CRC Report No. AV-7-07

RESEARCH RESULTS
UNLEADED HIGH OCTANE
AVIATION GASOLINE

FINAL REPORT
CRC PROJECT NO. AV-7-07

JUNE 2010

COORDINATING RESEARCH COUNCIL, INC.
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RESEARCH RESULTS
UNLEADED HIGH OCTANE AVGAS

(CRC Project No. AV-7-07)

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For the CRC UL AVGAS Development Group

JUNE 2010

CRC Aviation Committee
of the
Coordinating Research Council, Inc.

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LIST OF ABBREVIATIONS & SYMBOLS

AN	Amine Number equal to weight percentage of meta-Toluidine in a blend with reference grade *iso*-octane
AFETF	Aviation Fuels & Engine Test Facility (FAA Williams J Hughes Technical Center)
AOPA	Aircraft Owners & Pilots Association
ASTM	American Society for Testing and Materials
AVGAS	Aviation Gasoline
BHP	Brake Horsepower (also equates to IHP X mechanical efficiency)
BMEP	Brake Mean Effective Pressure = [792,000 X BHP]/ [CID X RPM]
BSFC	Brake Specific Fuel Consumption (lbs/hr/BHP)
°C	Degrees Centigrade
CEDI	Cessna Engine Detonation Indication System
CHT	Cylinder Head Temperature
CID	Cubic Inch Displacement
CR	Compression Ratio
DOE	Design of Experiment
EAA	Experimental Aircraft Association
EGT	Exhaust Gas Temperature
ETBE	Ethyl Tertiary Butyl Ether
EXP	Experimental
°F	Degrees Fahrenheit
FAA	Federal Aviation Administration
F/A	Fuel/Air Ratio
FAR	Federal Aviation Regulation
FR	Full Rich mixture setting
FBO	Fixed Base Operator
GA	General Aviation
GAMA	General Aviation Manufacturers Association
inHg	Inches of mercury

IHP	Indicated Horsepower = brake horsepower + frictional losses
IMEP	Indicated Mean Effective Pressure = [792,000 X IHP]/ [CID X RPM]
ISFC	Indicated Specific Fuel Consumption
LOP	Lean of Peak [Refers to fuel flow set lean of peak EGT]
MAP	Manifold Pressure, typically inches Hg absolute
MMT	Methylcyclopentadienyl Manganese Tricarbonyl
mmHg	Millimeters of mercury
MON	Motor Octane Number (ASTM D 2700)
MTBE	Methyl Tertiary Butyl Ether
OEM	Original Equipment Manufacturer
PN	Performance Number (ASTM D 909)
POH	Pilot Operating Handbook
PRF	Primary Reference Fuel
PSIG	Pounds per square inch gage
RPM	Revolutions Per Minute
RGL	Regulatory and Guidance Library (FAA)
ROP	Rich of Peak [Refers to fuel flow set to rich of peak EGT]
RVP	Reid Vapor Pressure
SAE	Society Automotive Engineering
TCDS	Type Certificate Data Sheet (FAA)
TDC	Top Dead Center (piston position)
TEL	Tetraethyl Lead
UL	Unleaded
100LL	100 Octane Low Lead AVGAS
Φ	Equivalence Ratio = (F/A)actual / (F/A) stoichiometric

FOREWORD

Multiple pre-existing reports including results of laboratory testing and full scale engine testing by several resources were used as the primary sources of information and data to compile this report which is intended to represent a composite summary of the research performed by the CRC UL AVGAS Development Group during the period of 2000 – 2007. The above data were supplemented by related meeting minutes, presentations, email communications, and other data and documents which were generated during this period by the CRC UL AVGAS Development Group. Where applicable throughout this report, the source of information or data is identified as a numbered reference. A numerical listing of these references is included at the end of this report. The author of this report has attempted to objectively document results in a summary manner using the above reference material; there are no changes to data or conclusions. In many cases, further discussion and graphical analyses are provided in an attempt to emphasize or further explore significant results, findings and conclusions.

As guided by the Mission Statement, the objective of the CRC UL AVGAS Development Group was to conduct research and testing that will facilitate development of the next generation aviation gasoline with the goal of ensuring the availability of the required technical information for the development of an unleaded aviation gasoline that meets the requirements of both the existing and future general aviation fleet. The work product of the CRC UL AVGAS Development Group is technical data which is made available to industry as a means of enabling the industry decision process relative to an unleaded AVGAS. The contents of this report fulfill that requirement.

ABSTRACT

Industry activities to develop an unleaded alternative to the current 100LL AVGAS were launched in the 1990's and have continued to evolve in both scope and industry level of participation into a major research initiative. Industry activities have focused on a formal collaborative industry research program with the goal of conducting research on fuels technology as related to the need for an unleaded high octane aviation gasoline capable of meeting the needs of both current and future aviation engines. The purpose of the CRC research was **not** to formulate a commercial blend but rather to conduct research and make the findings available to industry as a means of facilitating industry evaluation of unleaded AVGAS alternatives. The industry collaborative research program has been led by the Coordinating Research Council (CRC) Unleaded AVGAS Development Group. Working in parallel with this Group is the CRC Aviation Engine Octane Rating Group. The FAA William J. Hughes Technical Center's Aviation Fuel & Engine Test Facility (AFETF) has played a pivotal role in providing support and engine test facilities. The CRC research was guided by the objectives and constraints identified by the Group's Mission Statement.

In excess of 279 experimental unleaded high octane blends were formulated and tested by the CRC UL AVGAS Development Group. The objective of this report is to document the CRC UL AVGAS research activities and results to date as related to unleaded high octane aviation gasoline alternatives. Included in this CRC summary research report are documentation of unleaded blend formulations, properties, laboratory test results, engine test results, and related industry reports and data.

The research work of the CRC UL AVGAS Development Group included four major projects, each initiated pursuant to a test plan which provided for formulation of test fuels, test methods, and associated laboratory analysis. The CRC work included identification of critical fuel properties, statistical analysis of results, and assessment of laboratory data. Whereas other active industry alternative aviation fuel projects were focused on the evaluation of ethanol as an alternative aviation fuel, the CRC UL AGAS Development Group chose to focus its work on hydrocarbon based fuels with the addition of a select number of components to enhance octane quality.

PHASE I - MON SCREENING OF 202 UNLEADED FUEL BLENDS

During YR2000, the CRC UL AVGAS Development Group, using the best available industry knowledge, developed a matrix of technically viable base fuels and additives. The matrix was further segregated into subsets of petroleum-based and non-petroleum based fuels (such as ethanol). With consideration to the currently active ethanol based projects and the issues associated with ethanol as an aviation base fuel, a decision was reached to focus on the petroleum-based matrix. A research plan was subsequently created and the Development Group completed MON (motor octane number) testing during YR2001 of a group of 202 different blends representing the petroleum-based matrix. This matrix was a designed experiment structured around three base fuels (aviation, motor, and super alkylate) using six different octane-boosting components. The objective was to discern the MON characteristics of each of the 202 blends.

The test results were subjected to statistical analysis with mathematical models developed to predict trends, response, and MON performance. Results of the statistical analysis were presented at the SAE General Aviation conference held in April 2002. Certain blends yielded MON values in the 100 -104 range. Since the focus of the research was on engine octane satisfaction, properties such as vapor pressure, freezing point, heat content, and distillation

were not controlled as part of the experiment and were not evaluated for agreement with ASTM D910 AVGAS Specification.

PHASE II - FULL SCALE ENGINE TESTING OF 30 UNLEADED BLENDS

Research activities continued in YR2002 with full scale engine testing completed at both the FAA William J. Hughes Technical Center's Aviation Fuels & Engine Test Facility and at Cessna Aircraft using a group of 30 unleaded fuel blends developed from the YR2001 MON test program (202 blends). The 30 blends were designed to bracket a range of 97-105 MON using the mathematical models developed from the YR2001 MON screening program and were furnished to each of the test resources as anonymous blends, identified only by a blend number. The test fuels consisted of 15 aviation alkylate blends and 15 motor alkylate blends, each containing specific concentrations of the six different octane boosting components.

The FAA test program used a Lycoming large bore high compression ratio IO-540-K engine while a Lycoming IO-360 engine was used in the Cessna tests. The purpose of these tests was to evaluate knock characteristics of the unleaded fuel blends in representative critical engines. The engine tests included comparison with a baseline 100LL AVGAS. Sufficient data were obtained to allow evaluation of engine performance and mixture characteristics for each unleaded blend tested. In addition, laboratory analysis was completed in YR2002 for each of the 30 unleaded blends. This included component properties and a complete D910 characterization of each blend. Properties identified for each blend included density, vapor pressure, MON, supercharge rating, freezing point, aromatics, net heat of combustion, copper corrosion, water reaction, and distillation.

Test results indicated some of the unleaded blends were capable of providing knock-free operation in the engines tested. Whereas the primary focus of the research was to address engine octane satisfaction, properties such as vapor pressure, heat content, freeze point, and distillation were not controlled and were in most cases not in agreement with the ASTM D910 AVGAS Specification. No formulation was found to meet all ASTM D 910 requirements while simultaneously providing equivalent engine octane satisfaction to the baseline 100LL AVGAS.

PHASE III - FULL SCALE ENGINE TESTING OF 47 UNLEADED BLENDS

During the time period of YR2005 through YR2006, a test plan was developed which provided for continuation of full scale engine testing using a group of 47 unleaded fuel blends derived from the prior research results. Full scale engine testing was resumed and completed in YR 2007 at the FAA William J. Hughes Technical Center's Aviation Engine & Fuels Test Facility using this group of 47 UL blends. The test engine was a Lycoming IO-540-K model representative of a general aviation naturally aspirated large bore high compression ratio engine. The 47 UL blends were furnished as anonymous blends, identified only by a blend number and were formulated to meet the requirements identified. A similar protocol to Phase II was adopted which provided for evaluation of engine performance, laboratory analysis of bend properties, and statistical analysis of results. Detail engine test results were published by the FAA's AFETF. While some unleaded formulations offered equivalent engine octane satisfaction to the baseline 100LL AVGAS, none were found to simultaneously meet all the requirements of ASTM D 910.

PHASE IV - ENGINE TESTS OF LEADED & UNLEADED FUELS OF SIMILAR MON

Under the guidance of the CRC Octane Rating Group, full scale engine testing was performed at the FAA William J. Hughes Technical Center's Aviation Fuels & Engine Test Facility to

determine if leaded and unleaded fuels of the same laboratory MON offered the same engine octane satisfaction. Both high and mid octane fuels were evaluated, with results giving a quantitative insight into any operational differences. Such testing was of interest given that standard ASTM laboratory octane tests might be used to control unleaded AVGAS quality.

Specially blended samples of leaded 100LL and 91/98 AVGAS were prepared for the program. Both products met all ASTM D910 specifications except for the use of dye in the 91/98 which was colorless. The 100LL contained the maximum amount of lead permissible while the 91/98 contained 90% of the maximum. The octane quality of both the leaded and unleaded test fuels was determined by standard ASTM procedures; MON ASTM D 2700 and supercharge ASTM D 909. The high octane fuels were tested in a Lycoming IO540-K engine and the mid-octane fuels were tested in a Lycoming IO320-B engine. The fuels were stressed to the point of light detonation by performing both mixture lean-outs and by increasing the manifold pressure.

Under the conditions of the test, both the leaded 100LL and 91/98 AVGAS offered greater full size engine octane satisfaction when compared to the unleaded fuels of equivalent MON. Results indicated that a performance difference of up to approximately 3 MON may be present, more noticeably for fuels of higher octane quality. Detailed engine test results were published by the FAA's AFETF. This work highlighted the importance of understanding the critical link between laboratory procedures used to control AVGAS quality, fuel formulation, and full size engine performance.

1. INTRODUCTION

Industry activities to develop an unleaded alternative to the current 100LL AVGAS were launched in the 1990's and have continued to evolve in both scope and industry level of participation into a major research initiative. Industry activities have focused on a formal collaborative industry research program which has had the goal of conducting research on fuels technology as related to the need for an unleaded high octane aviation gasoline capable of meeting the needs of both current and future aviation engines. The purpose of the CRC research was **not** to formulate a commercial blend but rather to conduct research and make the findings available to industry as a means of facilitating industry evaluation of unleaded AVGAS alternatives. In excess of 279 experimental unleaded high octane blends were formulated and tested by the CRC UL AVGAS Development Group.

The industry collaborative research program has been led by the Coordinating Research Council (CRC) Unleaded (UL) AVGAS Development Group. Working in parallel with this Group is the CRC Aviation Engine Octane Rating Group. The FAA William J. Hughes Technical Center's Aviation Fuel and Engine Test Facility has played a pivotal role in providing support and engine test facilities.

The objective of this report is to document the CRC UL AVGAS research activities and findings to date as related to unleaded high octane aviation gasoline alternatives. Included in this CRC summary research report are documentation of unleaded blend formulations, properties, laboratory test results, engine test results, and related industry reports and data.

2. BACKGROUND

The criticality of the need for an acceptable high octane aviation gasoline is best put into perspective by an understanding of the breadth of the general aviation industry and the affected aircraft and engines.

