressed.

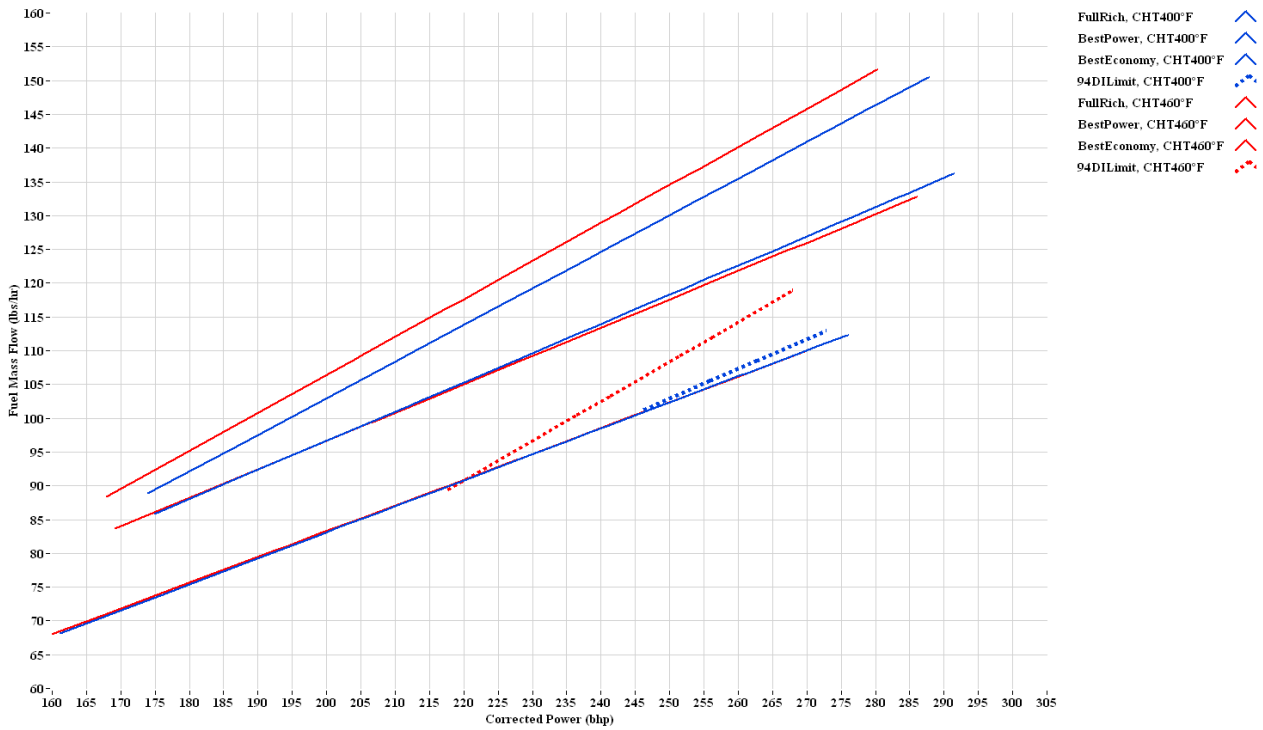

Figure 7. The IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at Maximum CHTs of 400 +5-0 °F and 460 +5-0 °F and 13° BTDC Ignition Timing

Figures 8 through 13 show the same data sets that were shown in figures 4 through 7, except that each plot displays the impacts of ignition timing retardation on anti-knock performance at a given maximum CHT. In all cases, the detonation-free operating window for the UL94 fuel was smaller than that of the 100LL fuel. However, under standard testing conditions of an extreme hot- and dry-day with 103 ± 3 °F IAT and <2% relative humidity, as shown in figure 13, the engine can operate at best power from 75% (215 BHP) to 86% power (246 BHP) with the UL94 fuel at 13° regarded ignition timing and 400 °F maximum CHT. When the engine is operated at 80% rated power setting, the fuel mixture can be leaned almost to the best economy at 86% power before encountering light detonation. It should be noted that under hot- and dry-day testing conditions, if an engine is operated at a simulated low altitude (e.g., 3500 ft), slightly increasing the relative humidity in the inlet air, the UL94 fuel may be able to perform detonation free operation at more advanced ignition timing and at higher maximum CHTs.

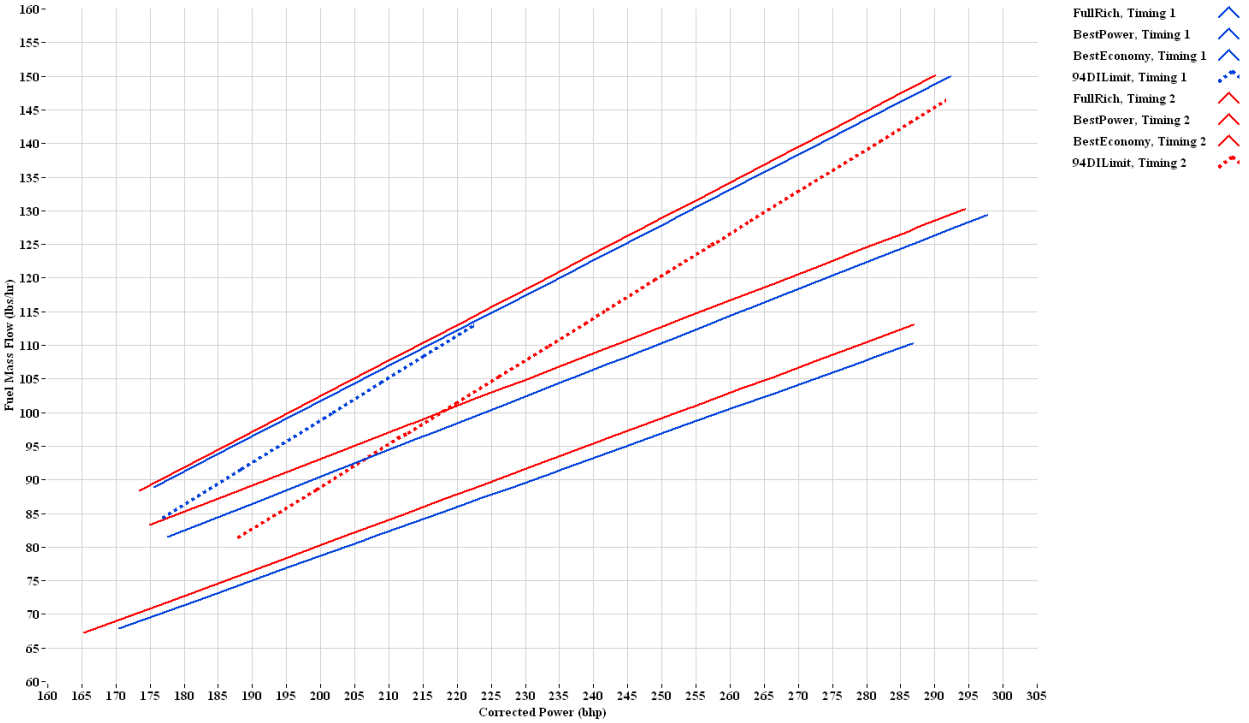

Figure 8. Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 19° BTDC Ignition Timing and at Maximum CHT of 460 +5-0 °F

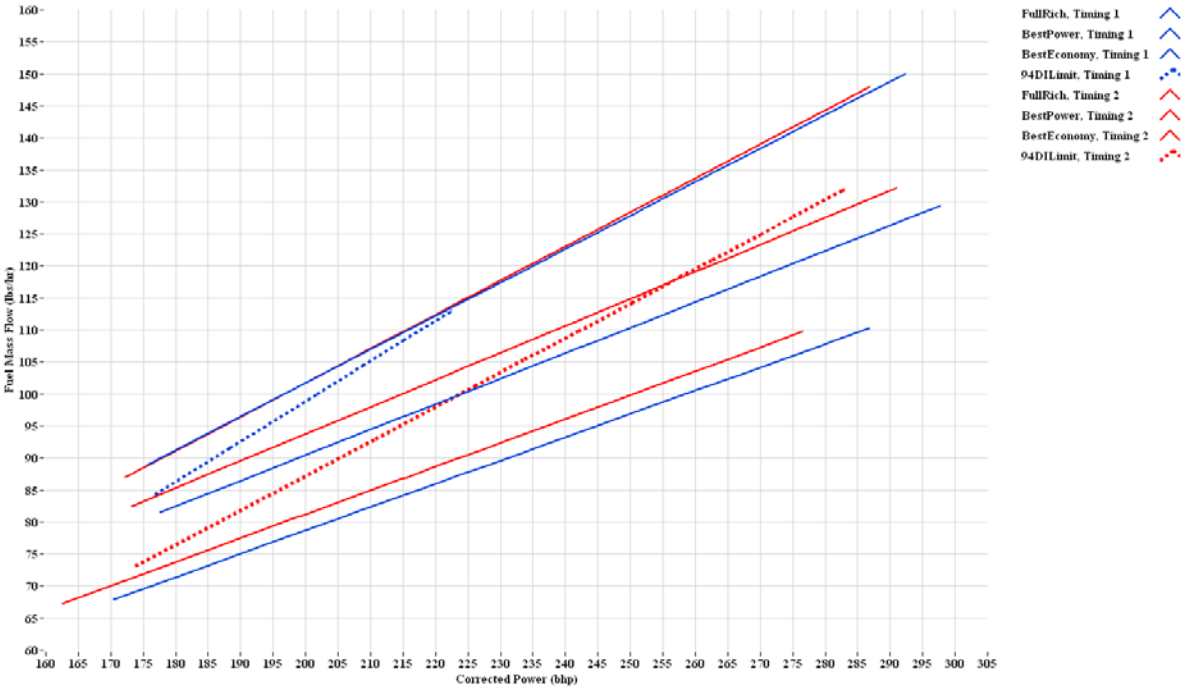

Figure 9. Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 16° BTDC Ignition Timing and at Maximum CHT of 460 +5-0 °F

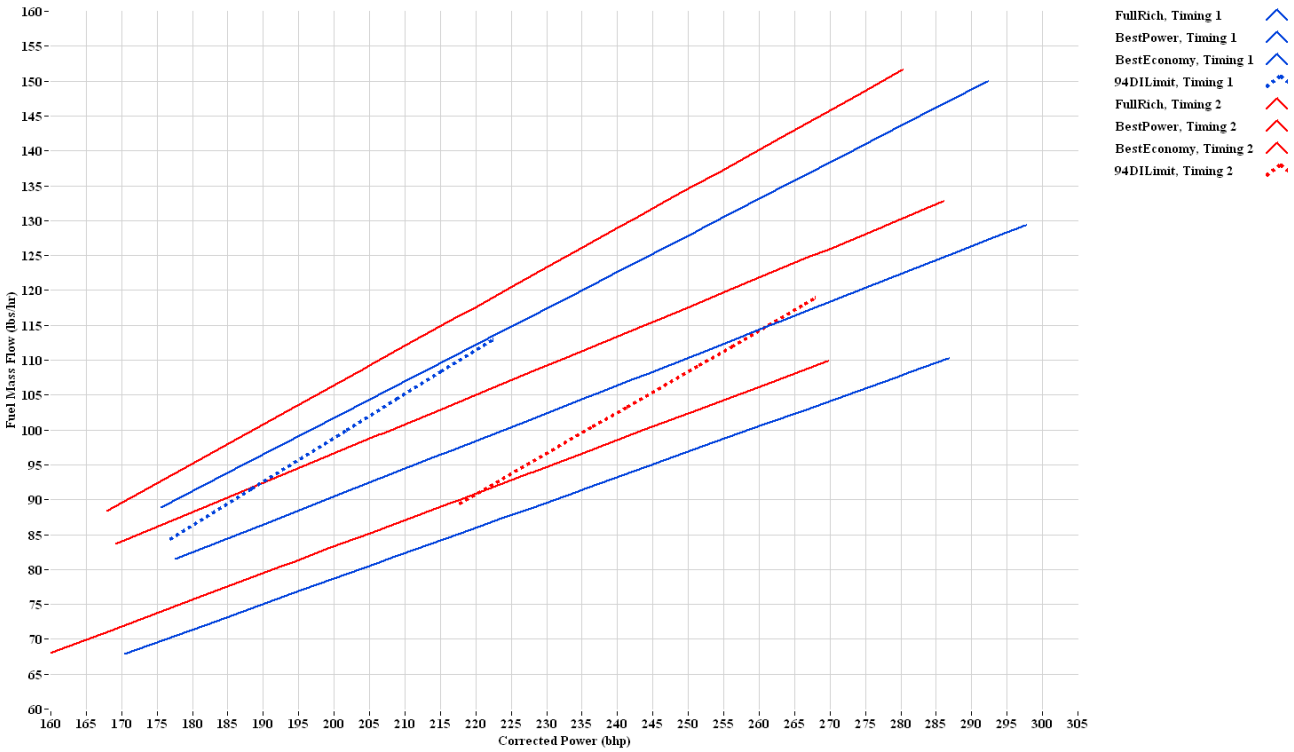

Figure 10. Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 13° BTDC Ignition Timing and at Maximum CHT of 460 +5-0 °F