According to the General Aviation Manufacturers Association, General Aviation is defined as all aviation other than military and commercial airlines.[(1)] General Aviation (GA) is an integral part of the United States' intermodal transportation system carrying 166 million passengers annually on general aviation aircraft ranging from two-seat training aircraft to intercontinental business jets. For those communities without scheduled air service, GA is the primary option for air transportation of passengers and cargo and is relied on by more than 5,000 communities for their air transportation needs.[(1)] GA contributed $150 billion to the nation's economy in 2005 and employed more than 1,265,000 people with nearly 70% of the GA hours flown associated with business purposes.

The total U.S. GA fleet in 2006 consisted of 225,007 aircraft with the piston powered fleet comprising 74% of the total.[(2)] In excess of 18,555 aircraft were multi-engine. The U.S. piston fleet in YR2006 consisted of 167,008 aircraft which is estimated to be 60% - 70% of the total worldwide piston fleet. NASA Report No. CR-1998-207639 indicates that the North American GA piston powered fleet of 189,348 aircraft in 1992 was 71.5% of the world wide piston aircraft fleet. [(3)] According to FAA statistics, total U.S. AVGAS consumption in 2006 was 351.6 million gallons where in excess of 17 million hours was flown by piston powered aircraft.[(2)]

Piston powered GA aircraft are almost exclusively powered by horizontally opposed spark ignition reciprocating engines configured in 4, 6, and 8 cylinder arrangements manufactured by original equipment manufacturers (OEM) Teledyne Continental Motors and Textron Lycoming as FAA approved products conforming to either CAR 13 Civil Air Regulations or 14 CFR 33 Federal Aviation regulations.

The FAA approved GA engines are both naturally aspirated and turbocharged with ratings from 100 BHP to in excess of 400 BHP. Fuels approved for operation in GA engines are specified in the FAA approved OEM continuous airworthiness data and the associated FAA TCDS (type certificate data sheet which may be accessed at http://rgl.faa.gov). The approved fuel is typically specified as aviation gasoline conforming to ASTM D 910 specification either minimum grade 80, 91 (older version of D 910) or 100LL. FAA certification of each engine model required that adequate detonation (knock) margins be demonstrated by test using a certified fuel of minimum quality while operating at worst case conditions for knock. Furthermore, FAA certification (ref AC33-47-1) requires that the lean limit fuel flow be set at least 12% above the fuel flow corresponding to limiting detonation. However, the FAA certification requirements do not require that the engine octane requirement be determined since historically the GA engines were designed to operate with the existing ASTM D 910 AVGAS. The reader is directed to reference (7) for a historical review of aviation gasoline.

Most older GA engine models are approved to operate with a minimum grade 80/87 AVGAS but are also approved to operate with the more readily available higher grade 100LL AVGAS; there is a small percentage approved to operate on an older minimum grade 91 AVGAS. GA engine models produced since the mid 1970's are mostly high output, high performance, high compression ratio engines which require a minimum grade 100LL AVGAS for adequate knock margin. The minimum grade 100LL fuel is specified in the engine FAA TCDS and the aircraft POH (Pilot Operating Handbook). The latter represents a significant implication in consideration that this group of GA engine models accounts for a large percentage of the annual GA hours flown. FAA statistics indicate that multi-engine aircraft which comprise less than 12% of the fixed wing fleet and are predominantly powered by high performance engines requiring 100LL, accounted for approximately half of the fuel consumed by the total piston fixed wing fleet in YR2006.[(2)]

Figure 1.0
Typical General Aviation Six Cylinder Engine
Spark Ignition

GA aircraft and engine products are shown through test and analysis to be compliant with the applicable FAA regulations. The FAA approval process for aircraft and engine products is a rigorous demanding process which substantiates the airworthiness of the product. Major changes to the approved fuel or engine octane requirements necessitate re-certification of the affected engines and aircraft.

With as many as 230,000 piston powered general aviation aircraft operating worldwide, industry estimates have indicated that as much as a third to one half of the fleet may require a high octane AVGAS equivalent to 100LL; however, industry experts believe it is this segment of the fleet which accounts for most of the general aviation flying time today. Therefore, the continued

availability of an appropriate high octane AVGAS is viewed as a critical need by the general aviation industry.

Reflecting the criticality of the dependence of the GA piston fleet on 100LL AVGAS, the concern regarding continued availability of 100LL, and environmental considerations relative to TEL, the GA industry precipitated the formation of a CRC Research Project in 1996 with a formal request from the General Aviation Manufacturers Association.

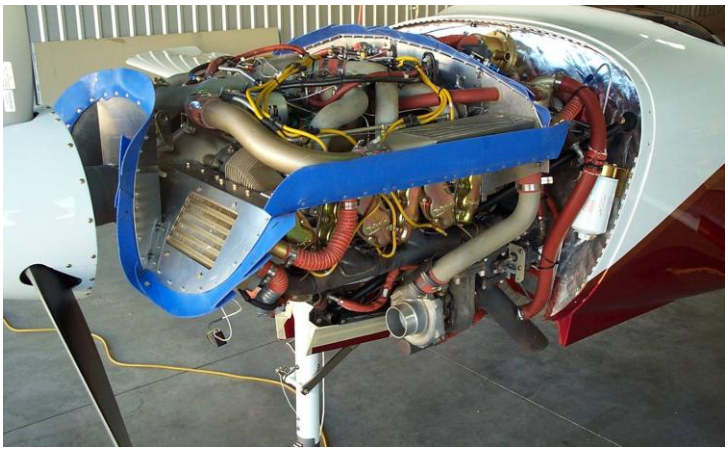

Figure 2.0
Installed 350 BHP Turbocharged Engine

Figure 3.0
Typical General Aviation Aircraft

3. CONCLUSIONS

Whereas early CRC Development Group evaluations determined that engine octane requirement is one of the most critical and challenging performance aspects associated with an unleaded AVGAS, the CRC research into unleaded aviation gasoline alternatives focused on meeting engine octane requirements while noting any compromise in other fuel parameters specified in ASTM D 910. CRC research results based upon full scale engine tests and laboratory MON tests of unleaded fuel blends evaluated for engine knock satisfaction did not

identify a transparent replacement for the 100LL AVGAS product. Although full scale engine tests indicated some blends were capable of providing knock free operation in the test engine, these blends represented the use of specialty chemicals which may require further evaluation with respect to environmental impact. Economic viability of the blends tested is not the jurisdiction of CRC and will need to be evaluated separately by industry. Furthermore, CRC test blend properties were not controlled for agreement with the ASTM D 910 specification as the primary focus was engine octane satisfaction.

Although some experimental blends of specialist components were shown to exceed the 100LL specification of 99.6 MON minimum, such formulations are very different as compared to the current ASTM D 910 product and potentially compromise other important fuel properties and specifications. Depending upon engine power output and configuration, high performance aviation engines can require unleaded fuels in excess of 100 MON to achieve knock free operation. Leaded AVGAS 100LL or 91/98 offers greater octane satisfaction in full size engines when compared to unleaded products of similar laboratory MON.

CRC test results are indicative of the significant challenge regarding a high octane unleaded AVGAS formulation and further serve as a reminder that aviation fuels represent specialized products optimized over many years to maximize performance and flight safety. Through the CRC, a broad range of Industry expertise and facilities have been made available to investigate this issue. Such groups, with input from all parties, and working in collaboration with industry offer a viable means of conducting meaningful research.

The goal remains a viable solution which assures performance and flight safety for both the existing and future general aviation fleets.

4. RELATED STANDARDS AND SPECIFICATIONS

Industry standards, specifications, and FAA documents and regulations relating to aviation gasoline, reciprocating aircraft engines and aircraft are listed as follows.

4.1. ASTM D 909, “Test Method for Knock Characteristics of Aviation Gasolines by the Supercharge Method.”

4.2. ASTM D 910, “Standard Specification for Aviation Gasoline.”

4.3. ASTM D 2700, “Standard Test Method for Motor Octane Number of Spark-Ignition Engine Fuels

4.4. ASTM D 6424, “Practice for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines.”

4.5. ASTM D 6812, “Ground-Based Octane Rating Procedure for Turbocharged/Super-charged Spark Ignition Aircraft Engines.”

4.6. FAA Advisory Circular 20-24B, “Qualification of Fuels, Lubricants, and Additives for Aircraft Engines.”

4.7. FAA Advisory Circular 23-16, “Powerplant Guide for Certification of Part 23 Aircraft”

4.8. FAA Advisory Circular 33-47-1, “Detonation Testing in Reciprocating Aircraft Engines.”

4.9. FAA Advisory Circular 33-2B, “Engine Type Certification Handbook”

4.10. FAA TCDS for engines and aircraft may be accessed at : http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgMakeModel.nsf/MainFrame

4.11. 14 CFR Part 33, FAA Certification Requirements for Reciprocating Aircraft Engines

4.12. 14 CFR Part 23 Subpart E, FAA Certification Requirements for Installed Powerplants

5. CRC UL AVGAS DEVELOPMENT GROUP

5.1. Organization & Membership

Membership of the CRC Unleaded AVGAS Development Group reached a level of over 60 individuals representing over 40 different organizations including international AVGAS manufacturing knowledge and aviation engine expertise. Working in parallel with this group, and with mostly a common membership, was the CRC Aviation Engine Octane Rating Group which was formed with the objective of developing a method to consistently rate aircraft engine octane requirement under harsh repeatable conditions and to determine the general aviation fleet octane requirements. The FAA and industry trade organizations AOPA, EAA and GAMA were significant contributors to the overall process and reflect the extent of support for this initiative. The FAA William J. Hughes Technical Center's Aviation Fuels & Engine Test Facility was instrumental in providing test facilities and funding in support of the CRC objectives.

Recognizing the large size of the CRC Unleaded AVGAS Development Group and the diverse membership, methods were evolved to facilitate progress. Formation of a small Task Group working as a subset of the CRC Development Group, use of a single lab for blending and analysis, and allocation of the FAA Technical Center engine test facility as the primary test resource were significant factors in achieving this goal. Parallel test programs at the FAA Technical Center and at Cessna Aircraft using different engines for the 30 unleaded blends further enhanced the research process and methods. These factors contributed to facilitating progress of the collaborative effort wherein Task Group members provided base fuels, blend components, and technical guidance with actual engine testing performed by the FAA Technical Center. Task Group participants included representation from the following organizations.

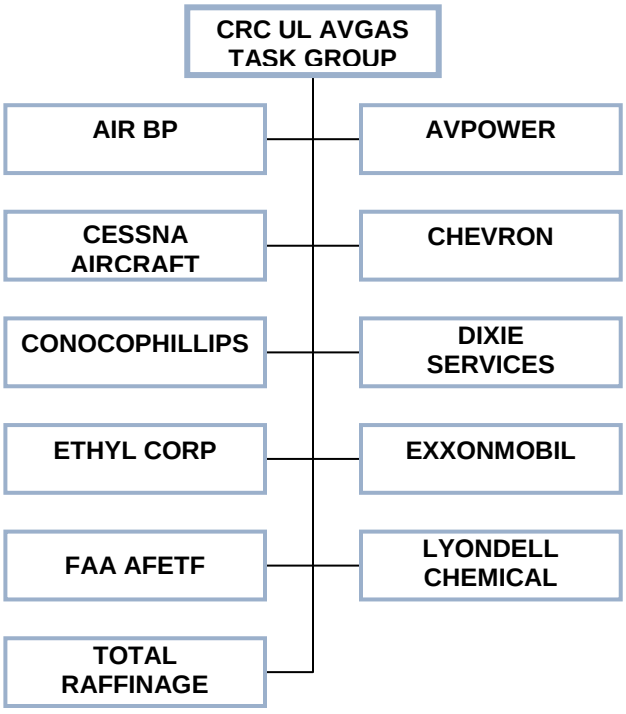

Figure 4.0
CRC UL AVGAS Task Group

5.2. Mission Statement

As a means of guiding the CRC research work, a Mission Statement was evolved early in the process with the goal of clearly identifying the research objectives and constraints. The following Mission Statement has remained in effect without change throughout the activity described within this report.

> *"The Unleaded Aviation Gasoline Development Group as organized under the sponsorship of the Coordinating Research Council has been formed with the objective of conducting research and testing that will facilitate development of the next generation aviation gasoline – a high octane unleaded aviation gasoline as an environmentally compatible, cost effective replacement for the current ASTM D910 100LL fuel. Consisting of representatives from the airframe manufacturers, engine manufacturers, fuel producers, FAA, AOPA, EAA, GAMA, and other interested parties, the CRC AVGAS Development Group acts as a steering committee, providing oversight and direction for research and testing.*
>
> *The CRC AVGAS Development Group is committed to an interactive, collaborative process with the goal of ensuring the availability of the required technical information for the development of an aviation gasoline that meets the requirements of both the existing and future general aviation fleet. Safety, reliable operation, and environmental awareness are driving principles."*

Significant aspects of the mission statement which provided guidance relative to the conduct of the CRC research project are highlighted as follows. The primary benefit of the mission statement was a means to ensure the research objectives remained focused and consistent throughout the project.