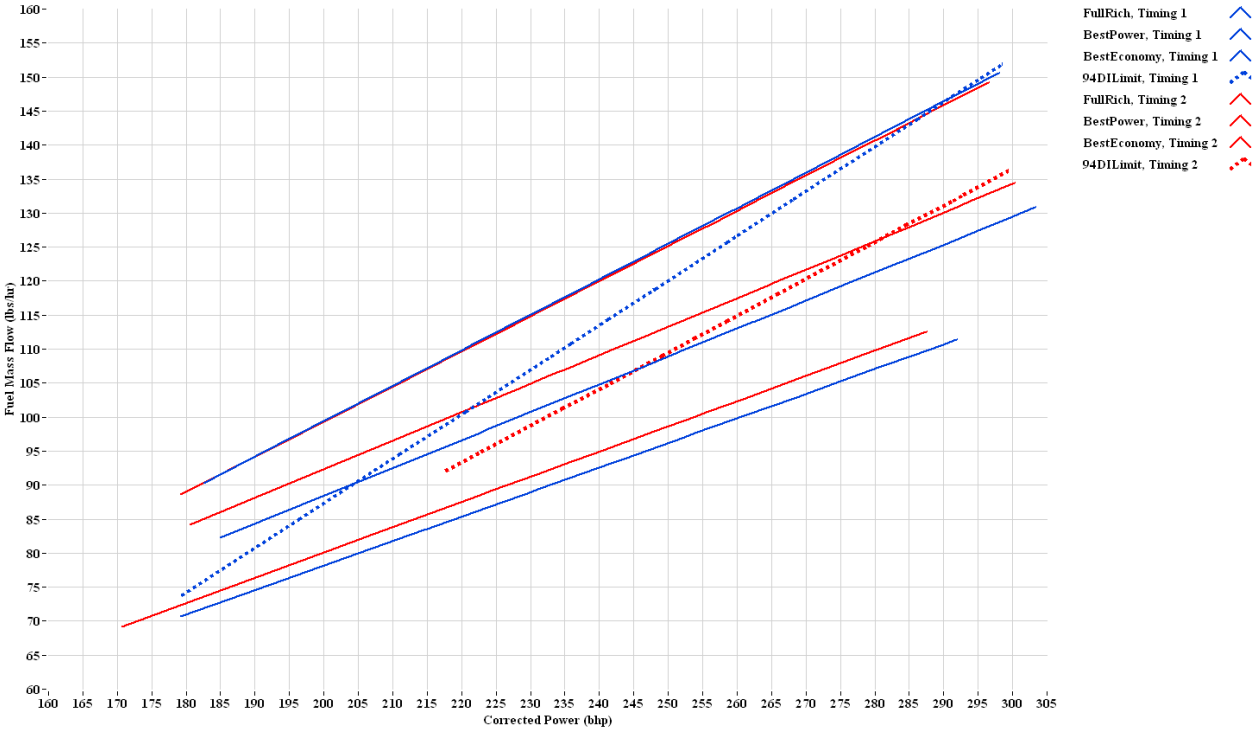

Figure 11. Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 19° BTDC Ignition Timing and at a Maximum CHT of 400 +5-0 °F

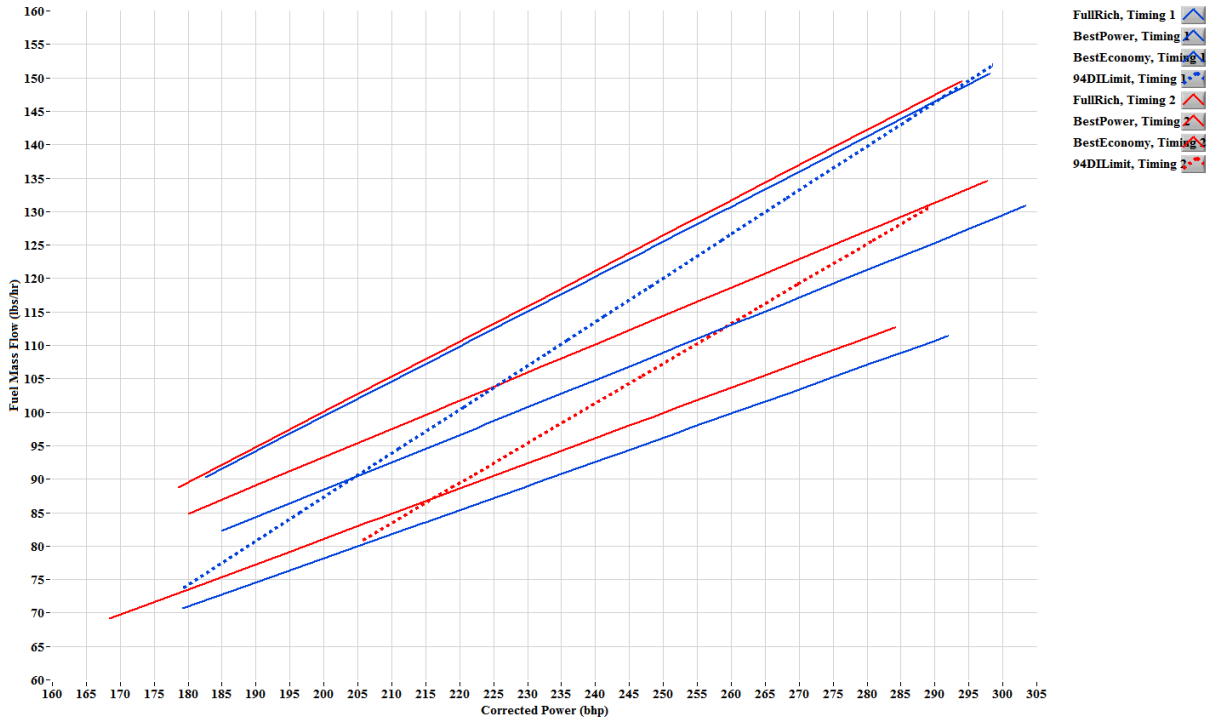

Figure 12. Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 16° BTDC Ignition Timing and at a Maximum CHT of 400 +5-0 °F

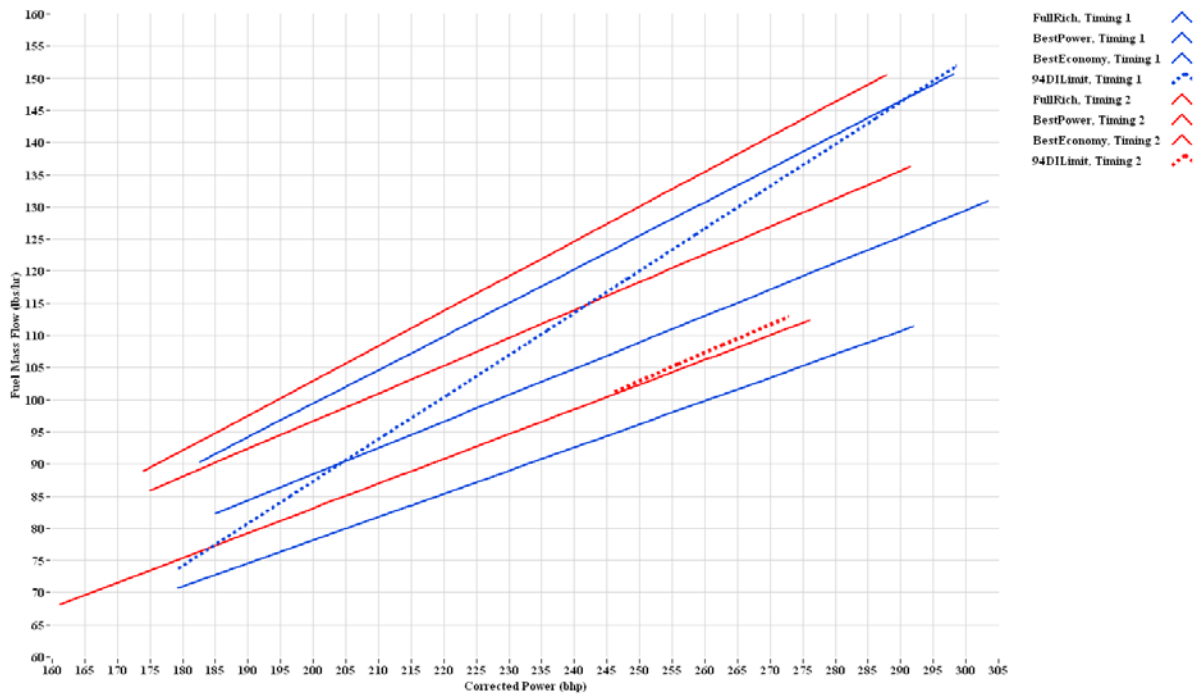

Figure 13. Comparison of IO-550-D Engine Power Performance for the UL94 and 100LL Fuels at 22° and 13° BTDC Ignition Timing and at a Maximum CHT of 400 +5-0 °F

In this report, fuel-to-air equivalence ratio is calculated by dividing the stoichiometric air to fuel ratio by the actual air to fuel ratio. Operating the engine at cruise power setting with fuel mixture near the equivalence ratio of 1.00 typically results in the highest EGTs, and the engine performance approaches the best economy power setting. When fuel-to-air equivalence ratios are greater than 1.00, the fuel blend is under the rich mixture condition. Leaning the mixture past the peak EGT requires the fuel-to-air equivalence ratio to be lower than 1.00. Depending on ignition timing and power setting, a F/R fuel flow falls between 1.30 and 1.40 of fuel-to-air equivalence ratio.

Figures 14 through 19 display the same data as shown in figures 4 through 13, but in a format that is more frequently used by the POWER laboratories' fuels team. Again, the 100LL fuel did not reach light detonation during this testing. As can be seen in figure 14, retarding ignition timing by 3° (19° BTDC) allowed the fuel mixture to be leaned approximately 0.10 (10%) further in fuel-to-air equivalence ratio at the same 460 +5-0 °F maximum CHT. Note that light detonation at this setting still occurs before the best power setting.

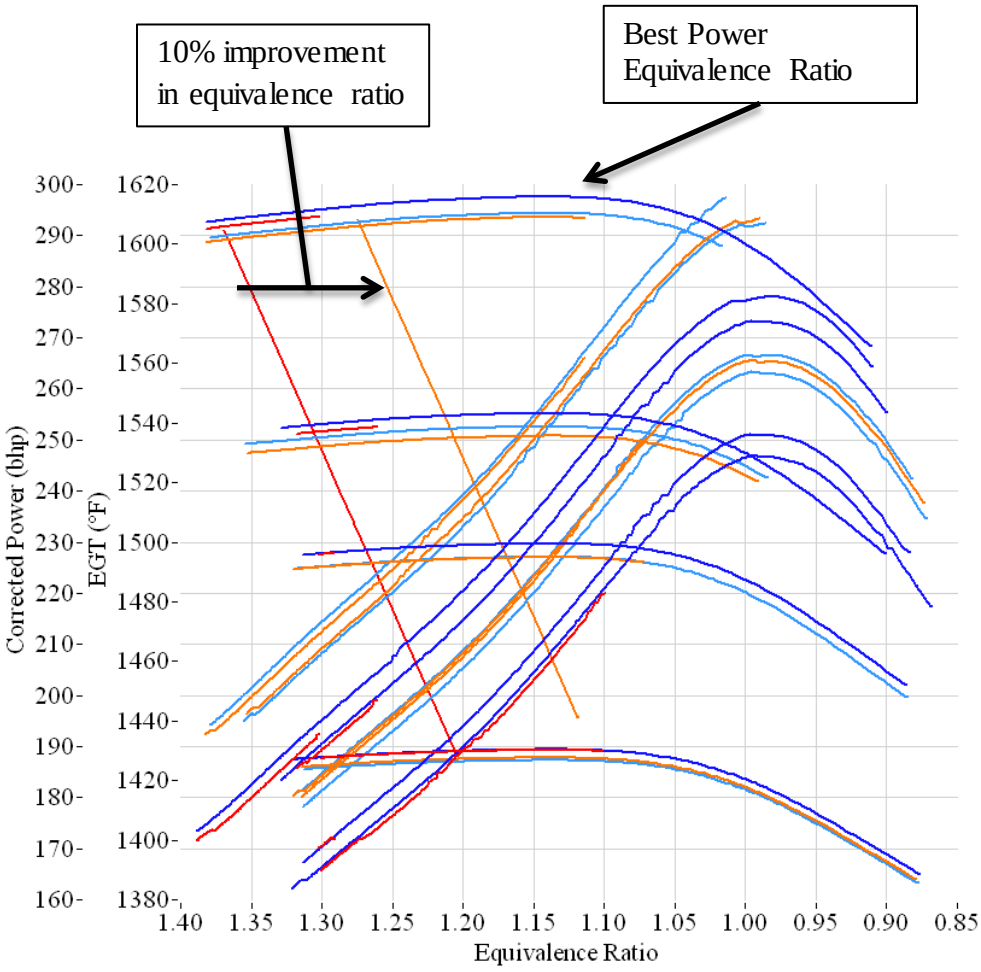

Figure 14. The IO-550-D Engine Detonation Performance for UL94 and 100LL Fuels at Ignition Timing of 22° and 19° and CHT 460 +5-0 °F (Red and orange lines represent equivalence ratios for UL94 at 22° and 19° BTDC ignition timing, respectively. Blue and light-blue lines are the performance curves of 100LL at 22° and 19° BTDC ignition timing, respectively.)

Figure 15 shows that retarding ignition timing by 6° (from 22° to 16° BTDC) allowed the fuel mixture to be leaned approximately 0.11 to 0.16 further of fuel-to-air equivalence ratio. This result is derived based on the best linear fit of the detonation data and provides a greater detonation margin relative to the standard ignition timing at the same maximum CHT of 460 +5-0 °F. Engine detonation at this retarded ignition timing (16° BTDC) still occurs at or before the best power setting.

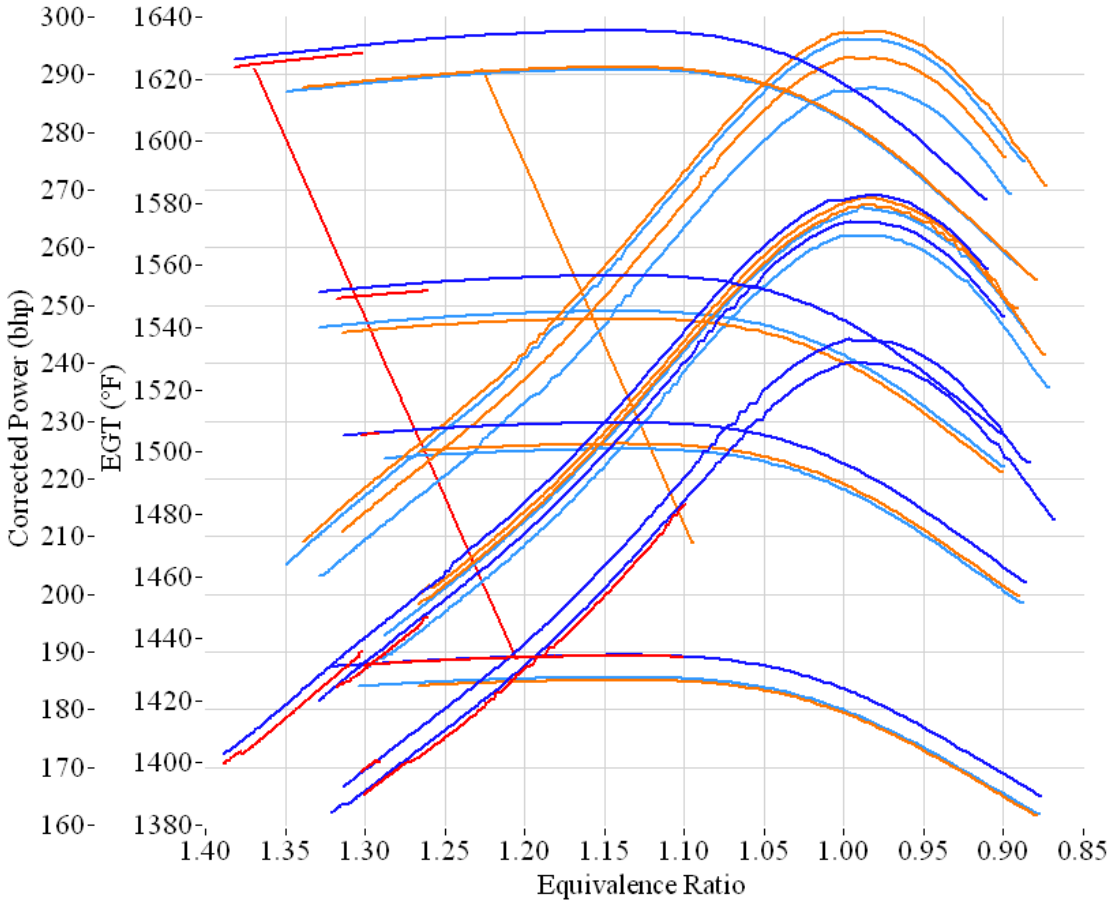

Figure 15. The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 16° BTDC and CHT 460 +5-0 °F (Red and orange lines represent UL94 performance at ignition timing of 22° and 16° BTDC, respectively. Blue and light-blue lines represent the performance of 100LL at ignition timing of 22° and 16° BTDC, respectively.)

Figure 16 shows that retarding the timing by 9° (from 22° to 13° BTDC) allowed the engine to be leaned approximately 0.20 to 0.31 further in fuel-to-air equivalence ratio, which provides a greater detonation margin relative to the standard ignition timing at the same maximum CHT of 460 +5-0 °F. Light detonation at this ignition timing still occurs at or before the best power setting.

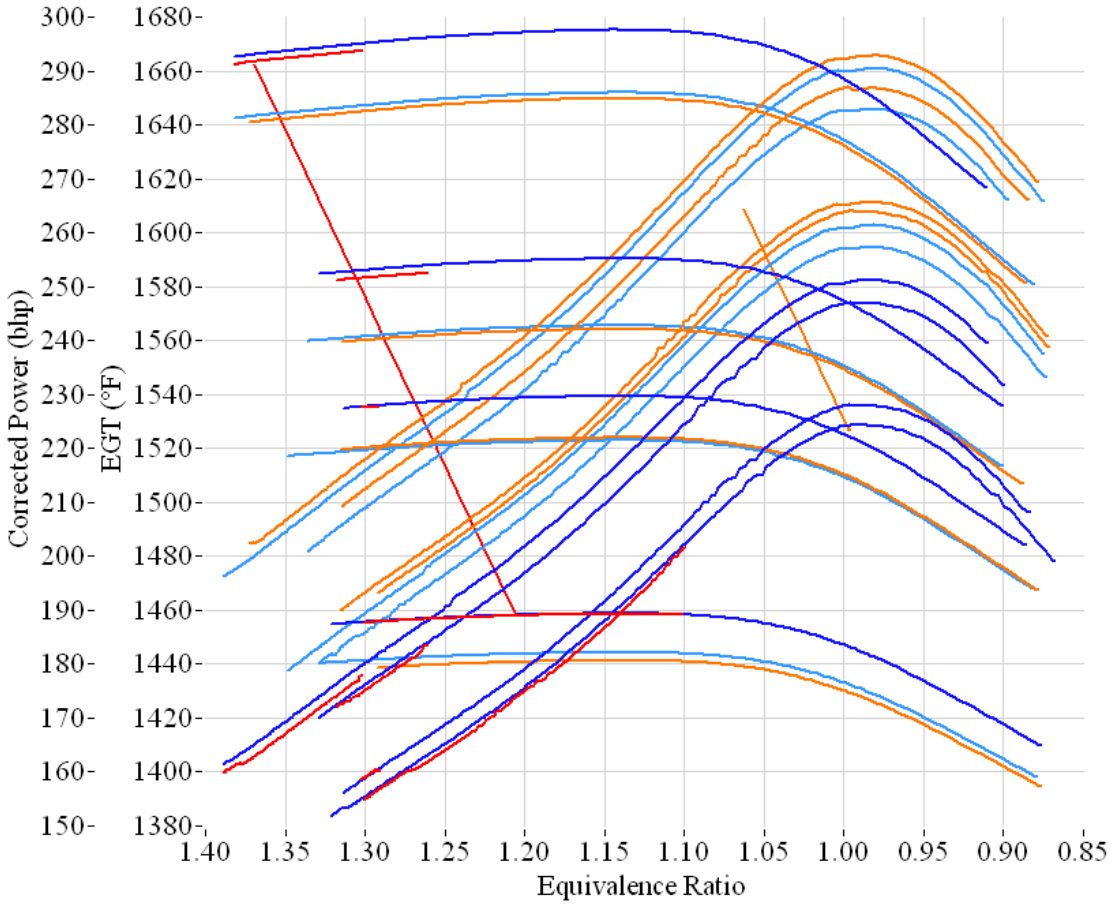

Figure 16. The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 13° BTDC and CHT 460 +5-0 °F (Red and orange lines represent the UL94 at 22° and 13° BTDC ignition timing, respectively. Blue and light-blue lines are the 100LL at 22° and 13° BTDC ignition timing, respectively.)

Figure 17 shows that retarding ignition timing by 3° (from 22° to 19° BTDC) allowed the engine to be leaned approximately 0.13 to 0.11 further in fuel-to-air equivalence ratio, obtained at maximum CHT of 400 +5-0 °F. These results provide a greater detonation margin relative to the standard ignition timing at the same maximum CHT. Note that light engine detonation at this retarded ignition timing still occurs at or before the best power setting.

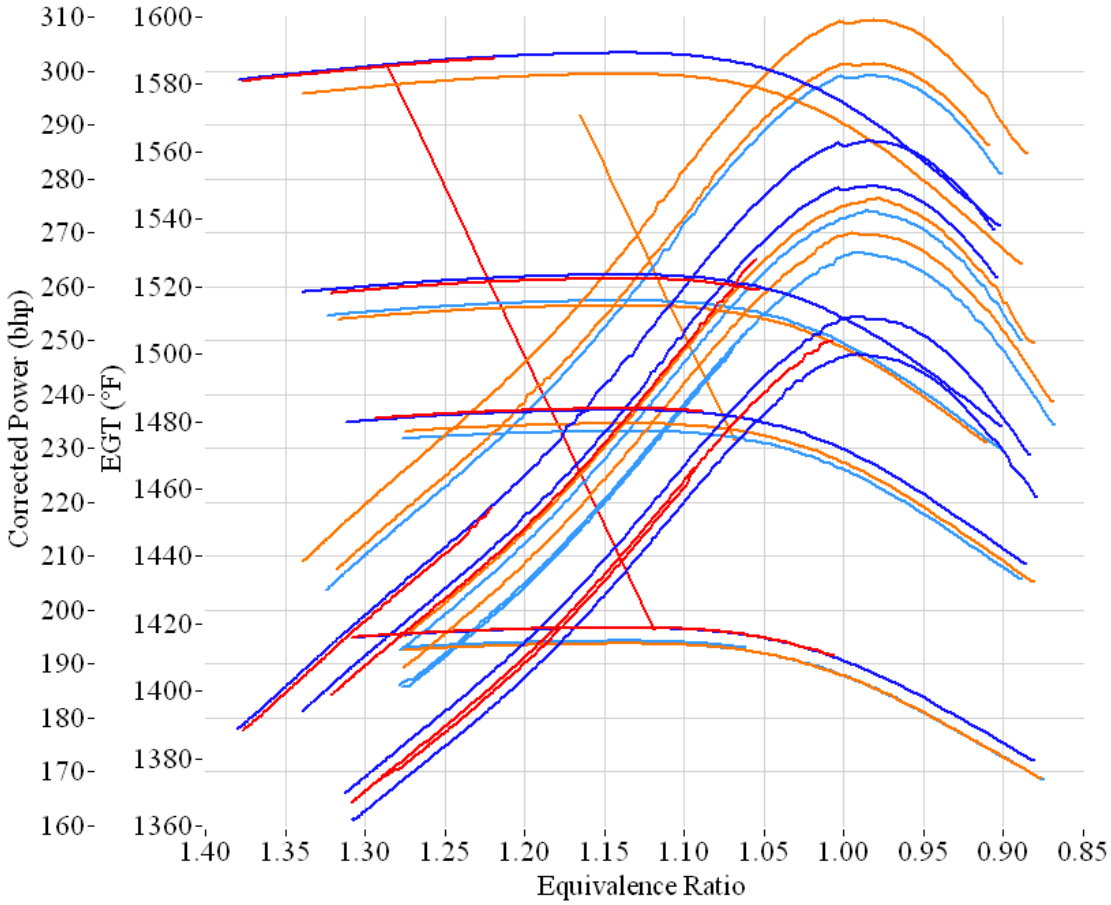

Figure 17. The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 19° BTDC and CHT of 400 +5-0 °F (Red and orange lines represent the performance of UL94 at 22° and 19°, respectively. Blue and light-blue lines are the performance curves of 100LL at 22° and 19° BTDC ignition timing, respectively.)

Figure 18 shows that retarding the ignition timing by 6° (from 22° to 16° BTDC) allowed the engine to be leaned approximately 0.25 to 0.16 fuel-to-air equivalence ratio, based on the best linear fit to the detonation data. This provides a greater detonation margin relative to the standard ignition timing at the same maximum CHT of 400 +5-0 °F. However, light engine detonation at this ignition timing still occurs at or before the best power setting.

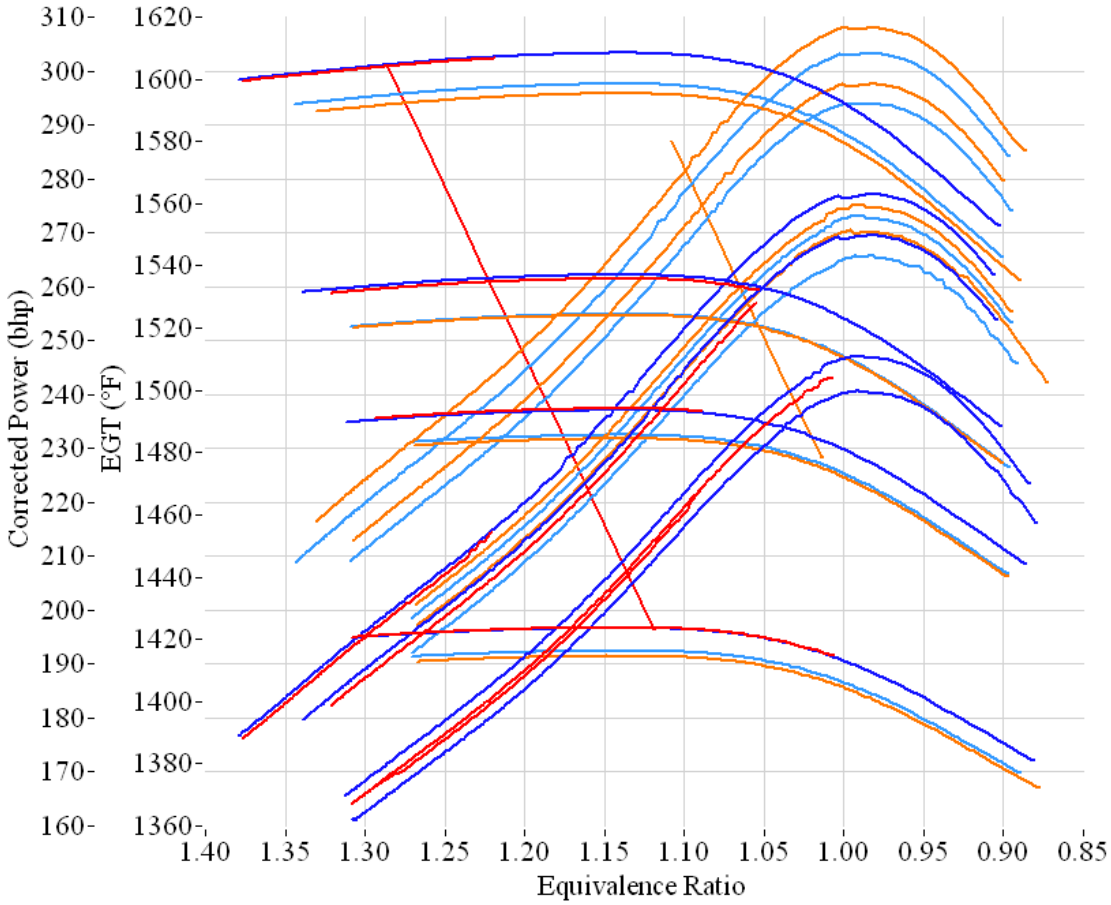

Figure 18. The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 16° BTDC and CHT 400 +5-0 °F (Red and orange lines represent the performance of the UL94 fuel at 22° and 16° BTDC ignition timing, respectively. Blue and light-blue lines are performance curves of the 100LL fuels at 22° and 16° BTDC ignition timing, respectively)

Figure 19 shows that the engine does not reach light detonation for the UL94 fuel when the ignition timing is retarded by 9° BTDC (from 22° to 13°) and the maximum CHT is reduced to 400 +5-0 °F.