- Conduct research and testing
- High octane unleaded replacement
- Providing oversight and direction for research
- Collaborative process
- Meeting requirements of existing and future fleets

5.3. CRC Octane Rating Group

The CRC Octane Rating Group was formed in 1991, before the Unleaded AVGAS Development Group. The Octane Rating Group consisted of mostly a common membership and upon formation of the UL AVGAS Development Group worked in parallel to support the CRC UL AVGAS Development Group. It also functioned as a collaborative industry effort wherein testing was performed at the FAA Technical Center's AFETF with fuels furnished by the petroleum companies. The primary objective of the octane rating group was to identify the maximum octane requirement of the current aircraft engine fleet. In order to accomplish this objective, the Octane Rating Group had to develop two ASTM standard practices, or methods, to consistently rate aircraft engine octane requirements under harsh, repeatable conditions representative of the operational environment. These methods were used to determine the unleaded fuel octane requirement of the general aviation fleet. The Octane Rating Group also developed unleaded primary reference fuels greater than 100 MON. It should be noted that an industry standard for octane rating aircraft engines and unleaded octane rating fuels > 100 MON did not previously exist; furthermore, the aviation method and fuels are significantly different as compared to automotive practice and require specialized facilities and expertise.

ASTM D 6424 and ASTM D 6812 constitute the two standard practices developed by the CRC Octane Rating Group. ASTM D 6424 was implemented in 1999 and applies to the octane rating of normally aspirated aircraft engines. ASTM D 6812 was released in 2002 and applies to the octane rating of turbocharged engines. Engines representative of the general aviation fleet were octane rated using these ASTM procedures to determine the unleaded octane requirement. Test results indicated a minimum unleaded octane requirement greater than 100 MON for naturally aspirated engines and higher for turbocharged engines depending upon engine power output and configuration. Such findings are consistent with the test results observed during the full scale engine testing reported in Section 6.6.

Engines octane rated at the FAA Technical Center included the following which are representative of the large bore high output engines which require a high octane aviation gasoline.

- TEXTRON LYOMING
  - TIO-540-J
  - IO-540-K
- TELEDYNE CONTINENTAL MOTORS
  - TSIO-550-E
  - IO-550-D

6. CRC UL AVGAS RESEARCH RESULTS

6.1. Research Group Protocol

The operational performance of AVGAS 100LL as manufactured to ASTM D 910 specification, is dependent on many parameters which are further discussed in Section 6.8 CRITICAL PROPERTIES AND OPERATIONAL ISSUES. One of the most significant properties of 100LL AVGAS as compared to other gasoline products is the very high octane quality of the fuel, 99.5 motor octane number (MON) minimum[6]. This comparatively high octane quality is necessary as required to meet the octane requirement of the thermally efficient high output GA engines which comprise a significant portion of the general aviation fleet. Based on a broad Industry consensus, the CRC UL AVGAS Development Group sought to investigate this fuel parameter first, while being aware that other critical properties would require assessment at a later date. As guided by the Mission Statement, the focus was research of unleaded AVGAS alternatives with the work product being research data which would enable industry to make decisions about possible blends and blend components. The CRC UL AVGAS research projects as documented in this report are summarized as follows in Section 6.2.

The CRC UL AVGAS Development Group, which functioned as a purely collaborative research initiative without the benefit of direct funding, further chose to focus its research efforts on hydrocarbon base fuels in consideration that non-hydrocarbon based fuels such as ethanol were being actively investigated by other well funded industry programs. Accordingly, the CRC UL AVGAS research projects were structured and planned to focus on unleaded blends using hydrocarbon based alkylates with additives selected to provide maximum octane effect. Ethanol was included in the investigations as an additive, but not as a base fuel.

Research presented within this report was not intended to address the merits of the ASTM supercharge rating or the MON rating, either pro or con, but rather documents test results consistent with the existing D 909 and D 2700 specifications where applicable.

6.2. Research Projects

During the period of YR2000 through YR2008, the CRC UL AVGAS Task Group (working as a subcommittee of the Development Group) planned, implemented, and completed four separate research projects involving test and evaluation of various unleaded high octane blends as shown in Figure 5.0. In excess of 279 unleaded blends were evaluated. Base fuels and additives evaluated by the CRC Group included those shown in Figures 6.0 and 7.0. Table 1.0 provides a chronological listing of significant research events and milestones.

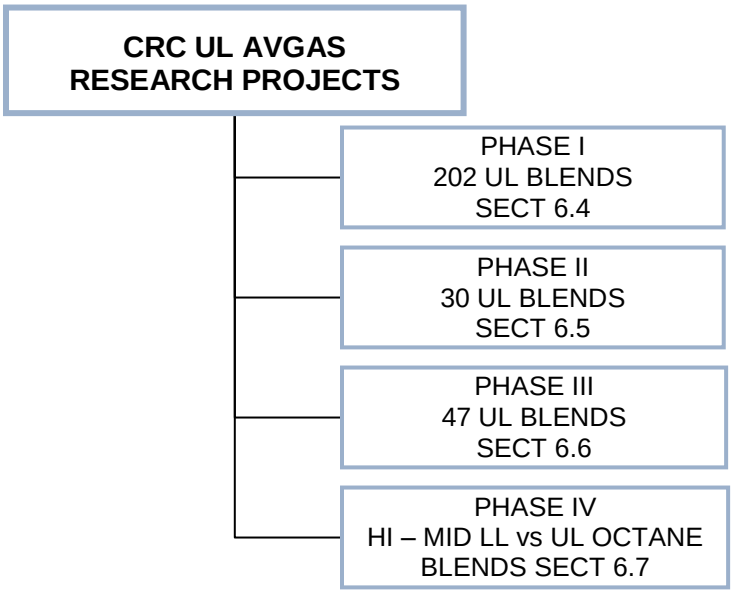

FIGURE 5.0
CRC UL AVGAS Research Projects

With the exception of Phase I which involved MON laboratory testing using a CFR engine, Phases II through Phase IV involved full scale engine testing of unleaded blends using a test engine representative of the general aviation fleet with an octane requirement of approximately 100 MON. Each of these project phases was executed as a collaborative research venture wherein the research plan was evolved by the CRC UL AVGAS Task Group (subset group of CRC UL AVGAS Development Group) with members providing blend components and base fuels which were tested and blended by a single lab with full scale engine testing performed by the FAA Technical Center. One of the projects included engine ground testing of the experimental blends by Cessna Aircraft (see Section 6.5). Funding for laboratory analysis and purchase of certain blend agents was provided by the FAA Technical Center.

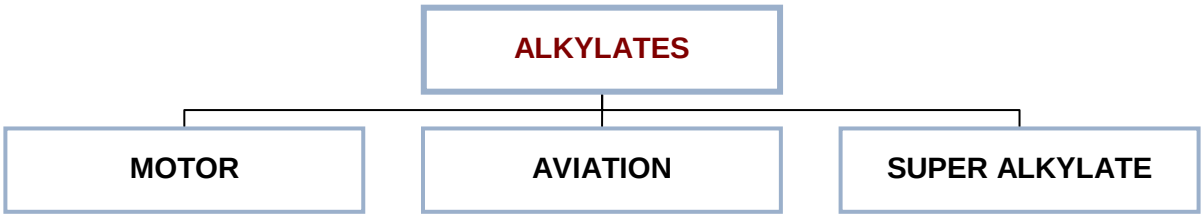

Figure 6.0
Alkylates Evaluated in CRC Experimental Blends

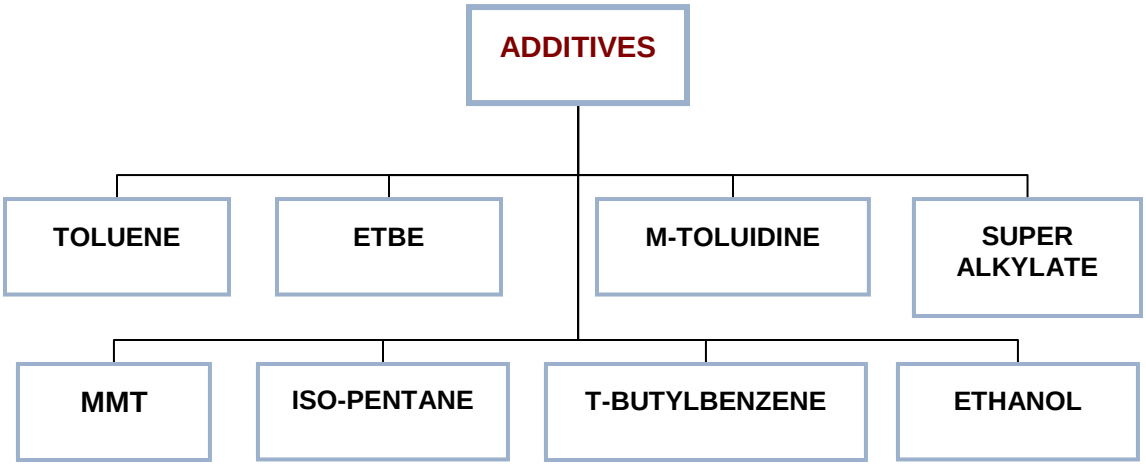

Figure 7.0
Additives Evaluated in CRC Experimental Blends

Table 1.0 Significant Research Events & Milestones CRC UL AVGAS Development Group & Octane Rating Group		
✓	1999	Paper Prepared by CRC Titled "Performance Characteristics of Future Unleaded Aviation Gasoline"
✓	1999	ASTM Standard Procedure for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines Released
✓	Sept 2000	Technically Viable UL Fuel Matrices Identified
✓	Nov 2000	MON Test Plan Developed
✓	April 2001	MON Screening Completed, 202 Blends
✓	June 2001	MON Test Data 202 Blends Disseminated to CRC Dev Group
✓	Nov 2001	YR2002 Engine Test Plan Developed for 30 UL Blends

✓	2002	ASTM Standard Procedure for Octane Rating Turbocharged Spark Ignition Aircraft Engines Released
✓	March 2002	Fuels Shipped for First Full Scale Engine Tests 30 UL Blends
✓	April 2002	Statistical Analysis 202 Blends Presented at SAE
✓	Sept 2002	Full Scale Engine Tests Completed, 30 UL Blends
✓	Sept 2002	D910 Characterization Completed, 30 UL Blends
✓	2003	Full Scale Engine Tests Completed Comparing Effect of Mid Range – High Octane Leaded vs Unleaded Fuels
✓	2004	Test Results Reports Released, 30 UL Blends
✓	2005	Test Plan Developed, Full Scale Engine Tests, 47 UL Blends
✓	2005	Test Plan Finalized, Full Scale Engine Tests, 47 UL Blends
✓	2006	Full Scale Engine Tests Completed of Leaded & Unleaded Fuels of Similar MON & Performance Number
✓	2007	Full Scale Engine Tests Completed, 47 UL Blends
✓	2007	Consideration Given to Expansion of CRC Research to Include Test of Engine Modifications
✓	2010	CRC Research Report Phase I – IV Released

6.3. Methods

The purpose of the CRC research described within this report was to investigate options for additives and base fuels that when combined in the absence of TEL offered the potential of satisfying the high octane requirement of the general aviation fleet. Research methodologies focused on a combination of laboratory MON screening, full scale engine knock tests of candidate unleaded fuel blends, and laboratory analyses of component and blend properties. Various other methods which are discussed as follows were utilized to facilitate attainment of the group's goals.

Complementing the basic test methodology was the decision to implement each test plan as a design of experiment (DOE) with the associated statistical analysis. Task Group Member ConocoPhillips played a key role in providing statistician support for design of experiments and associated analysis. Implementation of each test phase as a DOE for maximum effect and knowledge including evaluation of interactions of the blend components was a significant factor in the successful completion of the test phases listed in Figure 5.0.

Preceding the formal design of experiment for each test phase was a process wherein the expertise and specialty knowledge of the Task Group members combined to identify candidate alkylates, additives, blend constraints, component ranges for each of the test phases. Knowledge gained from each test phase was given consideration in formulating the plan for the next phase. Task Group Members representing the fuel producers, chemical manufacturers, and specialty labs played a vital role with respect to identification of components, volume fractions, and blend constraints. Input and guidance from Air BP, Chevron, ConocoPhillips, Dixie Services, Ethyl Corporation, ExxonMobil, Lyondell Chemical, and Total Raffinage was fundamental to the evolution of each research plan. In addition, these Task Group members collaborated to provide base fuels and additives in support of each test phase.

Use of a single laboratory for component analysis and blending was another aspect contributing to the successful implementation of the research methods described. Task Group Member Dixie Services provided laboratory analysis and test fuel blending for all of the test blends described in this report.

The availability of a well equipped dynamometer test cell and associated instrumentation was a significant factor in the successful completion of the engine screening tests. The availability and expertise of the FAA Technical Center test facility and staff was instrumental to the CRC research process. Without the FAA Technical Center's support and funding of component acquisition and blending, the outcome of the CRC research would have likely been quite different.

Research methods were also facilitated by testing of an identical batch of the Phase II 30 UL Blends by a different test facility employing a different test method. This tended to normalize the test results for the 30 UL blends. Cessna Aircraft's test facility provided an effective alternative test facility, which yielded results consistent with that observed at the FAA Tech Center.

6.3.1. Design of Experiment

Design of Experiment (DOE) is a structured organized method that is used to determine the relationship between variables which affect a process and the output of that process using the fewest trial runs. DOE provides that all relevant factors are varied systematically. Analysis of DOE results helps to identify optimal conditions, the factors that most influence the results, and those that least influence results, as well as details such as the existence of interactions and synergies between factors. DOE is a strategy to gather empirical knowledge based upon the analysis of experimental data. Research plans prepared for the Phase I and Phase III projects evaluating the 202 blends and 47 blends respectively were each planned and implemented using design of experiment methods. Subsequent statistical analysis of the data allowed the development of mathematical models which predict the MON rating of a fuel blend based upon the specified blend components and their respective compositions. The experimental design for the Phase I project was based upon a mixture and cubic design structures and resulted in 75 fuel blends for the seven-component aviation alkylate matrix, 75 fuel blends for the seven-component motor alkylate matrix, and 52 fuel blends for the six-component super alkylate matrix; replicate blends were included in each matrix to address experimental error.[10][24]

6.3.2. Laboratory Tests

Task Group Member Dixie Services was commissioned by the CRC Unleaded AVGAS Development Group to provide laboratory support consisting of component property and chemical analysis, experimental fuel blending, and property analysis of the blended unleaded test fuels. Unleaded blends and components evaluated during the CRC research projects were subjected to laboratory analyses and tests in accordance with the respective research plan as defined and implemented by the CRC Unleaded AVGAS Task Group; see Sections 6.4 – 6.7. Once a test plan was defined, the laboratory worked in conjunction with the engine test resource and the statistician developing the experimental design to define the volume or mass requirements for blend components and alkylates. Each unleaded blend prepared for full scale engine testing was assigned a coded identifier by the laboratory since each blend was furnished anonymously to the engine test facility; the unleaded blend composition was not provided to either engine test source prior to engine testing.

Whereas the Phase I MON screening of 202 unleaded blends consisted only of testing for Motor octane number using a CFR engine in accordance with ASTM D 2700, the entire Phase I test program was conducted totally within the laboratory facilities of the designated laboratory Dixie Services. Tables 2.0 and 3.0 summarize the laboratory testing performed on blend components and the unleaded fuel blends respectively in accordance with the applicable ASTM standards. See Sections 6.4 through 6.7 and Appendices A – C of this report for results of lab analysis and associated testing.

Table 2.0
Laboratory Testing of Component Chemical & Physical Properties
CRC UL AVGAS Research Projects

ASTM Test Method	Phase I Components	Phase II Components	Phase III Components	Phase IV Components
D 4052 Relative Density	Yes	No	Yes	NA
D 5191 Vapor Pressure	Yes	No	Yes	NA
D 2699 Research Octane No	Yes	No	No	NA
D 2700 Motor Octane No.	Yes	No	Yes	NA
D 2622 Sulfur Content	No	Yes	No	NA
D 5453 Sulfur Content	No	No	Yes	NA
E 1064 Water Content	Yes	No	Yes	NA
D 2360 Toluene Content	Yes	No	Yes	NA
D 5441 ETBE Content	Yes	No	Yes	NA
D 5501 Ethanol Content	Yes	No	NA	NA
D 850 Distillation Range	Yes	No	Yes	NA
D 86 Distillation %	Yes	No	Yes	NA

Table 3.0
Laboratory Testing of Fuel Properties
CRC UL AVGAS Research Projects

ASTM Test Method	Phase I 202 Blends	Phase II 30 Blends	Phase III 47 Blends	Phase IV Mid – Hi MON
D 2700 Motor Octane No.	Yes	Yes	Yes	Yes
D 910 Aviation Gasoline	No	Yes	No	Yes

D 909 Supercharge Rating	No	Yes	No	Yes
D 4052 Density	No	Yes	Yes	Yes
D 5191 Vapor Pressure	No	Yes	Yes	Yes
D 2386 Freeze Point	No	Yes	No	Yes
D 4809 Energy Content	No	Yes	No	Yes
D 130 Copper Corrosion	No	Yes	No	Yes
D 1094 Water Reaction	No	Yes	No	Yes
D 2831 Manganese Content	No	Yes	No	No
D 86 Distillation	No	Yes	No	Yes
D 1266 Sulfur Content	No	No	No	Yes
D 3341 Lead Content	NA	NA	NA	Yes

6.3.3. Engine Test Facilities

Several engine test facilities were used for the full scale engine testing. The primary test facility was located at the FAA Technical Center's Aviation Fuel & Engine Test Facility in Atlantic City, New Jersey. Full scale engine tests were also performed on the Phase II matrix of 30 unleaded blends at a Cessna Aircraft test facility in Wichita Kansas. Identical blends of the Phase II matrix of 30 unleaded blends were tested by both the FAA AFETF and by Cessna Aircraft. Although there were significant differences in test facilities and test methods described as follows, the test results are equally applicable in consideration the intent at each test facility was a comparative assessment of the unleaded test blends using a 100LL fuel as the baseline. Each test facility used an engine representative of worst case fleet naturally aspirated engines which require a high octane aviation gasoline.

6.3.3.1. FAA Technical Center Aviation Fuel & Engine Test Facility

The FAA's AFETF is a reciprocating engine test facility consisting of 3 fully equipped dynamometer test cells. CRC research full scale engine testing using the IO-540-K engine at the FAA Technical Center was performed in Test Cell No. 2 using an eddy-current dynamometer to load the engine. The engine was operated using the throttle control with the dynamometer load controller providing speed control of the engine which allowed engine speed to be accurately set and maintained for each power setting. Adjustable cooling air controls provided for variable cooling airflow to the engine cylinders which was regulated to maintain desired CHT for each test (see Section 6.3.3). Similarly, engine oil was cooled externally to the engine using test facility equipment which allowed engine oil inlet temperature to be adjusted and maintained at desired settings for each test. Inlet air temperature to the engine throttle was controlled for both temperature and humidity for all tests using facility air management equipment. Inlet air humidity was controlled to below 5% relative humidity with most test conditions being less than 1 grain of moisture per lb of dry air. Inlet air pressure was not controllable and was equivalent to ambient air barometric pressure for each test. Test facility

instrumentation included mass airflow measurement of both fuel flow and engine induction airflow. The engine was fitted with a conventional exhaust manifold which directed the exhaust gases into a facility exhaust collector. Details of the FAA Aviation Fuels and Test Facility, test equipment, and instrumentation are addressed in the FAA reports listed in Section 9.0 References[12][14][15]. Figures 8, 9, and 10 are images of the FAA test cell, engine installation, and control room console. See also reference (9) for prior FAA testing of unleaded AVGAS.

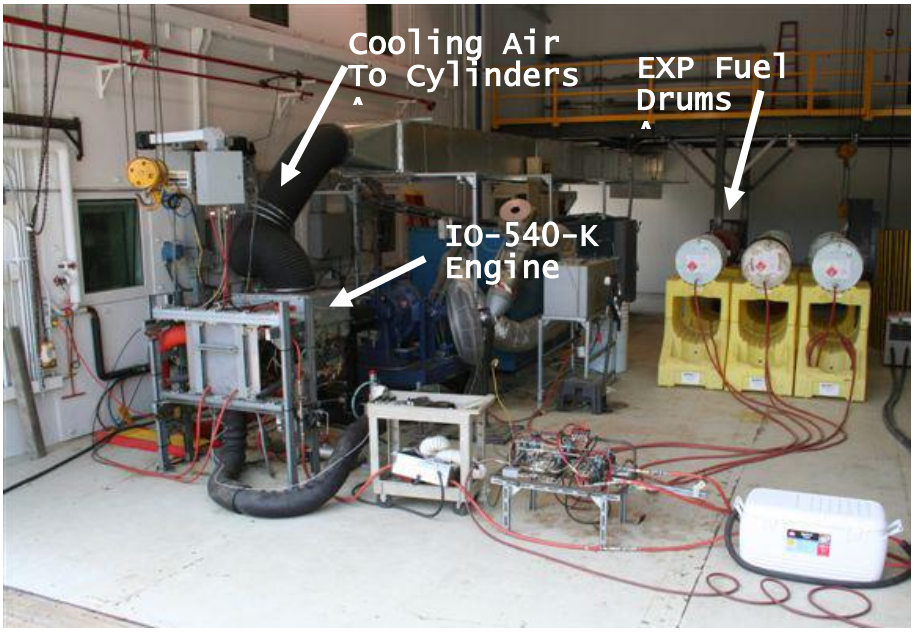

Figure 8.0
FAA AFETF Dynamometer Test Cell No. 2

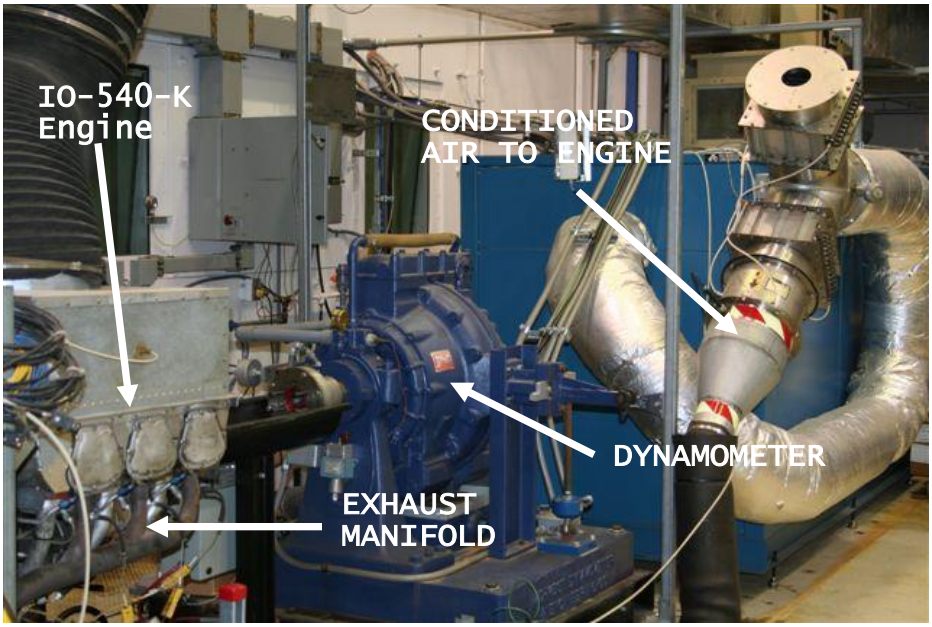

Figure 9.0
FAA AFETF Dynamometer & Induction Air System

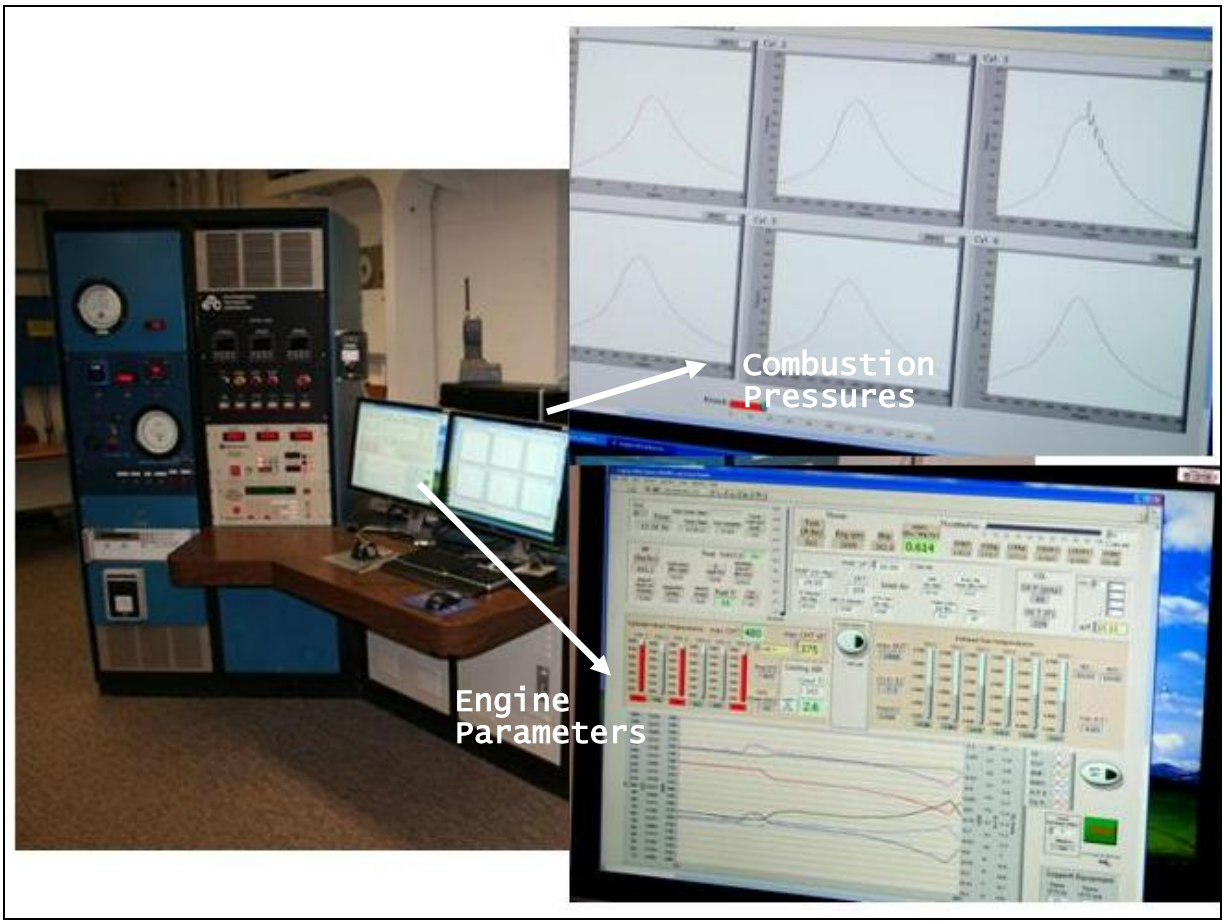

Figure 10.0
FAA AFETF Dynamometer Control Station

6.3.3.2. Cessna Aircraft Test Facility

Cessna's Unleaded Fuels Development Test Stand employed a Cessna model 172 aircraft fuselage with the test engine installed within the standard production cowling using C172 standard baffling and exhaust manifold. The aircraft fuselage (less wings and tail structure) was ground secured in a manner to act as a test bed for the engine. The engine was fitted with a fixed pitch propeller which provided the means for loading the engine and a source of cooling air for the cylinders and oil cooler. A torquemeter installed between the propeller and engine output shaft provided for measurement of engine torque; see Figure 12.0. The engine was operated from a control room remote from the fuselage using the engine throttle. Inlet air temperature to the engine throttle was controlled for temperature only using test facility air temperature management equipment consisting of a hot air heater. Inlet air pressure and humidity were not controllable and were equivalent to ambient air barometric pressure and humidity for each test. Sequence of back to back tests with baseline 100LL and test fuels insured uniformity in ambient pressure and humidity. Test facility instrumentation included mass measurement of fuel flow. Details of the Cessna test facility, test equipment, and instrumentation are addressed in the Cessna report listed in Section 9.0 References[13].