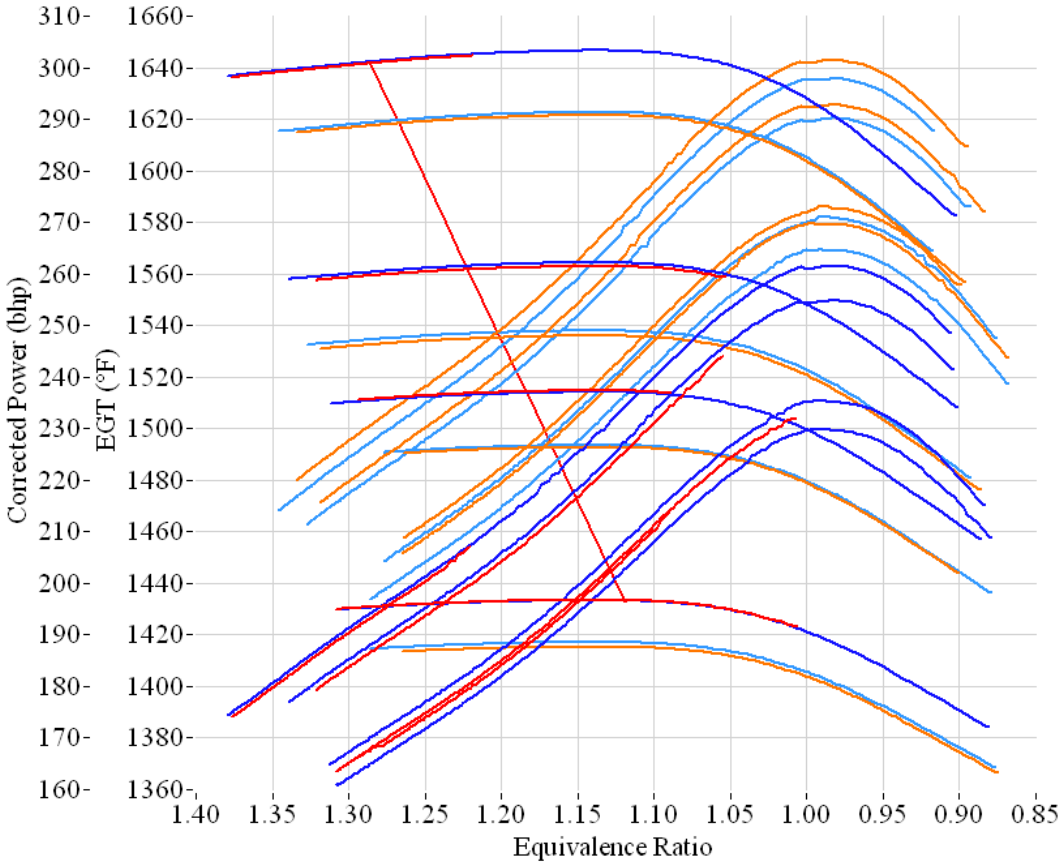

Figure 19. The IO-550-D Engine Detonation Performance for the UL94 and 100LL Fuels at an Ignition Timing of 22° and 13° and CHT 400 +5-0 °F (Red and orange lines represent the performance of UL94 at 22° and 13° BTDC ignition timing, respectively. Blue and light-blue lines are the performance curves of the 100LL fuel at 22° and 13° BTDC ignition timing, respectively.)

The effects of maximum CHT reduction and ignition timing retardation for the UL94 fuel on the light detonation as functions of fuel-to-air equivalence ratio are shown in figures 20 through 23. At the standard 22° ignition timing, a 60°F decrease in maximum CHT from 460 +5-0 °F to 400 +5-0 °F results in 0.1 to 0.14 improvement in fuel-to-air equivalence ratio and an increase for the engine power output. Figures 20 and 21 show the corrected engine power as functions of fuel-to-air equivalence ratios under light engine detonation conditions.

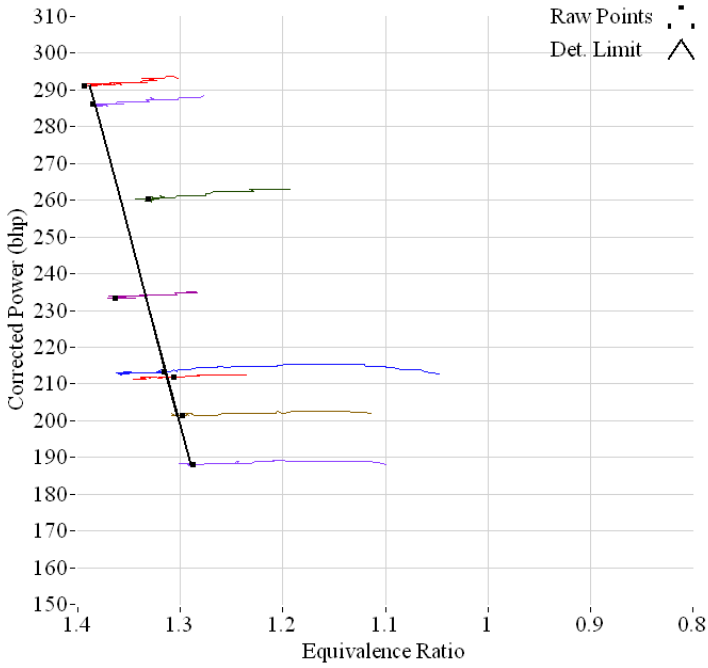

Figure 20. Light Detonation Equivalence Ratio for the UL94 Fuel at 460 +5-0 °F Maximum CHT and Standard 22° BTDC Ignition Timing, for IO-550-D

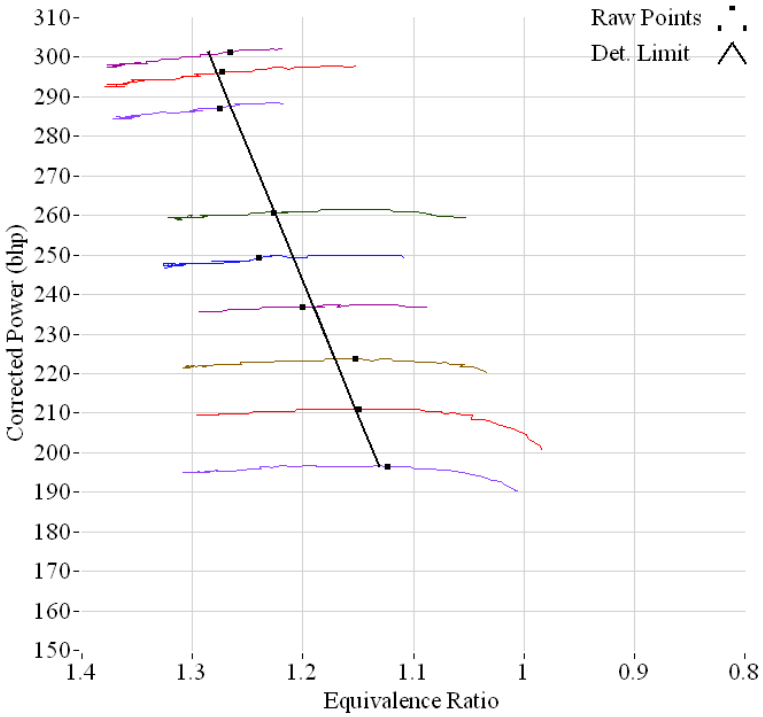

Figure 21. Light Detonation Equivalence Ratio for the UL94 Fuel at 400 +5-0 °F Maximum CHT and Standard 22° BTDC Ignition Timing, for IO-550-D

At 460 +5-0 °F maximum CHT, retarding the ignition timing by 3° (from 22° to 19° BTDC) resulted in a 0.16 to 0.2 decrease in light detonation equivalence ratio. Decreasing the maximum CHT as well as retarding ignition timing by 3° BTDC results in a 0.28 to 0.23 decrease in light detonation equivalence ratio. However, the lowest light detonation equivalence ratio is still above the stoichiometric equivalence ratio of 1.0 at the cruise power setting. Light detonation equivalence ratio with 3° retardation or 19° ignition timing is shown in figures 22 and 23.

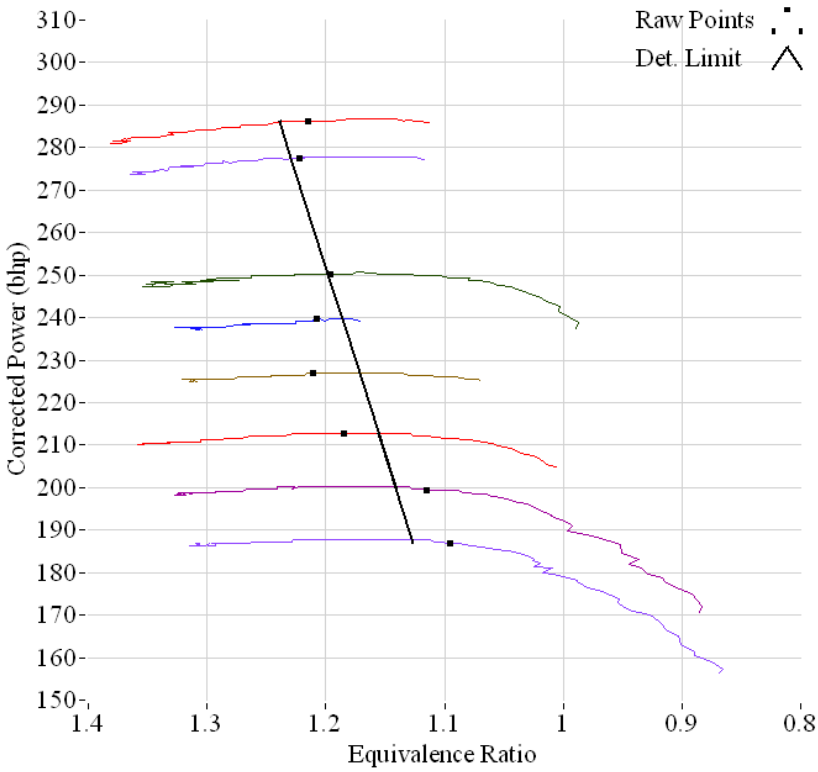

Figure 22. Light Detonation Equivalence Ratio for the UL94 Fuel at 460 +5-0 °F Maximum CHT and 19° BTDC Ignition Timing, for IO-550-D

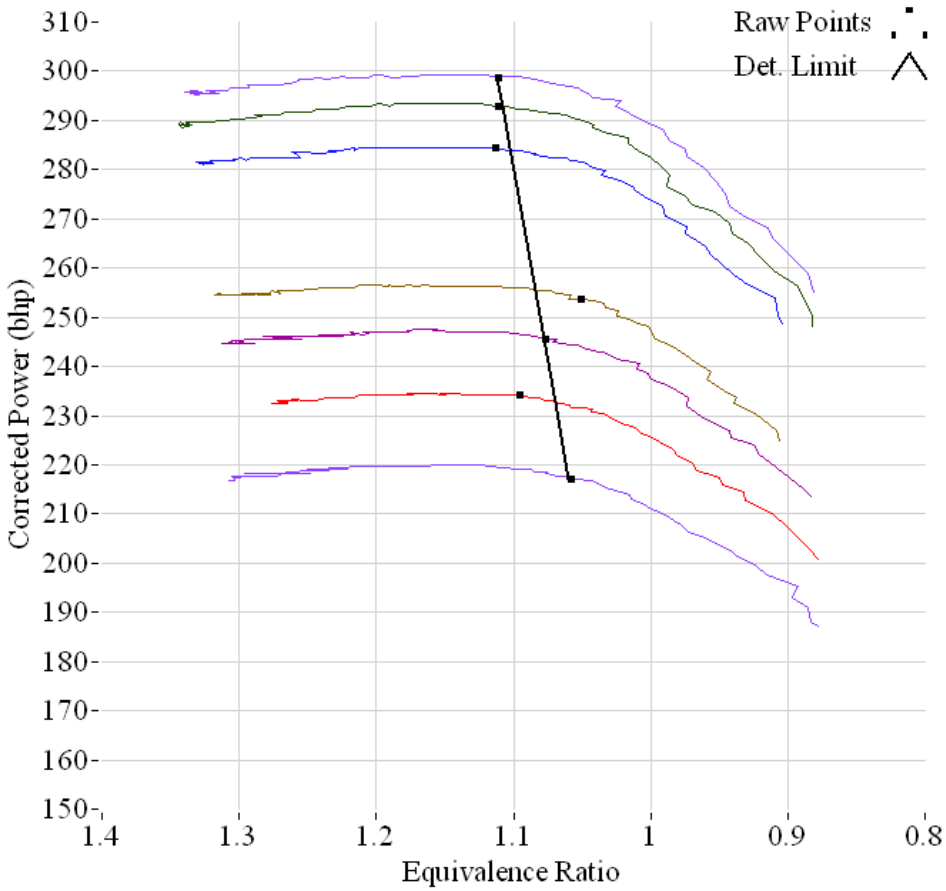

Figure 23. Light Detonation Equivalence Ratio for the UL94 Fuel at 400 +5-0 °F Maximum CHT and 19° BTDC Ignition Timing, for IO-550-D

At 460 +5-0 °F maximum CHT, retarding the ignition timing by 6° (from 22° to 16° BTDC) results in a 0.17 to 0.22 decrease in light detonation equivalence ratio depending on the engine power. Decreasing maximum CHT as well as retarding the engine ignition timing by 6° BTDC results in an a 0.27 to 0.29 decrease in light detonation equivalence ratio. However, the lowest light detonation equivalence ratio occurs at approximately the stoichiometric equivalence ratio of 1.00 at approximately the 80% power setting. Light detonation equivalence ratios with 6° retarded or 16° ignition timing are shown in figures 24 and 25.

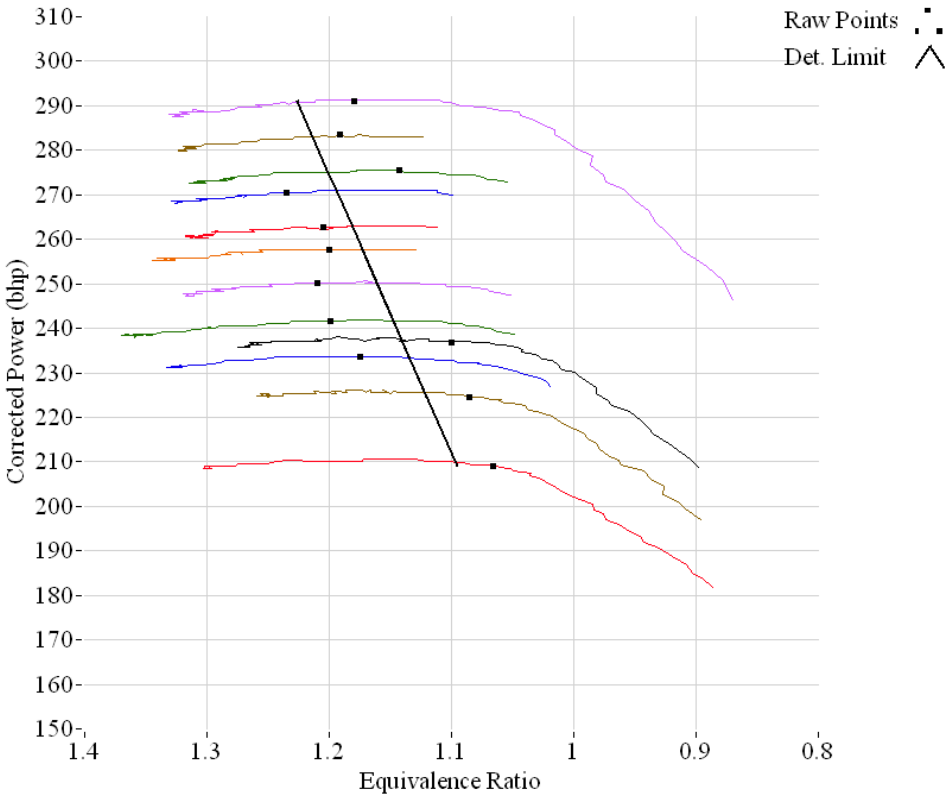

Figure 24. Light Detonation Equivalence Ratio for the UL94 Fuel at 460 +5-0 °F Maximum CHT and 16° BTDC Ignition Timing, for IO-550-D

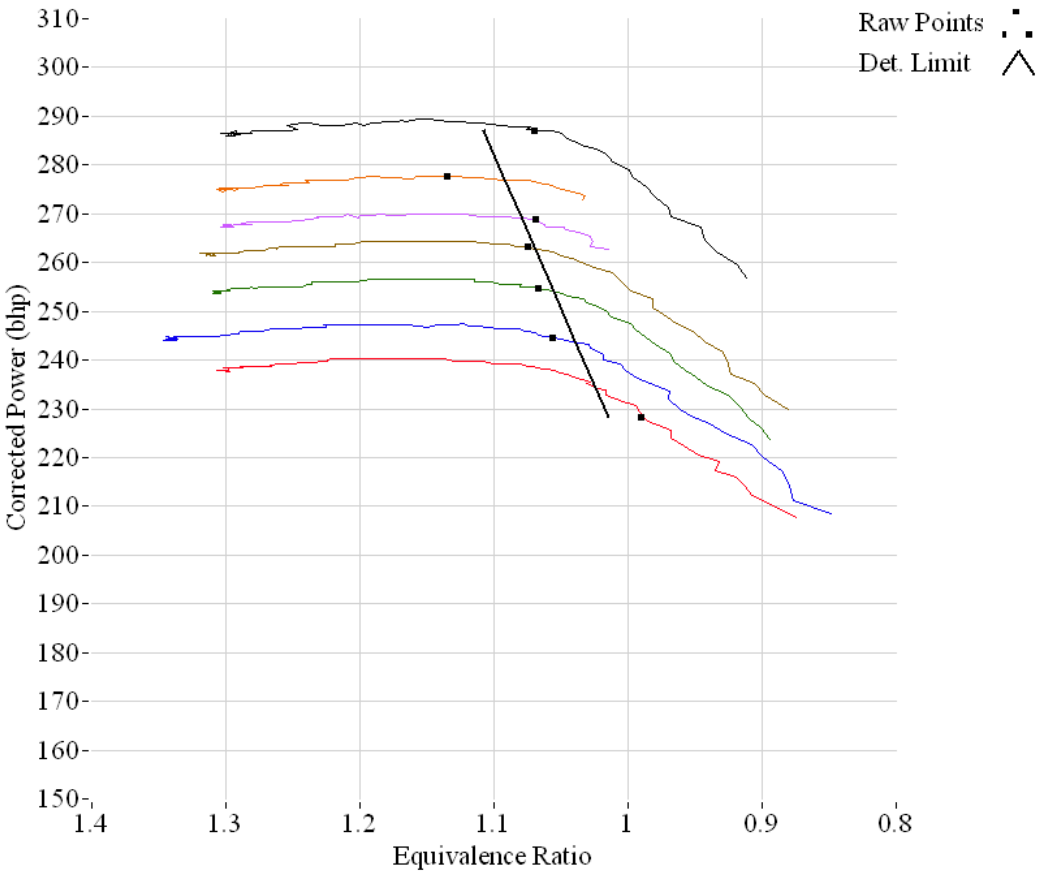

Figure 25. Light Detonation Equivalence Ratio for the UL94 Fuel at 400 +5-0 °F Maximum CHT and 16° BTDC Ignition Timing, for IO-550-D

At 460 +5-0 °F maximum CHT, retarding the ignition timing by 9° (22° to 13° BTDC) results in a 0.33 to 0.31 decrease in light detonation equivalence ratio, which is dependent on engine power. When power settings are lower than approximately 88% of rated power, the engine can be operated below the detonation threshold through peak EGT. As indicated in figure 19, with CHT reduced to 400 +5-0 °F, combined with the ignition timing retarded to 19° BTDC, the engine operated without light detonation at any of the power settings tested, even when the engine was leaned past peak EGT. It should be noted that the results are not shown in the figures because detonation was not observed. However, it should also be noted that, at the takeoff power setting, with WOT and F/R fuel mixture, the IO-550-D engine lost 12 BHP when engine ignition timing was retarded by 9°. Light detonation equivalence ratios with 9° retarded or 13° ignition timing is shown in figure 26.

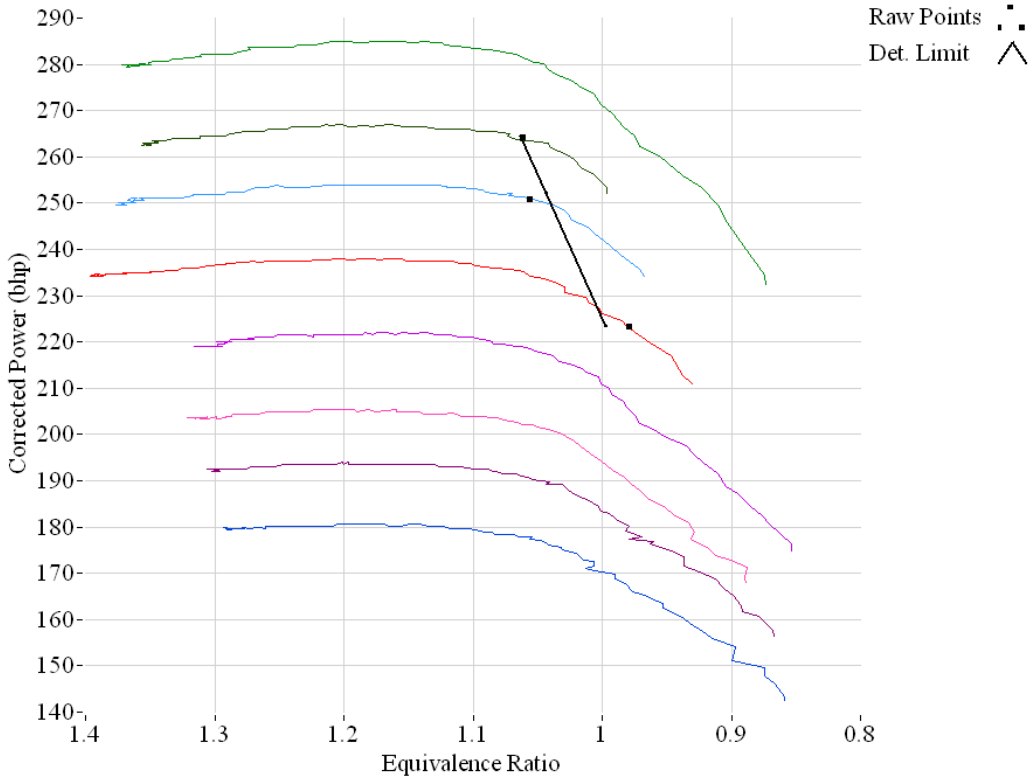

Figure 26. Light Detonation Equivalence Ratios for the UL94 Fuel at 460 +5-0 °F Maximum CHT and 13° BTDC Ignition Timing, for IO-550-D

As shown in figure 20, even at the F/R mixture and at most power settings, as well as under the extreme conditions of this testing, the UL94 fuel is exhibiting only light detonation. Retarding the ignition timing by 3° BTDC or reducing the maximum CHT to 400 °F have similar effects and allow for the engine to be operated below light detonation at rich mixture settings. Along with the improvement of the engine detonation performance, the retardation of ignition timing has the undesirable effects of increasing EGT and reducing engine power.

Retarding the ignition timing by 9° to 13° BTDC results in an increase in EGT of approximately 80 °F, as shown in figures 27 and 28. Figures 27 and 28 also clearly display an approximate 4% reduction in engine power output due to the ignition timing retardation. Whereas this research was performed to determine potential adjustments to the IO-550-D engine for detonation free operation on UL94 and that retardation of the ignition timing was very effective at reducing the engine octane requirement, FAA approval for such would likely require extensive FAA certification testing.

A summary of all results presented for the IO-550-D engine is shown in table 5.

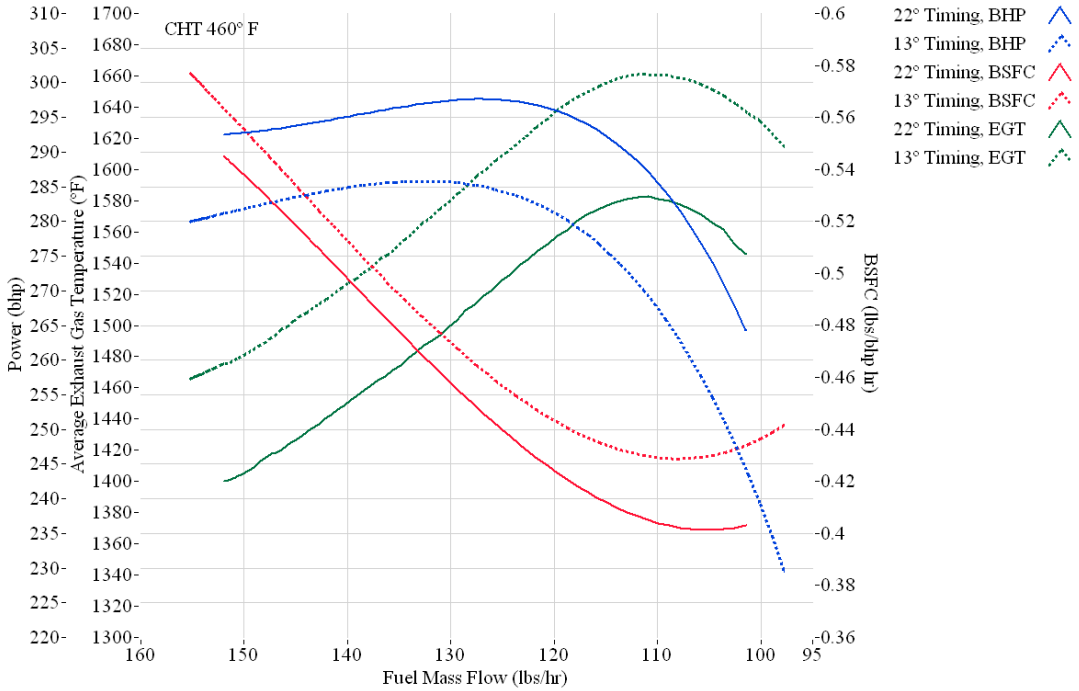

Figure 27. Effect of Ignition Timing on Average EGT With 460 +5-0 °F CHT at 2700 RPM and Takeoff Power Setting, for IO-550-D