Figure 11.0
Cessna 172 Engine Ground Test Rig

Figure 12.0
Cessna Ground Test Rig, IO-360 Engine in C172 Fuselage

6.3.4. Test Engines

The following describes the engines used for testing of the unleaded AVGAS blends evaluated during the CRC projects listed in Figure 5.0. Two different engines were used for the CRC Phase II and Phase III projects with both being representative of a large segment of the general aviation engine fleet which requires a high octane aviation gasoline. A large bore six cylinder 300 BHP naturally aspirated engine with 8.7:1 CR was used as the primary test engine at the FAA Technical Center[12][14][15]. A large bore four cylinder naturally aspirated engine with 9:1 CR

representative of those rated at 200 BHP was used as the primary test engine for the Cessna Aircraft testing of the 30 unleaded AVGAS blends[13]. FAA Technical Center Phase IV comparative testing of leaded vs unleaded fuels included use of a large bore mid octane requirement four cylinder engine rated at 160 BHP on 91/96 AVGAS. Large bore high compression ratio engines tend to have greater octane requirements as compared to smaller bore lower compression ratio engines.

6.3.4.1. FAA AFETF IO-540-K Engine

A Textron Lycoming model IO-540-K engine was used for the CRC Phase II and Phase III full scale engine tests performed at the FAA AFETF. The IO-540-K is a large bore 8.7:1 CR, six cylinder, aircooled, horizontally opposed, fuel injected engine and was viewed as being one of the most demanding naturally aspirated engines relative to octane requirement. The IO-540-K is representative of the large bore six cylinder naturally aspirated engines rated on 100LL AVGAS which power a large segment of the general aviation fleet. The IO-540-K engine is an FAA certified engine with a maximum continuous rating of 300 BHP at 2700 RPM.[25]

In order to adapt a pressure transducer for measurement of combustion pressure, each cylinder head was modified by drilling and tapping the head for installation of a high temperature, water cooled piezoelectric pressure transducer as shown below in Figure 11,0. Details of this pressure transducer and associated signal processing are documented in each of the related FAA Technical Center AFETF Reports[12][14][15]. Installation of the pressure transducer was in accordance with ASTM Standard Practice D 6424 for Octane Rating Naturally Aspirated Spark Ignition Aircraft Engines[4]. Engine knock was monitored by processing the combustion pressure signal through a numerical analyses routine as specified by ASTM D 6424.

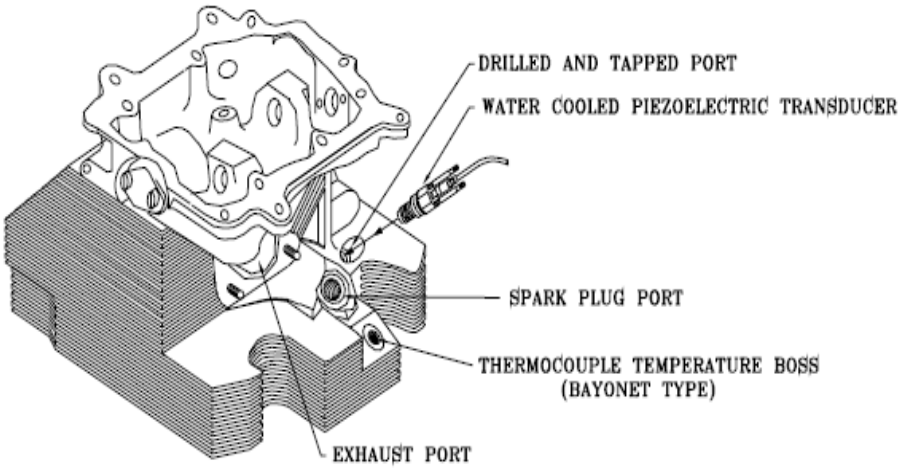

Figure 13.0
Cylinder Head Modification
FAA Tech Center AFETF IO-540-K Engine

6.3.4.2. FAA AFETF IO-320-B Engine

A Textron Lycoming model IO-320-B engine was used during the Phase IV comparative fuels testing at the FAA Technical Center. The IO-320-B is a large bore 8.5:1 CR, four cylinder, aircooled, horizontally opposed, fuel injected engine and was viewed as being typical of those mid-octane requirement engines approved for operation with 91/96 AVGAS. The IO-320-B engine is an FAA certified engine with a maximum continuous rating of 160 BHP at 2700 RPM.[(26)] Similar to the IO-540-K engine, each cylinder on the IO-320-B engine was fitted with a cylinder pressure transducer as specified by ASTM Standard Practice D-6424 as a means of monitoring combustion pressure and detonation.

6.3.4.3. Cessna IO-360-X124 Engine

A Textron Lycoming model IO-360-X124 engine was used for the full scale engine testing performed on the 30 unleaded experimental AVGAS blends at the Cessna Aircraft test facility. The IO-360-X124 is a large bore 9:1 CR, four cylinder, aircooled, horizontally opposed, fuel injected engine and was viewed as being one of the most demanding naturally aspirated engines relative to octane requirement. The IO-360-X124 is representative of the large bore four cylinder naturally aspirated engines which power a large segment of the general aviation fleet. The Textron Lycoming model IO-360 engine is an FAA certified engine with a maximum continuous rating of 200 BHP at 2700 RPM. The IO-360-X124 engine used for the Cessna full scale engine tests was a stock engine except compression ratio was increased from the normal 8.7 CR to 9:1 CR; the RSA5 fuel injector was also recalibrated to increase the full rich fuel flow range by approximately 17%.

There were no modifications to the cylinder heads on the IO-360 engine as performed on the engine used for FAA testing. An alternate means was used to sense cylinder knock during the Cessna engine tests as described in the following Section 6.3.5.3.

6.3.5. Engine Test Procedures

The following provides a summary description of the full scale engine test procedures used for testing of the unleaded AVGAS blends evaluated during the CRC projects listed in Figure 5.0. Although the engine test procedures applied by the FAA Technical Center's AFETF and by Cessna Aircraft were significantly different, the results are viewed as being equally applicable considering the intent was a comparative assessment of each unleaded blend relative to engine knock performance as compared to the baseline 100LL AVGAS. Identical blends of the Phase II matrix of 30 unleaded blends were tested by both the FAA AFETF and by Cessna Aircraft. Prior to engine knock testing of the unleaded blends by the FAA AFETF, the test engine was octane rated using unleaded reference fuels in accordance with ASTM Standard Practice D 6424 which prescribes the recommended practice for octane rating aviation spark ignition engines[(4)]. The Cessna test procedure for evaluation of the 30 UL blends was based upon a Cessna company test procedure wherein the engine is stressed to more readily induce engine knock by operating the engine at significantly elevated inlet air temperatures. Similar to the FAA AFETF procedure, the Cessna procedure provided a comparative assessment of engine knock performance with each of the 30 UL blends as compared to a baseline 100LL AVGAS.

6.3.5.1. Mixture Lean Out Test

The basic knock test procedure at both the FAA Technical Center and at Cessna Aircraft provided for conducting what aviation reciprocating engine engineers refer to as a “mixture lean out” wherein the fuel flow to the engine is reduced incrementally from the approximate full rich rating to the leanest point possible as limited by either severe engine knock or engine roughness, while monitoring combustion for indications of engine knock.

As background, conventional spark ignition general aviation engines are typically rated at 100% BHP referred to as maximum continuous BHP, with a full rich (FR) fuel mixture equivalent to .090 - .100 F/A which is a richer mixture than the best power fuel setting. Depending upon engine and aircraft models, the cruise lean fuel mixture may be manually set to correspond to 100°F rich of peak EGT (ROP), peak EGT, or 25°F – 50°F lean of peak EGT (LOP) for some later engine models; see Figure 14.0.

Figure 14.0 illustrates the generalized mixture characteristics representative of conventional general aviation spark ignition engines. Note that Figure 14.0 is a representation of reciprocating engine mixture characteristics; actual trends and values may differ depending upon engine model, combustion chamber configuration, and induction manifold design. The generalized mixture ratio curve is a graphical representation of aviation spark ignition engine mixture performance and effects, and is derived from the data developed during formal FAA certification. FAA regulations specify that mixture ratio curves (also referred to as mixture lean out) be conducted at various power settings sufficiently to define the mixture characteristics of the engine. The generalized mixture curve illustrates the response of BHP, BSFC, CHT, and EGT as the fuel flow is varied for conditions of fixed RPM and MAP. As shown in the test results reports, individual CHT and EGT values are plotted versus fuel flow[12-15]. This curve is also representative of cruise flight conditions where the cruise power setting sequence consists of first setting power using RPM and MAP while maintaining FR mixture, followed by leaning the mixture to the setting specified by the aircraft POH such as 100°F rich of Peak EGT, peak EGT, or 25°F - 50°F lean of peak EGT as allowed by some later model engines.

Figure 14.0 can also be used to model or predict engine BHP and BSFC performance at other F/A settings. For conditions of fixed RPM and MAP (as obtainable on an aircraft equipped with a constant speed propeller), the engine airflow is constant with the only variable being fuel mass flow. Knowing the BHP, EGT, CHT at a given F/A or fuel flow, Figure 14.0 can then be used to estimate BHP, BSFC, EGT, and CHT at other F/A or fuel flow for the conditions of constant MAP and RPM.

FAA AFETF and the Cessna Phase II lean out curves performed during knock testing (see Section 6.5.4) represent a derivative of Figure 14.0 since hottest CHT was maintained at limit value during the FAA testing by adjusting the amount of cooling airflow provided to the cylinders using a test facility adjustable cooling air blower. Similarly, the lean outs performed during the Cessna testing present a derivative of Figure 14.0 since the engine was configured with a fixed pitch propeller where RPM varied while using the throttle to maintain the test condition MAP as fuel flow was leaned.

The mixture lean out test and the associated generalized mixture ratio curve offer the aircraft engine engineer an effective tool for evaluating engine mixture characteristics in addition to serving as a tool for modeling engine performance at other fuel flow settings. The utility, in the case of the CRC full scale engine testing, provided the basis for consistently evaluating engine knock for multiple fuels as a function of F/A.