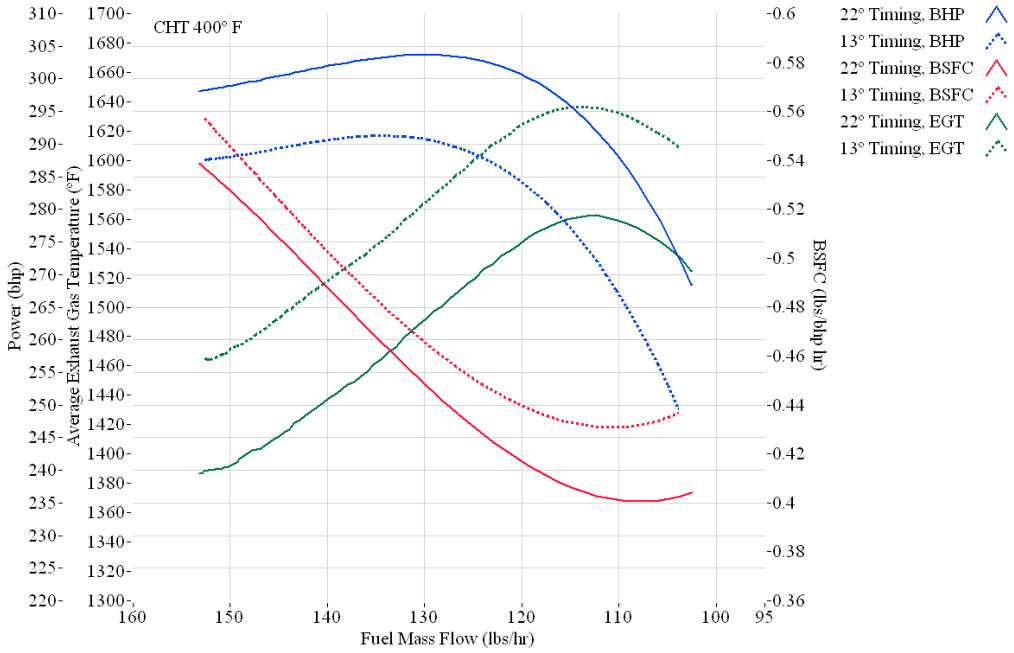

Figure 28. Effect of Ignition Timing on Average EGT With 400 +5-0 °F CHT at 2700 RPM and Takeoff Power Setting, for IO-550-D

Table 5. Summary of the Anti-Knock Performance of the UL94 Fuel at Various Engine Ignition Timing and Maximum CHTs in the IO-550-D Engine

Ignition Timing	Max CHT (°F)	Fuel Mixture Leaned to		Power Loss (BHP)
		Best Power Setting	Best Economy Power Setting	
Standard 22°/22°	460	No	No	0
Standard 22°/22°	400	Yes (<74% Rated Power)	No	0
3° Retarded	460	Yes (<73% Rated Power)	No	3
3° Retarded	400	Yes (<93% Rated Power)	No	3
6° Retarded	460	Yes (<85% Rated Power)	No	5
6° Retarded	400	Yes (<96% Rated Power)	Yes (<73% Rated Power)	5
9° Retarded	460	Yes	Yes (<70% Rated Power)	12
9° Retarded	400	Yes	Yes (<82% Rated Power)	12*

*These conditions also result in 80 °F increase in EGT.

3.2 IO-540-K ENGINE TEST RESULTS.

Table 6 lists the light detonation fuel mass flow and corrected power outputs along with the repeatability of the test results from the UL94 fuel. The test was carried out at sea level under the extreme hot- and dry-day conditions with an IAT of 103 ± 3°F. The maximum CHT was reduced from 475 +5-0 °F to 425 +5-0 °F at takeoff and 85% power settings. When maximum CHT was reduced to 400 +5-0 °F, the test was carried out at 3500 ft altitude with an IAT of 90 ± 3 °F. The power settings in this test were 100% (takeoff), 75%, and 65% rated power. Each test was repeated twice with mixture lean out until a targeting power was reached. A total of 32 data points were tested.

The test results included in table 6 are minimum and maximum fuel mass flow rates at light detonation and the corresponding corrected power. Light detonation was used to define all of these results for all points tested. As indicated in table 6, the repeatability of the tests was excellent.

Similar results for the 100LL fuel are listed in table 7. At the targeted 65% power setting, only one test reached 2% detonation intensity and the other had a maximum detonation intensity of 1.3%. At the reduced temperature conditions, only the takeoff point reached 2% detonation intensity onset, and both the target 65% and 75% rated power settings showed a maximum detonation intensity percentage near zero. Both replicates at the targeted 85% rated power point were 1.5% or lower in detonation intensity level.

Table 6. Repeatability of IO-540-K Engine Testing Data for UL94 Fuel at 2% Detonation Intensity Onset

Targeted Engine Speed (RPM)	Maximum CHT (°F)	Power Setting	IAT (°F)	Minimum Fuel Flow at Light Detonation (lb/hr)	Maximum Fuel Flow at Light Detonation (lb/hr)	Average Fuel Flow at Light Detonation (lb/hr)	FF Difference (lb/hr)	Minimum Corrected Power at Light Detonation (BHP)	Maximum Corrected Power at Light Detonation (BHP)	Average Corrected Power at Light Detonation (BHP)	Corrected Power Difference (BHP)
2700	475 +5-0	Takeoff	103 ± 3	165.4	165.4	165.4	0	278	279	278.5	1
2600	475 +5-0	85	103 ± 3	147.2	148.6	147.9	1.4	252	252	252	0
2450	475 +5-0	75	103 ± 3	123.3	123.8	123.6	0.5	220	220	220	0
2350	475 +5-0	65	103 ± 3	103.3	105.1	104.2	1.8	190	190	190	0
2700	425 +5-0	Takeoff	103 ± 3	161.4	161.4	161.4	0	287	287	287	0
2600	425 +5-0	85	103 ± 3	139.9	140.2	140.1	0.3	255	257	256	2
2450	400 +5-0	75	90 ± 3	111.6	111.9	111.8	0.3	225	226	225.5	1
2350	400 +5-0	65	90 ± 3	91.9	94.1	93.0	2.2	193	193	193	0

Table 7. Repeatability of IO-540-K Engine Testing Data for 100LL Fuel at 2% Detonation Intensity Onset

Targeted Engine Speed (RPM)	Maximum CHT (°F)	Power Setting	IAT (°F)	Minimum Fuel Flow at Light Detonation (lb/hr)	Maximum Fuel Flow at Light Detonation (lb/hr)	Average Fuel Flow at Light Detonation (lb/hr)	FF Difference (lb/hr)	Minimum Corrected Power at Light Detonation (CBHP)	Maximum Corrected Power at Light Detonation (CBHP)	Average Corrected Power at Light Detonation (CBHP)	Corrected Power Difference (CBHP)
2700	475 +5-0	Takeoff	103 ± 3	119.3	123.6	121.5	4.3	290	292	291	2
2600	475 +5-0	85	103 ± 3	105.1	105.5	105.3	0.4	259	260	260	1
2450	475 +5-0	75	103 ± 3	89.9	91.8	90.9	1.9	226	227	227	1
2700	425 +5-0	Takeoff	103 ± 3	113.1	116.3	114.7	3.2	289	292	291	3

Figures 29 through 31 show the corrected power, average EGT, and light detonation at 2% detonation intensity as a function of a fuel-to-air equivalence ratio for the 100LL and UL94 fuels. The testing maximum CHTs are 475 °F and 425 °F for figures 29 and 30, respectively. Figure 31 shows light detonation at 75% and 65% rated cruise power settings with 400 °F maximum CHT under extreme hot- and dry-day conditions for a 3500 ft altitude.

At the takeoff and 85% rated power setting, the UL94 fuel reached the 2% detonation intensity onset with maximum CHT of 475 +5-0 °F, as shown in figure 29. The test was carried out at sea level under extreme hot- and dry-day conditions and with less than a 0.5 lb/hr change in fuel mass flow from F/R fuel flow. In this testing condition, this flow rate was too small to create a measurable change in the fuel-to-air equivalence ratio. Under the same conditions, the 100LL fuel was able to be leaned to 45.4 and 43.3 lb/hr at the takeoff and 85% rated power setting, respectively, before reaching the 2% detonation intensity onset. This corresponds to 60 °F and 50 °F before the peak EGT at takeoff and at the targeted 85% power setting, respectively.

Figure 29 also shows that at 475 °F maximum CHT and under the same extreme hot- and dry-day conditions, as well as at sea level, the UL94 fuel approached the 2% detonation intensity onset with fuel mass flow changes of 6.1 and 6.0 lb/hr from the F/R fuel mass flow at 75% and 65% power settings, respectively. These are approximately equivalent to a 0.05 equivalence ratio and are not measurable in fuel-to-air equivalence ratio. At the 75% power setting, the 100LL fuel mixture could be leaned to 40.5 lb/hr before reaching the 2% detonation intensity onset, which corresponds to 30 °F before peak EGT. At the 65% power setting, only one replicate reached the 2% detonation intensity onset.

Figure 30 shows that under the reduced 425 +5-0 °F maximum CHT, the UL94 fuel mixture leaning from F/R for takeoff to 85% power settings with 2% detonation intensity onset requires 6.3 and 8.6 lb/hr fuel mass flow changes. These correspond to 0.06 and 0.09 decreases in equivalence ratio, respectively. Note that the fuel-to-air equivalence ratio for an F/R mixture is 1.50 to 1.47. Under the same operating conditions, the 100LL fuel leaned toward the 2% detonation intensity onset at takeoff needs 53.7 lb/hr fuel mass flow change from the F/R fuel flow, which corresponds to a fuel mixture setting at peak EGT. At the same reduced maximum CHT and 85% power setting, the 100LL fuel did not reach the light detonation, indicating that, at this power setting, the 100LL would not generate engine detonation.

As shown in table 6 the reduced maximum CHT of 400 +5-0 °F and at 3500 ft under extreme hot- and dry-day conditions, the UL94 fuel reached 2% detonation intensity with 17.8 and 16.9 lb/hr fuel mass flow changes from the F/R fuel mixture for the 75% and 65% rated cruise power settings, respectively . As shown in figure 31, these correspond to 0.19 to 0.18 fuel-to-air equivalence ratio changes based on F/R. It is important to note that these fuel mixtures are still under rich condition with the fuel-to-air equivalence ratio greater than 1.0 and, therefore, the EGT is lower than its theoretical peak temperature. This makes the light detonation point occur within the current operating envelope, therefore under these conditions of reduced CHT and 3500 ft altitude hot day temperatures the IO-540-K could not be operated under “normal” power and mixture settings, under the controlled conditions of this test.

At the same reduced 425 +5-0 °F maximum CHT, the 100LL fuel reached 2% detonation intensity at takeoff (figure 31). At 85% power setting and 425 +5-0 °F maximum CHT, 75%, and 65% power settings with 400 +5-0 °F maximum CHT, the fuel was leaned 75 ° to 85 °F past peak EGT without reaching light detonation. Additionally, at the 75% and 65% rated cruise power settings, there was no detectable detonation when the mixture leaned 75 to 85 °F past the peak EGT. These results are shown in figures 30 and 31, respectively. With the UL94 fuel, the peak EGT cannot be determined because of the heavy detonation preventing further mixture leaning to the peak EGT condition. This occurs with both the 475 +5-0 °F and reduced 425 or 400 +5-0 °F maximum CHT at all power settings. The result indicates that under the extreme hot- and dry-day temperature conditions, when operated on UL94 fuel, an equivalence ratio 0.37 to 0.35 units richer than the 100LL fuel was needed for equivalent operation at less than light detonation (figure 29). Based on these results, the IO-540-K may not be operated under the "normal" operating envelope for this engine on UL94 fuel with any of the conditions tested.

It should be noted that based on past research by the FAA WJHTC, repeating these tests with increased engine inlet air relative humidity would reduce the severity of the test, this could result in reduced fuel flows at the light detonation point with the UL94 fuel, even under extreme hot-day condition at sea level and low altitude inlet air temperatures.

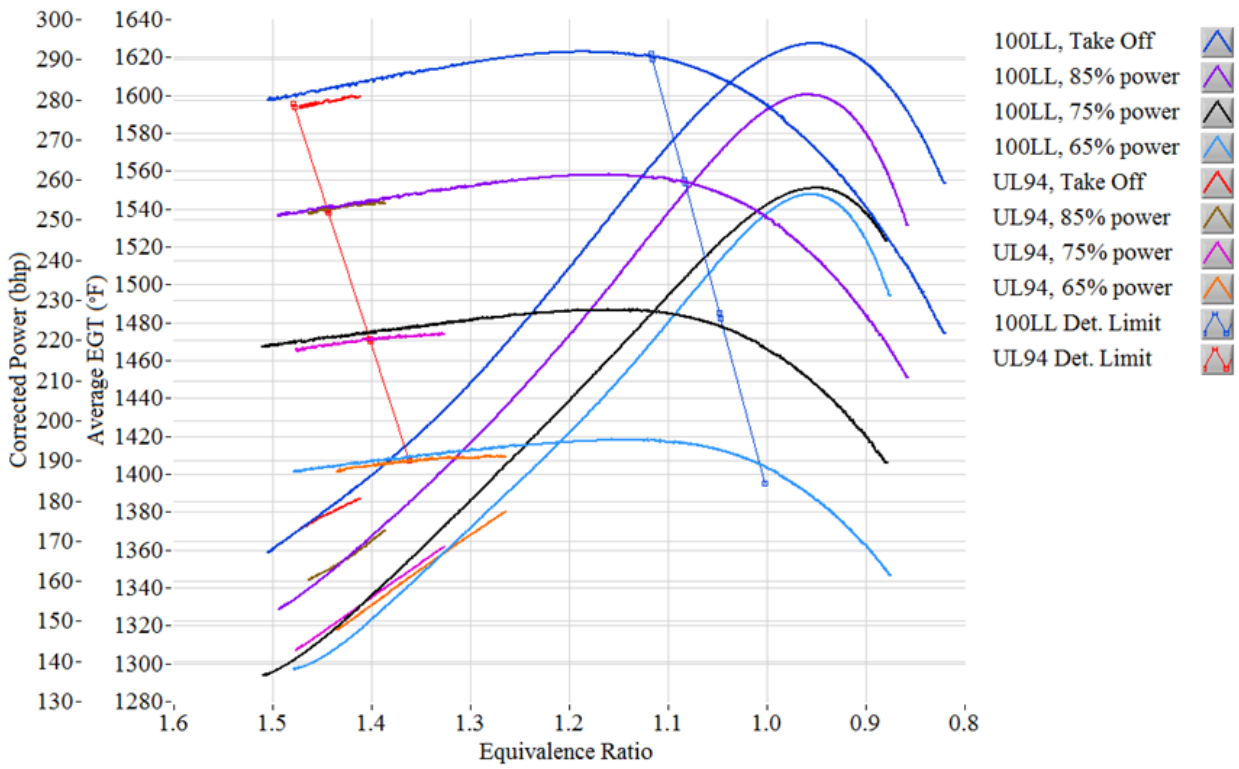

Figure 29. The IO-540-K Engine Light Detonation Power and EGT as Functions of Fuel-to-Air Equivalence Ratio on the Extreme Hot- and Dry-Day and at Sea Level Conditions (475 +5-0 °F Maximum CHT)

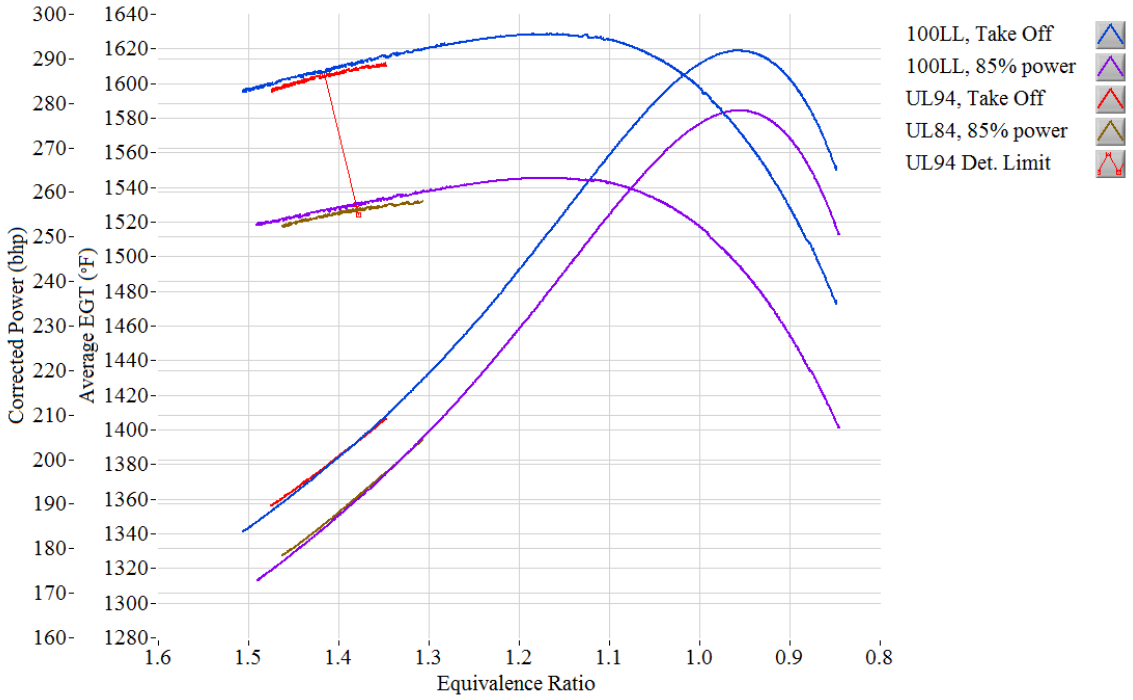

Figure 30. The IO-540-K Engine Light Detonation Power and EGT as Functions of Fuel-to-Air Equivalence Ratio on the Extreme Hot- and Dry-Day and at Sea Level Conditions (425 +5-0 °F Maximum CHT)

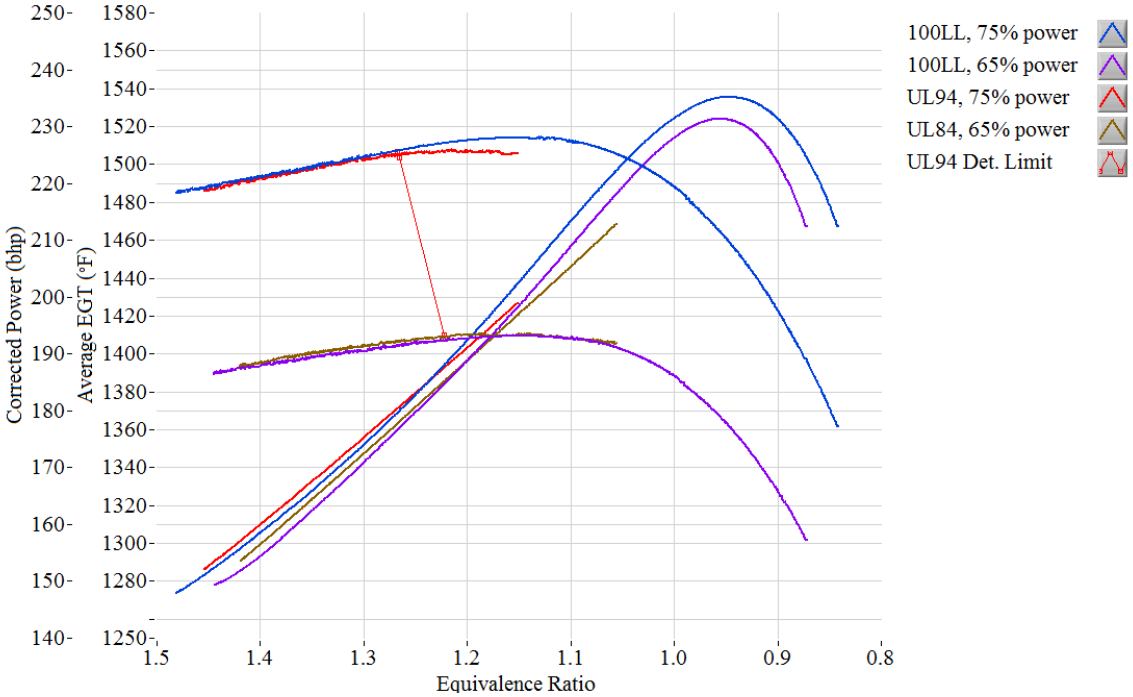

Figure 31. The IO-540-K Engine Light Detonation Power and EGT as Functions of Fuel-to-Air Equivalence Ratio on the Extreme Hot- and Dry-Day and at 3500 ft Altitude Conditions (400 +5-0 °F Maximum CHT)

3.3 IO-360-DB ENGINE TEST RESULTS.

Figure 33 shows the light detonation locations and corrected power as functions of fuel mass flow for the UL94 fuel that was tested based on an IO-360-DB engine. The standard 20° BTDC ignition timing was applied for these tests. At 75% or greater rated power settings, light detonation was experienced within 2.0 lb/hr of the F/R fuel mass flow under extreme hot- and dry-day conditions.

Figure 32 shows that, at 65% rated power setting, light detonation was approximately 9.0 lb/hr leaner than that at F/R condition, or a 12.7% reduction in fuel mass flow. However, the 100LL fuel did not reach light detonation at any power settings. At the reduced maximum CHT (figure 33) and takeoff power setting, light detonation was approximately 7.0lb/hr leaner than that at F/R, or a 6.3% reduction in fuel mass flow. At 85% rated power setting, the light detonation of the 100LL fuel was approximately 5.0 lb/hr leaner than that at F/R, or a 5.3% reduction in fuel mass flow. At 75% rated power setting, the light detonation was approximately 8.0 lb/hr leaner than that of F/R, or a 10.9% reduction in fuel mass flow. At 65% power setting, the light detonation was approximately 14.0 lb/hr leaner than that at F/R setting, or a 21% reduction in fuel mass flow.

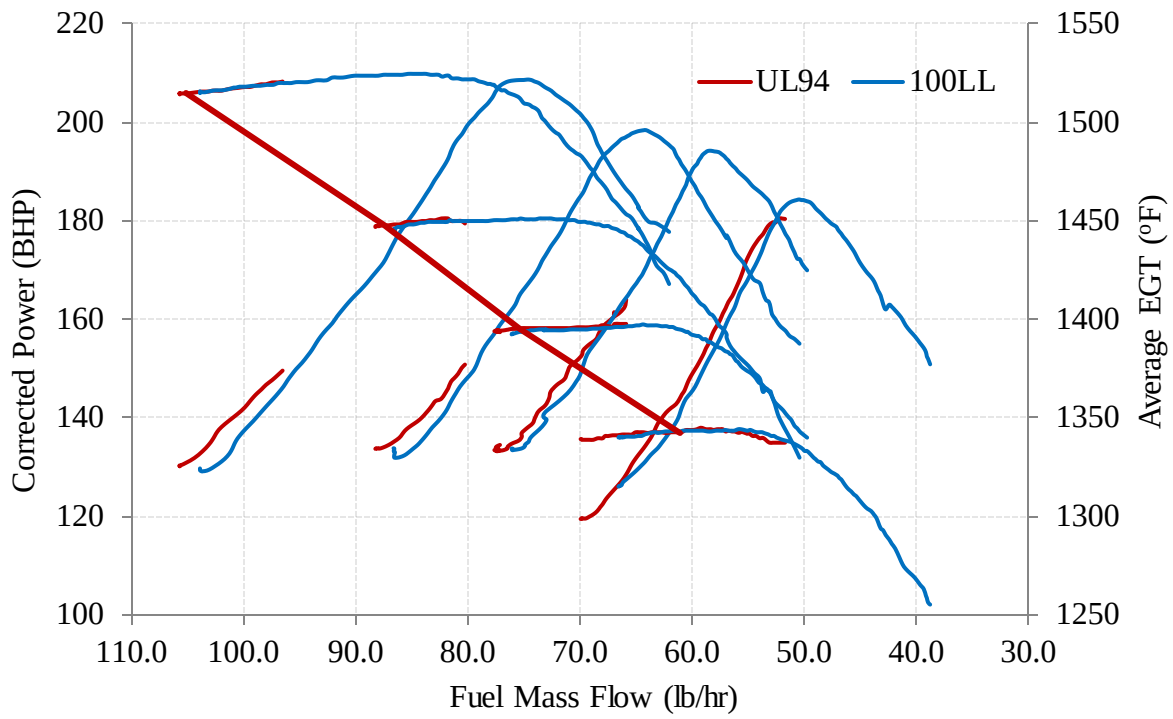

Figure 32. The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (460 +5-0 °F maximum CHT and standard 20° ignition timing)

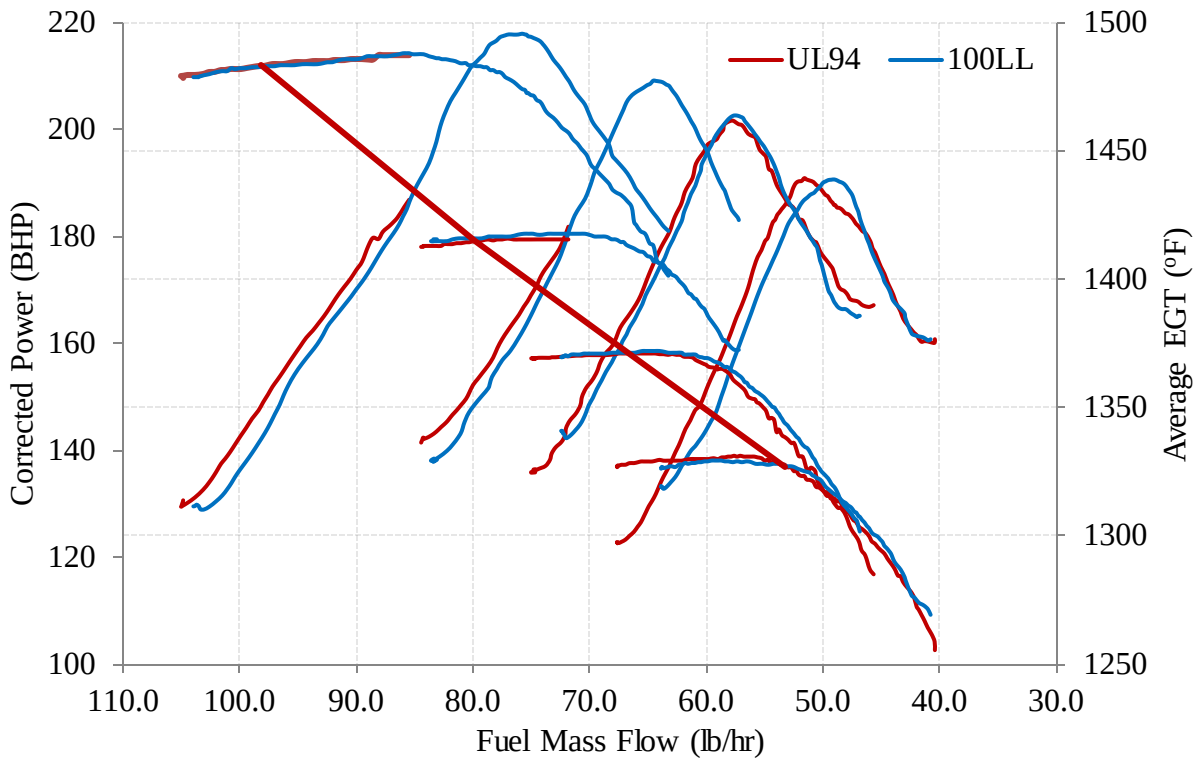

Figure 33. The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (400 +5-0 °F maximum CHT and standard 20° ignition timing)

Figures 34 and 35 depict light detonation and corrected power for the UL94 fuel obtained from the IO-360-DB engine test with the engine ignition timing retarded by 3° to 17° BTDC. At 65% rated power setting, light detonation was not reached at either temperature. Figure 34 shows that, at takeoff conditions, there was a 3 BHP (1.4% of rated power) reduction in power as a result of retarding the ignition timing. The light detonation was approximately 13.0 lb/hr leaner than that at F/R setting, or a 12.1% reduction in fuel mass flow. At 85% rated power, light detonation was approximately 20.0 lb/hr leaner than that at F/R condition, or a 22% reduction in fuel mass flow. At a 75% power setting, light detonation was approximately 15.0 lb/hr leaner than that at F/R condition, or an 18.8% reduction in fuel flow.