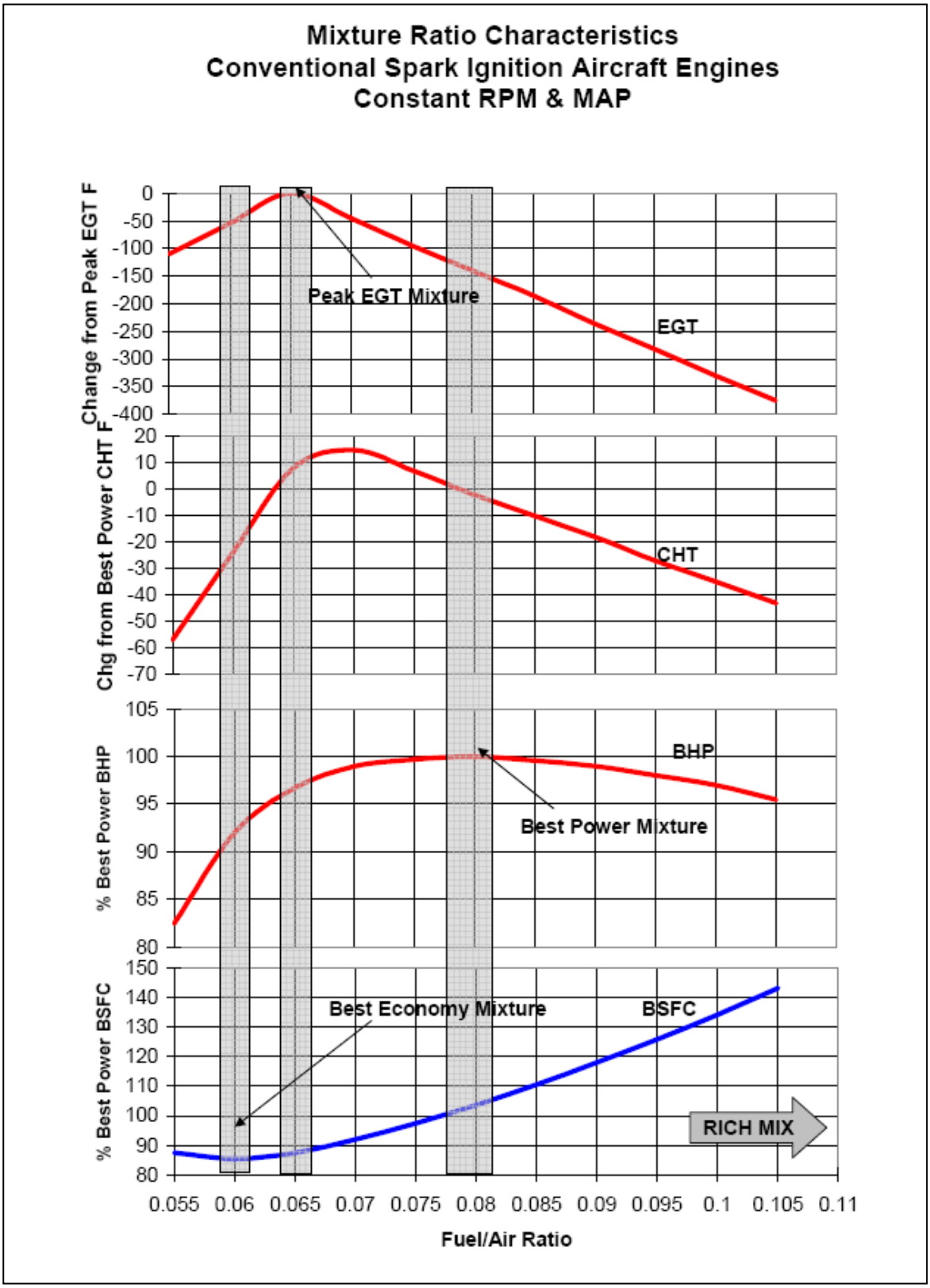

Figure 14.0
Aviation Spark Ignition Engine
Mixture Characteristics

6.3.5.2. FAA Technical Center AFETF Test Procedures

The following procedures including instrumentation and test protocol were followed by the FAA Technical Center's AFETF during full scale engine testing of the Phase II, Phase III, and Phase IV unleaded fuel research projects. The Textron Lycoming model IO-540-K engine was used for each of the test phases with a Lycoming model IO-320-B also used for Phase IV testing. Engine instrumentation for each of the tests included those parameters listed in Table 4.0 which are extracted from the instrumentation lists in each of the respective FAA Reports [12][14][15]. As described in Section 6.3.4.1, each cylinder head was instrumented to include a piezoelectric pressure transducer for monitoring of combustion pressure as a means of indicating engine knock. The order of fuel test sequence was controlled to minimize the risk of lead carry-over and to verify repeatability. The test sequence followed for the Phase II 30 UL blends and the Phase III 47 UL blends is outlined in Table 5.0.

The procedure for conducting the knock tests of the UL blends involved setting the power level and leaning the fuel flow in increments of 5% beginning at or near the full rich setting and continuing to lean until heavy knock or instability was encountered while maintaining 103°F ±3°F induction air temperature at the inlet of the engine throttle body with CHT (hottest head) and oil temperature maintained at limit values. Hottest CHT was maintained at 475°F ±3°F with the other CHT maintained within 50°F of the hottest CHT. Oil temperature into the engine maintained at 245°F +10/-0°F for all knock testing. Induction air relative humidity was maintained at less than 5% using the test cell equipment.

For each of the fuel flow settings described in the above procedure, the display of combustion pressure versus crank angle (see Figure 10.0) as provided by the cylinder head pressure transducer was monitored for signs of engine knock. Once each lean fuel flow setting had stabilized, combustion pressures were observed for signs of knock; an indication of knock was then analyzed and graded for severity in accordance with the process described in the FAA reports [12][14][15].

Table 4.0
Engine Instrumentation List
FAA AFETF IO-540-K Engine

Instrumentation	Symbol	Units	Location
Cylinder Head Temp 1-6	CHT	°F	Cylinder Head
Exhaust Gas Temp 1-6	EGT	°F	Exhaust Stack Within 2" of Flange
Induction Air Temp	IAT	°F	Intake air duct just upstream of throttle
Induction Air Pressure	IAP	In. Hg. Abs	Intake air duct just upstream of throttle
Induction Air Relative Humidity	-	-	Intake air ducting upstream of engine
Mass Air Flow	K	Lbs/Hr	Intake air duct upstream of engine
Air/Fuel Ratio	A/F	Calculated	Calculated
Manifold Pressure	MAP	In. Hg. Abs	Engine Intake Plenum

Engine Speed RPM	RPM	RPM	Dynamometer Shaft
Engine Torque	TORK	Ft-lbs	Dynamometer Load Cell
Brake Horsepower	BHP	Calculated	Calculated using TORK & RPM
Fuel Flow	FF	Lbs/hr	Mass flow meter after metering unit
Oil Temp	Oil T	°F	To engine from cooler
Oil Pressure	Oil P	psig	Accessory Case

Table 5.0
FAA AFETF Test Sequence
Testing of Phase II & Phase III UL Blends

Sequence	Test Description
1	Baseline Power Calibration With 100LL
2	Octane Rate Engine Per ASTM D 6424 Using Unleaded Ref Fuels
3	Knock Test Engine Using UL Blends 3.1 100% BHP, 2700 RPM 3.2 85% BHP, 2600 RPM 3.3 75% BHP, 2450 RPM 3.4 65% BHP, 2350 RPM
4	Octane Rate Engine Per ASTM D 6424 Using Unleaded Ref Fuels
5	Knock Test Engine Using Min Spec 100LL 4.1 100% BHP, 2700 RPM 4.2 85% BHP, 2600 RPM 4.3 75% BHP, 2450 RPM 4.4 65% BHP, 2350 RPM
6	Octane Rate Engine Using Leaded Ref Fuels

6.3.5.3. Cessna Aircraft Test Procedures

The following procedures including instrumentation and test protocol were followed by Cessna Aircraft during full scale engine testing of the Phase II unleaded fuels. See Section D of the Cessna report, reference 13, for a complete description of the Cessna test protocol. A Textron Lycoming model IO-360-X124 engine was used for the Cessna 30 UL fuel matrix test program. Engine instrumentation for the Cessna test included those parameters listed in Table 6.0 which are extracted from the instrumentation lists contained in the Cessna Test Results Report [13]. Cessna sequence of testing of the Phase II 30 UL blends is outlined in Table 7.0.

Table 6.0 Engine Instrumentation List Cessna Test Rig, Lycoming IO-360-X124 Engine			
Instrumentation	**Symbol**	**Units**	**Location**
Cylinder Head Temp 1-4	CHT	°F	Cylinder Head
Exhaust Gas Temp 1-4	EGT	°F	Exhaust Stack Within 2" of Flange
Intake Air Temp	IAT	°F	Intake duct just upstream of throttle
Intake Air Pressure	IAP	In. Hg. Abs	Intake duct just upstream of throttle
Mass Air Flow	N/A	N/A	N/A
Air/Fuel Ratio	A/F	N/A	N/A
Manifold Pressure	MAP	In. Hg. Abs	Engine Intake Plenum
Engine Speed RPM	RPM	RPM	Engine Tachometer
Engine Torque	TORQ	Ft-lbs	Torquemeter between engine & propeller
Brake Horsepower	HP	Calculated	Calculated using TORQ & RPM
Fuel Flow	FMFR	Lbs/hr	Flowmeter
Fuel Flow	FVFR	Gals/hr	Calculated
Oil Temp	Oil T	°F	Into Engine
Oil Pressure	Oil P	psig	Engine

The Cessna procedure for conducting the knock tests of the 30 UL blends involved setting the power level using the engine throttle and leaning the fuel flow in increments of 3-5% full rich fuel flow (approximately 0.5 GPH) beginning at or near the full rich setting and continuing to lean until heavy knock or until detonation free operation re-emerged on the lean side of best power while maintaining 230°F ±2°F induction air temperature at the inlet of the engine throttle body. CHT were not controlled but were allowed to respond naturally to change in fuel mixture. Cessna test management (see Section D of reference 13) required the engine CHT be within 50°F of the hottest CHT and that CHT and oil temperature into the engine be stabilized at 400°F and 200°F respectively prior to beginning a test. Induction air relative humidity was not controlled but was documented for the ambient air conditions for each test. Back to back testing of the baseline 100LL and the test fuel ensured uniformity in ambient pressure and humidity. Cessna testing of each unleaded fuel was performed at three separate power settings which were established by setting manifold pressure (27 MAP, 25.5 MAP, & 24 MAP) using the engine throttle with the fixed pitch propeller loading the engine at the resulting engine speed.

Whereas the Cessna test method relied upon a fix pitch propeller to load the engine, the resulting engine performance followed the classical propeller load curve (Figure 15.0) as fuel flow was leaned during the fuel detonation test. To accommodate the multiple variables of BHP

and RPM, engine loading was characterized in terms of BMEP using the equation of Figure 16.0; see also Figure 2A, Section A of reference 13.

$$BHP_2 = BHP_1 \times [RPM_2/RPM_1]^3$$

Where BHP = TORQUE X RPM/ 5252

& TORQUE = FT-LBS

Figure 15.0 – Propeller Load Curve Relationship

BMEP = [972000 X BHP]/ [Displacement X RPM]

Where Displacement = Cubic Inches

Figure 16.0 – Engine BMEP Computation

Table 7.0
Cessna Test Sequence
Testing of Phase II UL Blends

Sequence	Test Description
1	Knock Test Engine Using UL Blends 1.1 27 MAP 1.2 25.5 MAP 1.3 24 MAP
2	Knock Test Engine Using Baseline 100LL 2.1 27 MAP 2.2 25.5 MAP 2.3 24 MAP
Test Conditions: 1) Fixed pitch propeller; 2) Fixed throttle position for each MAP setting; 3) Engine loading expressed in terms of BMEP = f (BHP, RPM)	

For each fuel flow setting described in the above Cessna test procedure, each cylinder was monitored for indication of knock using the Cessna CEDI Model 422M100 engine detonation indication system which senses combustion knock using a force (pressure) sensitive washer located under one spark plug of each cylinder. Figure 17.0 illustrates the force sensitive washer, charge amplifier, and digital display of knock intensity for a single cylinder. Combustion intensity numbers displayed on the CEDI digital display panel indicators were recorded using a data acquisition system as described in the reference 13 report.

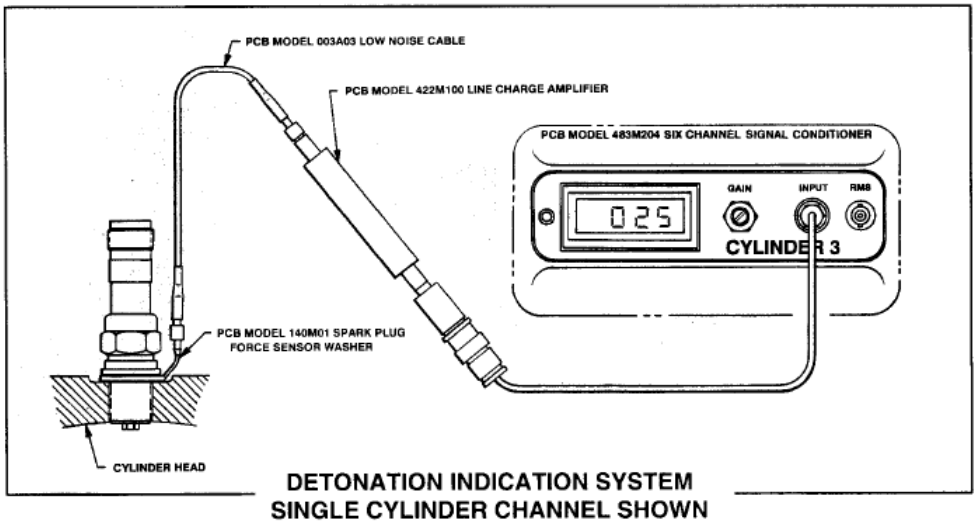

Figure 17.0
Cessna Engine Detonation Indication System

6.4. PHASE I Results – MON Lab Tests 202 UL Blends

6.4.1. Background

The first research project involving testing of unleaded AVGAS alternatives was launched during the fourth quarter of YR2000 following a September 2000 meeting of the CRC Unleaded AVGAS Development Group at the FAA William J. Hughes Technical Center[17] ,and a subsequent November 2000 [18] meeting of the CRC UL AVGAS Task Group which finalized and implemented plans for the CRC Phase I Research Project.

During a September 6-7, 2000 meeting of the CRC Unleaded AVGAS Development Group at the FAA William J. Hughes Technical Center, it was agreed that a working group consisting of those organizations and individuals interested in participating in a collaborative MON screening test of unleaded aviation gasoline blends, would meet later in the fall of YR2000 with the objective of formulating a test plan and logistics for implementing MON testing of the UL AVGAS matrix developed during the September 6-7, 2000 meeting. It was further agreed during the September 6-7 meeting that ConocoPhillips would investigate options for conducting the MON screening test as a design experiment and provide recommendations to the CRC research group. A meeting of the CRC UL AVGAS Task Group (a working group subcommittee of the CRC UL AVGAS Development Group) was subsequently held on November 8, 2000 at which time a firm plan was implemented for the Phase I Research Project.