However, the 100LL fuel did not reach light detonation at any of the power settings. Under the reduced maximum CHT (figure 35) at takeoff power settings, there was a 4 BHP (1.9% of rated power) reduction in power as a result of retarding the ignition timing. Light detonation was 22 lb/hr leaner than that at F/R condition, or a 22% reduction in fuel flow. At 85% power, light detonation was approximately 18 lb/hr leaner than at F/R condition, or a 21% reduction in fuel mass flow. At a 75% power setting, light detonation did not occur.

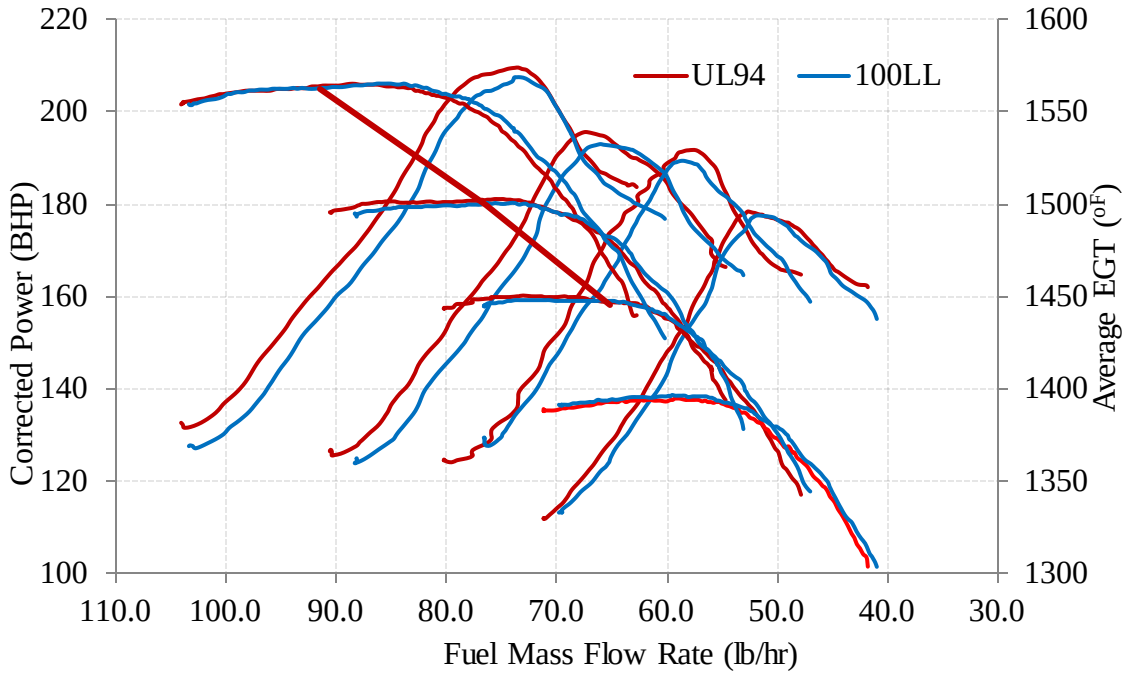

Figure 34. The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (460 +5-0 °F maximum CHT and retarded 17° ignition timing)

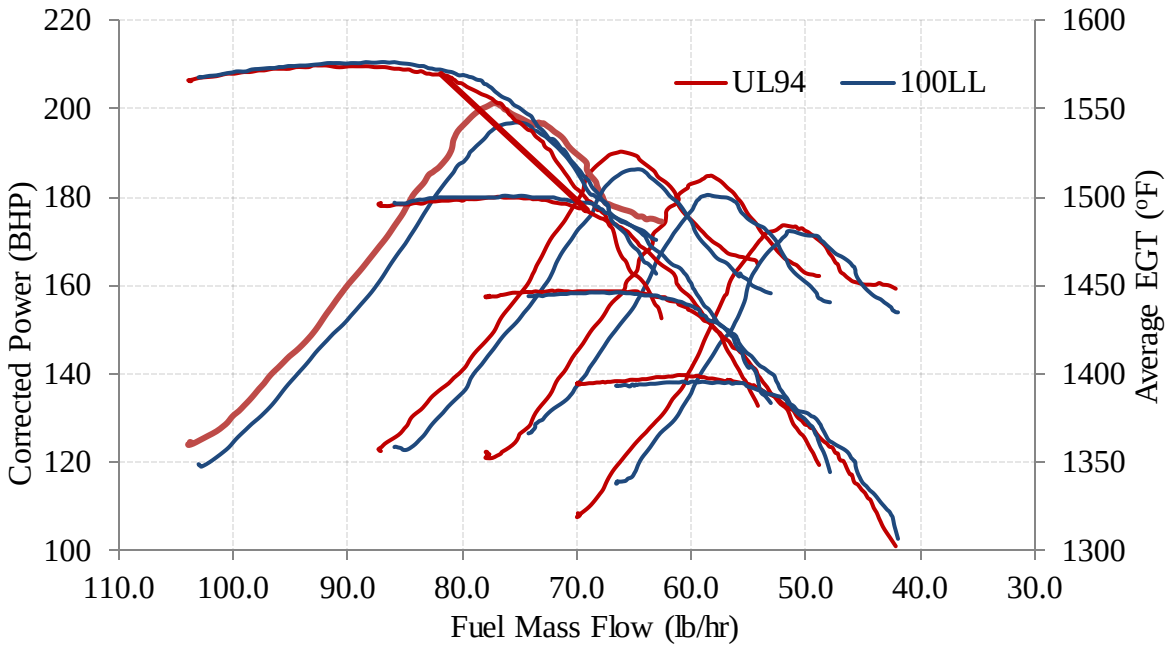

Figure 35. The IO-360-DB Engine Light Detonation Power and EGT as Functions of Fuel Mass Flow Under Extreme Hot- and Dry-Day Conditions (400 +5-0 °F maximum CHT and retarded 17° ignition timing)

4. CONCLUSIONS.

The anti-knock performance of unleaded 94 (UL94) fuel, performed at the Federal Aviation Administration (FAA) William J. Hughes Technical Center's (WJHTC) Propulsion and Airpower Engineering Research (POWER) laboratories was compared to that of a locally purchased 100 low-lead (100LL) fuel in three high-octane demand engines that are certificated on minimum approved 100LL fuel. The fuels were tested under extreme hot- and dry-day standard at sea level for the engine inlet air temperature (IAT) and at a maximum allowable cylinder head temperature (CHT). The fuels were also tested at reduced maximum CHTs and reduced IATs to simulate higher altitude operational conditions and at retarded ignition timing settings. Results show that UL94 fuel was unable to be operated at takeoff power setting under extreme hot- and dry-day conditions at maximum allowable CHT at standard ignition timing without reaching light detonation in all three engines.

4.1 CONTINENTAL IO-550-D ENGINE.

At the standard 22°/22° before-top-dead-center (BTDC) ignition timing and 460 °F maximum CHT, less than light detonation for the UL94 fuel was limited to full-rich fuel mixture at 222 brake horsepower (BHP) a reduction of 70 BHP from actual maximum power. Reducing the maximum CHT from 460 °F to 400 °F allowed less than light detonation at the takeoff power setting. At a reduced 400 °F maximum CHT temperature, the UL94 fuel could be leaned only to the best power setting at power settings less than 74% of rated maximum engine power, but could not be leaned to the best economy power setting without detonation.

At a 3° retardation in ignition timing, to 19°/19° BTDC, the engine was able to be operated at less than light detonation at the full power setting, but the fuel mixture at this ignition condition was unable to be leaned to the best economy power setting. The engine could be leaned only to the best power setting below approximately 73% rated power. With both 3° retardation in ignition timing and a reduction in maximum CHT to 400 °F, the UL94 fuel was not able to be leaned to the best economy. The 3° retardation in ignition timing resulted in an approximate 3 BHP engine power loss compared to the rated maximum engine power.

Retarding 6° ignition timing, to 16°/16° BTDC, but setting the maximum CHT at 460 °F, the UL94 fuel could be leaned to the best power setting below approximately 85% rated power, but not to the best economy power setting without experiencing light detonation. At both 6° retarded ignition timing and 400 °F reduced maximum CHT, the fuel could be leaned to the best economy below approximately 73% rated power. The 6° retardation in ignition timing resulted in an approximate 5 BHP power loss from the rated maximum power.

A 9° retardation in ignition timing, to 13°/13° BTDC, with 460 °F maximum CHT enabled the UL94 fuel to be leaned to the best economy power setting below 70% rated power. At both 9° retardation in ignition timing and a reduced 400 °F maximum CHT, the UL94 fuel was able to be leaned to the best economy power setting below approximately 82% rated power. Significantly, a 9° retardation in ignition timing would result in an approximate 12 BHP power loss from the rated maximum power, which is slightly more than 4% of rated power loss. Additionally, this combination resulted in an exhaust gas temperature increase of approximately 80 °F.

4.2 LYCOMING IO-540-K ENGINE.

With the IO-540-K engine and at full-rich (F/R) fuel mixture, as well as at the maximum CHT of 475 +5-0 °F, the UL94 fuel experienced light detonation at takeoff and 85% rated power. At 75% and 65% rated power settings, it was possible for the fuel to be operated at the F/R fuel flow under the same temperature conditions. Reducing maximum CHT to 425 +5-0 °F allowed the engine to be operated at takeoff and 85% rated power at F/R fuel flow, but not with a 12% margin. The 75% and 65% cruise power settings reducing the maximum CHT to 400 +5-0 °F and with the IAT adjusted to the extreme hot- and dry-day standard for a 3500 ft altitude temperature resulted in an improvement to the detonation free operation region but still resulted in detonation within the engine's current operating envelope. At these cruise power settings and with the reduced CHT and 3500 ft altitude temperatures, this engine would be able to operate on the full-rich mixture schedule with greater than the 12% margin referenced in AC 33-47, under the conditions tested.

4.3 CONTINENTAL IO-360-DB ENGINE.

Retarding the ignition timing by 3° to 17°/17° BTDC, allowed the engine to be operated without detonation at the takeoff power setting and at F/R fuel mixture. Under the same testing conditions, but at the standard 20°/20° BTDC, ignition timing, the engine experienced greater than light detonation at F/R fuel mass flow. Testing results also indicated that at retarded ignition timing, the IO-360-DB engine was able to be operated detonation free at power settings below 65% rated power and 460 +5-0 °F maximum CHT, or at power settings below 75% rated power with 400 +5-0 °F maximum CHT.

This research addressed the anti-knock performance of UL94 fuel in several high-compression, high-octane demand engines under extreme hot- and dry- (<2% relative humidity) day, sea-level conditions. This research further attempted to reduce the maximum allowable CHTs and the engine IAT along with the engine ignition timing to determine under what conditions these engines could be operated with less than light detonation on UL94. This research did not address the technical, operational, or approval challenges from seeking regulatory approval for any such changes.

5. REFERENCES

1. ASTM Standard D2700, "Standard Test Method for Knock Characteristics of Motor and Aviation Fuels by the Motor Method," ASTM International, West Conshohocken, Pennsylvania, DOI: 10.1520/D2700, www.astm.org

2. FAA UAT ARC Final Report, Unleaded Aviation Gasoline Transition Aviation Rulemaking Committee, February 17, 2012.

3. ASTM Standard D910, "Standard Specification for Aviation Gasoline," ASTM International, West Conshohocken, Pennsylvania, DOI: 10.1520/D0910, www.astm.org

4. ASTM Standard D909, "Standard Test Method for Knock Characteristics of Motor and Aviation Fuels by the Supercharge Method," ASTM International, West Conshohocken, Pennsylvania, DOI: 10.1520/D0909-00, www.astm.org

5. Teledyne Continental Aircraft Engine Service Bulletin M89-7R1, "Engine Operation After Cylinder Replacement and/or Major Overhaul," Teledyne Industries, Inc., Mobile, Alabama, August 1989.

6. ASTM Standard D6424, "Standard Practice for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines," ASTM International, West Conshohocken, Pennsylvania, DOI: 10.1520/D6424-04AR10, www.astm.org

7. Federal Aviation Administration, "Detonation Testing in Reciprocating Aircraft Engines," Advisory Circular 33-47, June 27, 1988.