NOTE……Phase I Research provided for laboratory MON screening of 202 unleaded fuel blends. Test criteria was blend MON performance in accordance with ASTM D 2700 Standard Test Method.

Discussions during the CRC Unleaded AVGAS Development Group meeting of September 6-7, 2000 led to development of a matrix of technically viable base fuels and blend components described as the Primary Matrix which is included in this report as Table 8.0; the additives and base fuels identified were based upon octane quality as being the primary requirement. Several compounds were noted as being "non-consensus". The Primary Matrix was further refined during the September 2000 meeting into a more manageable structure, Matrix Subsets, Table 9.0, which segregated the technically viable compounds into petroleum based and non-petroleum based fuel groups. Several changes to the above matrices were debated and subsequently agreed upon by the CRC Task Group. With consideration to the well funded ethanol research projects in effect at that time and the issues associated with ethanol as a primary base fuel, the decision was made to focus on the petroleum based matrix for the MON screening test. It was further agreed both Motor Alkylate and the metal based compound MMT would be included in the Petroleum Based category of the Matrix Subsets as a technically viable base fuel and additive respectively.

Table 8.0
September 7, 2000
Primary Matrix [17]
Technically Viable Base Fuels & Additives

ADDITIVE	***BASE FUEL***				
	(A) Aviation Alkylate	**(B) Motor Alkylate**	**(C) Super Alkylate**	**(D) Ethanol**	**(E) ETBE**
1) Super Alkylate	0-50% (vol)	0-50% (vol)	N/A	N/A	N/A
2) Toluene	0-25% (vol)	0-25% (vol)	0-25% (vol)	N/A	N/A
3) ETBE	0-30% (vol)	0-30% (vol)	0-30% (vol)	N/A	N/A
4) *m*-Toluidine ①	0-10% (wgt)	0-10% (wgt)	0-10% (wgt)	N/A	N/A
5) Ethanol ①	0-5% (vol)	0-5% (vol)	0-5% (vol)	N/A	N/A
6) MMT ①	0-0.1% g/gal	0-0.1% g/gal	0-0.1% g/gal	N/A	N/A
7) *iso*-Pentane	N/A	N/A	N/A	0-15% (vol)	N/A
8) *n*-Butane	0-10% (vol)	0-10% (vol)	0-10% (vol)	N/A	0-5% (vol)
9) Bio-Diesel	N/A	N/A	N/A	0-1% (vol)	N/A

Notes: ① Indicates non-consensus component
② Test Method – MON, Supercharge, Full Engine, or Other
③ The above extracted from Appendix G, CRC Meeting Minutes Sept. 7, 2000 [17]

Table 9.0 September 7, 2000 Matrix Subsets [17] Grouped for Manageable Test Plan					
	BASE FUEL				
	PETROLEUM BASED			***NON-PETROLEUM BASED***	
	1st Test Group	**Test Group TBD**	**2nd Test Group**	**3rd Test Group**	**4th Test Group**
ADDITIVE	**(A) Aviation Alkylate**	**(B) Motor Alkylate**	**(C) Super Alkylate**	**(D) Ethanol**	**(E) ETBE**
Toluene	0-25% (vol)	0-25% (vol)	0-25% (vol)	N/A	N/A
ETBE	0-30% (vol)	0-30% (vol)	0-30% (vol)	N/A	N/A
m-Toluidine ①	0-10% (vol)	0-10% (vol)	0-10% (vol)	N/A	N/A
iso-Pentane	N/A	N/A	N/A	0-15% (vol)	N/A
n-Butane	0-10% (vol)	0-10% (vol)	0-10% (vol)	N/A	0-5% (vol)
Bio-Diesel	N/A	N/A	N/A	0-1% (vol)	N/A
Notes: ① Indicates non-consensus component ② The above extracted from Appendix H, CRC Meeting Minutes Sept. 7, 2000 [17]					

Pursuant to a November 2000 meeting of the CRC UL AVGAS Task Group, an updated matrix identified as CRC Phase I Unleaded AVGAS Test Matrix, dated November 8, 2000, was created and is included below as Table 10.0. This matrix represents the refined matrix of base fuels and additives that served as the basis for the Phase I MON screening research project. This matrix identifies the blend components and their respective boundaries for blend compositions.

Table 10.0 November 8, 2000 CRC Phase I Unleaded AVGAS Test Matrix Aklylate & Blend Component Boundaries [18]			
	BASE FUEL		
ADDITIVE	**(A) Aviation Alkylate**	**(B) Motor Alkylate**	**(C) Super Alkylate**
Super Alkylate % vol	0 - 50%	0 - 50%	N/A
Toluene % vol	0 - 25%	0 - 25%	0 - 25%
ETBE % vol	0 - 30%	0 - 30%	0 - 30%
m-Toluidine % vol	0 - 10%	0 - 10%	0 - 10%

Ethanol % vol	0 - 5%	0 - 5%	0 - 5%
Manganese, g Mn/gal	0 - 0.1	0 - 0.1	0 - 0.1

Notes:
① Above matrix was finalized and agreed upon during the November 7, 2000 meeting
② Test Method – MON screening using ASTM D 2700 test method
③ Participants – Dixie Services, ChevronTexaco, Ethyl, ExxonMobil, Cessna, ChevronTexaco, FAA Technical Center, Lyondell Chemical, Ultramar Diamond, ConocoPhillips
④ Contents extracted from Appendix D, CRC Meeting Minutes Nov. 8, 2000 [17]

6.4.2. Research Plan

The Phase I Research Plan was implemented as an industry collaborative effort. Objective of the Phase I research was to conduct motor octane number (MON) screening ONLY of the unleaded blends derived from the Table 10.0 Matrix in accordance with ASTM D 2700. Although it was recognized that other fuel properties such as volatility, vapor pressure, and heating value are critical to an acceptable AVGAS, the objective of the Phase I project was to explore the relationships and influences of the various blend components relative to MON. [10] Logistics, member assignments, time frame, and funding for executing the MON screening were identified by the research plan. A single independent laboratory was designated by the Task Group to conduct the blending, component property analysis, and the ASTM D 2700 motor octane number tests. Funding support for the laboratory analysis and testing was provided by the FAA Technical Center. Blend components and base fuels were provided by member organizations as identified in the Table 11.0 Logistics Plan. Using the boundary conditions of the Table 10.0 Matrix, a design experiment was developed to accommodate and evaluate the range of compositions relative to MON performance only.

6.4.2.1. Matrix Components

The Phase I test matrix involved the use of three base fuel components which are described in the Appendix A report as follows. [10]

> ***"AVIATION ALKYLATE -*** a petroleum refinery produced stream that is a major component of current aviation gasolines. It consists of a mixture, primarily of branched hydrocarbons, with a high concentration of iso-octane. (Iso-octane, 2,2,4-trimethylpentane, possesses excellent anti-knocking properties. The pure compound is a primary reference fuel used in the ASTM test methods for determining octane ratings for both aviation and motor gasolines, having a defined value of 100 octane.)"
>
> ***"MOTOR ALKYLATE –*** a similar refinery produced stream that is an important component of automobile gasolines. Motor alkylate differs from aviation alkylate in that it contains a wider range of compounds including more low and high boiling components, which typically results in slightly lower octane values than aviation alkylate."
>
> ***"SUPER ALKYLATE –*** a term used to describe a potential chemical stream that could be used as a high octane blending component in automobile gasoline. It is currently produced by dimerization of isobutylene with subsequent hydrogenation of the reaction mixture. The resulting product stream contains over 90% iso-octane and therefore possesses a higher octane value than aviation alkylate." Super alkylate was selected as a candidate component at the beginning of the CRC research in consideration that

plants previously committed to production of MTBE might be converted to make super alkylate; this production capability ultimately did not materialize.

Five different components were included in the Phase I matrix as blend agents with the objective of evaluating their contribution to octane enhancement of the resulting blend. These components which are described below are classified as aromatic hydrocarbons, ethers, alcohols, aromatic amines, and organometallic manganese compounds. [10]

> ***"TOLUENE –*** selected as the aromatic hydrocarbon based upon its wide use in current aviation gasolines."
>
> "***ETBE -*** Ethyl-*tertiary*-butyl ether produced from ethanol and isobutylene in refinery located or independent production facilities, was selected as the ether based compound based on its known value as an octane enhancing component in automobile gasolines."
>
> ***"meta*-Toluidine (3-aminotoluene, 3-methylaniline)** – was selected as the aromatic amine based on its octane improving performance in a preliminary study conducted by the Task Group several years earlier in which nine blends of aviation alkylate, *meta*-toluidine and methyl-*tertiary*-butyl ether were tested for motor octane number."
>
> ***"ETHANOL*** – (ethyl alcohol) was a preferred choice for the alcohol component because of its history of use in automobile gasolines."
>
> ***"MMT*** – Methylcyclopentadienyl manganese tricarbonyl was selected for evaluation as a non-lead metal based octane improver based on its history of use in automobile gasoline."

6.4.2.2. Design Experiment

Integral to the research plan was implementation of the MON test matrix as a design experiment. The experimental design for the Phase I matrix was based on mixture and cubic design structures which resulted in 75 fuel blends including replicates for the seven component aviation and motor alkylate matrix, and 52 blends including replicates for the six component super alkylate matrix. [10][24] Replicate blends were included in each matrix to assess experimental error resulting in a total of 202 test blends.[10] Resulting blends and their compositions are contained in Exhibit II of Appendix A. See also the presentation included in Appendix C for further discussion on the design experiment.

6.4.2.3. Logistics Plan

The Phase I Research Plan provided for a fuel matrix structured around three base fuels (aviation alkylate, motor alkylate, and super alkylate) using six different octane enhancing components as listed in Table 10.0. Component materials used in preparation of the test blends were provided by the CRC UL AVGAS Task Group members. A single independent laboratory, Dixie Services, was commissioned by the Task Group to formulate the blends and to conduct the specified testing consisting of motor octane number testing of each blend in accordance with ASTM D 2700. Laboratory testing included testing of blend components for physical properties as listed in Exhibit I of Appendix A. Logistics were agreed upon with each member organization providing the fuel, component, or service as summarized in the Table 11.0 Logistics Plan.

Table 11.0 CRC Phase I Logistics Plan	
Task Group Member	**Component, Material, Service Provided**
Cessna Aircraft	Ethanol
ChevronTexaco	Motor Alkylate
ConocoPhillips	Design Experiment, Statistical Analysis of Results
ConocoPhillips	Aviation Alkylate, ETBE
Dixie Services	Component Physical Property Tests, Blending
Dixie Services	MON Testing
Ethyl Corp.	MMT (Manganese)
ExxonMobil	*meta*-Toluidine
FAA Tech Center AFETF	Funding for MON D 2700 testing
Lyondell Chemical	Super Alkylate
Ultramar Diamond Shamrock	Toluene

6.4.3. Test Results

Phase I testing was initiated in March 2001 and was completed during April 2001 at the laboratory facilities of Dixie Services in Galena Park, Texas. Results of the component property analyses and the MON testing of the unleaded blends are documented in the Reference 10 report by Dixie Services dated November 2004 which is attached as Appendix A. Exhibit II of Appendix A identifies the blend compositions as derived from the design experiment along with the associated MON rating as determined by ASTM D 2700 for each of the 202 mixtures. The Exhibit II mixture compositions and MON test results were distributed to the CRC Task Group Membership in May 2001 for review and comments. The Exhibit II MON results are further discussed in the following Section 6.4.3.2.

6.4.3.1. Blend Component Properties

Blend component physical properties including motor octane number as determined by the applicable ASTM test method are summarized below in Table 12.0 which is extracted from Exhibit I of Appendix A. ETBE analysis was conducted by test method ASTM D 5441 (MTBE gas chromatography method), but calibrated for impurities typical of ETBE. [(10)]

Table 12.0
Phase I MON Testing 202 Unleaded Blends
Component Properties [(10)]

ASTM Test Method	Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	Ethanol	*meta*-Toluidine
D 4052 Relative Density, 15.56ºC	0.6949	0.6928	0.7001	0.8718	0.7468	0.7940	0.9934
D 4052 API Gravity °	72.1	72.8	70.6	30.8	58	46.7	10.9
D 5191 Vapor Press, DVPE, psi	4.84	8.59	1.78	0.88	4.54	2.16	< 0.10
D 2699 Research Octane Number	93.4	93.6	100.5	116.7	111.1	107.2	NA
D 2700 Motor Octane Number	91.5	91.3	99.6	108.3	97.8	93.0	NA

E 1064 Water Content, mass %	NA	NA	NA	NA	0.0485	0.0903	NA
D 2360 Toluene Content, mass %	NA	NA	NA	99.94	NA	NA	NA
D 5441* ETBE Content, mass %	NA	NA	NA	NA	97.03	NA	NA
D 5501 Ethanol Content, mass %	NA	NA	NA	NA	NA	99.69	NA
D 850 Distillation Range, °C	NA	NA	NA	0.6	NA	NA	NA
D 86 Distillation, % evaporated °C	-	-	-	-	-	-	-
IBP	43.5	32.0	97.0	-	68.5	-	-
5	66.0	50.5	97.5	-	70.0	-	-
10	77.5	62.5	98.0	-	70.5	-	-
20	87.0	81.0	98.0	-	71.0	-	-
30	92.0	91.0	98.5	-	71.0	-	-
40	96.0	95.5	99.0	-	71.5	-	-
50	98.5	99.0	99.5	-	71.5	-	-
60	100.5	101.0	100.0	-	72.0	-	-
70	102.5	104.5	100.5	-	72.5	-	-
80	105.5	109.0	102.0	-	72.5	-	-
90	111.5	121.5	107.5	-	73.0	-	-
95	121.0	157.0	124.0	-	74.5	-	-
End	148.0	187.5	192.5	-	85.5	-	-
Recovery	98.0	97.9	99.1	-	99.1	-	-
Residue	1.4	1.2	0.8	-	0.8	-	-
Loss	0.6	0.9	0.1	-	0.1	-	-

6.4.3.2. Blend MON Results

Resulting motor octane numbers for each of the 202 unleaded fuel blends as determined by ASTM D 2700 laboratory testing are summarized in Exhibit II of Appendix A. The following Tables 13.0 through 20.0 represent MON ranking of the Exhibit II test results data as related to effect of certain components and component combinations.

Table 13.0 illustrates MON ranking for Aviation Alkylate blends No. 1 -75. Table 14.0 ranks MON for Aviation Alkylate blends 1-75 for the condition of 0 % super alkylate. Table 15.0 indicates MON values for Aviation Alkylate blends for the condition of 0 % super alkylate, 0 % m-Toluidine, and 0 % MMT.

Table 16.0 illustrates MON ranking for Motor Alkylate blends No. 76-150. Table 17.0 ranks MON for Motor Alkylate blends 76 - 150 for the condition of 0 % super alkylate. Table 18.0 indicates MON values for Motor Alkylate blends for the condition of 0 % super alkylate, 0 % m-Toluidine, and 0 % MMT.

Table 19.0 illustrates MON ranking for Super Alkylate blends 151 – 202. Table 20.0 ranks MON for Super Alkylate blends for the conditions of 0 % m-Toluidine and 0 % MMT.

Table 13.0
Phase I **Aviation Alkylate Blends No. 1 - 75**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED BY MON

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
49	1.000	0.000	0.000	0.000	0.000	0.000	0.051	92.16
64	0.616	0.176	0.158	0.000	0.000	0.050	0.001	93.32

17	0.700	0.000	0.250	0.000	0.000	0.050	0.100	93.69
71	0.629	0.250	0.053	0.062	0.000	0.006	0.000	94.48
30	0.461	0.079	0.195	0.231	0.000	0.034	0.000	94.71
44	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.90
16	0.650	0.000	0.000	0.300	0.000	0.050	0.000	95.10
52	0.729	0.000	0.197	0.051	0.022	0.002	0.000	95.34
72	0.450	0.500	0.000	0.000	0.000	0.050	0.000	95.71
48	0.753	0.000	0.056	0.178	0.000	0.013	0.100	95.74
7	0.250	0.500	0.250	0.000	0.000	0.000	0.000	95.87
46	0.583	0.144	0.248	0.000	0.015	0.011	0.085	96.42
39	0.743	0.133	0.000	0.078	0.010	0.035	0.078	96.55
27	0.244	0.389	0.250	0.085	0.000	0.032	0.040	96.74
37	0.364	0.260	0.197	0.177	0.003	0.000	0.065	96.98
12	0.073	0.328	0.250	0.300	0.000	0.050	0.033	97.26
63	0.348	0.500	0.122	0.000	0.007	0.023	0.056	97.34
40	0.652	0.021	0.127	0.121	0.029	0.050	0.052	97.50
28	0.453	0.500	0.000	0.047	0.000	0.000	0.100	97.61
38	0.871	0.000	0.053	0.000	0.041	0.036	0.000	97.67
35	0.466	0.219	0.010	0.300	0.005	0.000	0.082	97.93
9	0.871	0.000	0.053	0.000	0.041	0.036	0.000	97.96
2	0.306	0.366	0.069	0.212	0.000	0.047	0.100	98.18
29	0.347	0.079	0.241	0.271	0.025	0.038	0.100	98.32
43	0.748	0.015	0.000	0.200	0.037	0.000	0.000	98.34
36	0.253	0.497	0.000	0.230	0.000	0.020	0.027	98.50
3	0.514	0.008	0.134	0.300	0.034	0.011	0.041	98.64
5	0.061	0.500	0.201	0.174	0.013	0.050	0.000	98.96
25	0.000	0.500	0.189	0.300	0.000	0.011	0.100	99.64
19	0.336	0.378	0.200	0.005	0.033	0.048	0.100	100.00
32	0.574	0.375	0.000	0.000	0.040	0.012	0.045	100.37
45	0.164	0.388	0.084	0.300	0.028	0.036	0.000	100.54
26	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.57
60	0.127	0.338	0.250	0.241	0.034	0.011	0.000	100.64
73	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.70
23	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.89
4	0.494	0.118	0.250	0.032	0.064	0.043	0.021	100.94
18	0.215	0.500	0.107	0.141	0.035	0.002	0.048	100.94
8	0.333	0.288	0.138	0.168	0.050	0.025	0.050	101.01
47	0.333	0.288	0.138	0.168	0.050	0.025	0.050	101.06
69	0.418	0.275	0.000	0.208	0.049	0.050	0.002	101.08
10	0.725	0.106	0.065	0.037	0.067	0.000	0.100	101.17
70	0.505	0.000	0.245	0.169	0.073	0.008	0.078	101.18
53	0.333	0.288	0.138	0.168	0.050	0.025	0.050	101.26
66	0.860	0.000	0.000	0.000	0.090	0.050	0.100	101.30
59	0.471	0.139	0.000	0.298	0.071	0.021	0.040	101.68
20	0.693	0.000	0.183	0.010	0.086	0.027	0.100	101.69
58	0.101	0.500	0.000	0.300	0.049	0.050	0.100	101.80
75	0.107	0.321	0.202	0.300	0.069	0.000	0.100	101.89
41	0.314	0.000	0.250	0.300	0.086	0.050	0.000	101.92
74	0.618	0.000	0.042	0.203	0.097	0.039	0.054	101.96

1	0.296	0.156	0.118	0.300	0.079	0.050	0.085	102.08
34	0.107	0.321	0.202	0.300	0.069	0.000	0.100	102.32
62	0.842	0.002	0.000	0.045	0.100	0.011	0.027	102.32
33	0.650	0.000	0.250	0.000	0.100	0.000	0.033	102.39
14	0.711	0.001	0.134	0.004	0.100	0.050	0.000	102.40
67	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.40
6	0.121	0.500	0.250	0.050	0.065	0.014	0.100	102.50
22	0.346	0.387	0.174	0.009	0.080	0.003	0.021	102.54
42	0.193	0.136	0.250	0.300	0.100	0.022	0.054	102.66
57	0.000	0.435	0.212	0.239	0.076	0.039	0.041	102.68
61	0.600	0.000	0.000	0.300	0.100	0.000	0.100	102.68
13	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.74
51	0.564	0.257	0.043	0.000	0.100	0.036	0.065	102.80
15	0.210	0.251	0.250	0.139	0.100	0.050	0.100	102.81
11	0.444	0.100	0.134	0.227	0.092	0.004	0.000	102.84
31	0.292	0.500	0.000	0.099	0.078	0.032	0.000	103.02
68	0.413	0.328	0.000	0.166	0.093	0.000	0.069	103.16
54	0.092	0.500	0.027	0.300	0.081	0.000	0.000	103.48
21	0.278	0.326	0.197	0.078	0.100	0.022	0.000	103.58
55	0.400	0.500	0.000	0.000	0.100	0.000	0.092	103.58
56	0.111	0.457	0.078	0.238	0.100	0.016	0.100	103.93
24	0.100	0.500	0.250	0.000	0.100	0.050	0.000	104.16
50	0.078	0.472	0.000	0.300	0.100	0.050	0.000	104.96
65	0.000	0.500	0.250	0.151	0.100	0.000	0.015	104.98

Table 14.0
Phase I **Aviation Alkylate Blends**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED FOR 0% SUPER ALKYLATE

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
49	1.000	0.000	0.000	0.000	0.000	0.000	0.051	92.16
17	0.700	0.000	0.250	0.000	0.000	0.050	0.100	93.69
44	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.90
16	0.650	0.000	0.000	0.300	0.000	0.050	0.000	95.10
52	0.729	0.000	0.197	0.051	0.022	0.002	0.000	95.34
48	0.753	0.000	0.056	0.178	0.000	0.013	0.100	95.74
38	0.871	0.000	0.053	0.000	0.041	0.036	0.000	97.67
9	0.871	0.000	0.053	0.000	0.041	0.036	0.000	97.96
70	0.505	0.000	0.245	0.169	0.073	0.008	0.078	101.18
66	0.860	0.000	0.000	0.000	0.090	0.050	0.100	101.30
20	0.693	0.000	0.183	0.010	0.086	0.027	0.100	101.69
41	0.314	0.000	0.250	0.300	0.086	0.050	0.000	101.92
74	0.618	0.000	0.042	0.203	0.097	0.039	0.054	101.96
33	0.650	0.000	0.250	0.000	0.100	0.000	0.033	102.39
61	0.600	0.000	0.000	0.300	0.100	0.000	0.100	102.68

Table 15.0
Phase I Aviation **Alkylate Blends**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED FOR 0% SUPER ALKYLATE, 0% M-Toluidine, 0% MMT

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
44	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.90
16	0.650	0.000	0.000	0.300	0.000	0.050	0.000	95.10

Table 16.0
Phase I **Motor Alkylate Blends No. 76 - 150**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED BY MON

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
124	1.000	0.000	0.000	0.000	0.000	0.000	0.051	92.16
139	0.616	0.176	0.158	0.000	0.000	0.050	0.001	93.03
92	0.700	0.000	0.250	0.000	0.000	0.050	0.100	93.41
146	0.629	0.250	0.053	0.062	0.000	0.006	0.000	93.86
119	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.44
105	0.461	0.079	0.195	0.231	0.000	0.034	0.000	94.47
91	0.650	0.000	0.000	0.300	0.000	0.050	0.000	94.94
127	0.729	0.000	0.197	0.051	0.022	0.002	0.000	95.05
123	0.753	0.000	0.056	0.178	0.000	0.013	0.100	95.09
147	0.450	0.500	0.000	0.000	0.000	0.050	0.000	95.64
82	0.250	0.500	0.250	0.000	0.000	0.000	0.000	95.66
114	0.743	0.133	0.000	0.078	0.010	0.035	0.078	96.00
121	0.583	0.144	0.248	0.000	0.015	0.011	0.085	96.00
102	0.244	0.389	0.250	0.085	0.000	0.032	0.040	96.28
112	0.364	0.260	0.197	0.177	0.003	0.000	0.065	96.42
113	0.871	0.000	0.053	0.000	0.041	0.036	0.000	96.50
84	0.871	0.000	0.053	0.000	0.041	0.036	0.000	96.88
115	0.652	0.021	0.127	0.121	0.029	0.050	0.052	96.90
138	0.348	0.500	0.122	0.000	0.007	0.023	0.056	97.33
103	0.453	0.500	0.000	0.047	0.000	0.000	0.100	97.55
87	0.073	0.328	0.250	0.300	0.000	0.050	0.033	97.66
110	0.466	0.219	0.010	0.300	0.005	0.000	0.082	97.82
77	0.306	0.366	0.069	0.212	0.000	0.047	0.100	98.00
78	0.514	0.008	0.134	0.300	0.034	0.011	0.041	98.06
118	0.748	0.015	0.000	0.200	0.037	0.000	0.000	98.13
104	0.347	0.079	0.241	0.271	0.025	0.038	0.100	98.21
111	0.253	0.497	0.000	0.230	0.000	0.020	0.027	98.41
80	0.061	0.500	0.201	0.174	0.013	0.050	0.000	99.22
94	0.336	0.378	0.200	0.005	0.033	0.048	0.100	99.35
100	0.000	0.500	0.189	0.300	0.000	0.011	0.100	100.00

120	0.164	0.388	0.084	0.300	0.028	0.036	0.000	100.09
107	0.574	0.375	0.000	0.000	0.040	0.012	0.045	100.14
85	0.725	0.106	0.065	0.037	0.067	0.000	0.100	100.48
135	0.127	0.338	0.250	0.241	0.034	0.011	0.000	100.51
79	0.494	0.118	0.250	0.032	0.064	0.043	0.021	100.61
144	0.418	0.275	0.000	0.208	0.049	0.050	0.002	100.62
98	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.64
101	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.64
145	0.505	0.000	0.245	0.169	0.073	0.008	0.078	100.80
148	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.83
122	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.86
93	0.215	0.500	0.107	0.141	0.035	0.002	0.048	100.87
95	0.693	0.000	0.183	0.010	0.086	0.027	0.100	100.88
128	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.90
83	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.96
141	0.860	0.000	0.000	0.000	0.090	0.050	0.100	101.02
134	0.471	0.139	0.000	0.298	0.071	0.021	0.040	101.54
76	0.296	0.156	0.118	0.300	0.079	0.050	0.085	101.66
89	0.711	0.001	0.134	0.004	0.100	0.050	0.000	101.74
133	0.101	0.500	0.000	0.300	0.049	0.050	0.100	101.76
116	0.314	0.000	0.250	0.300	0.086	0.050	0.000	101.84
108	0.650	0.000	0.250	0.000	0.100	0.000	0.033	101.86
81	0.121	0.500	0.250	0.050	0.065	0.014	0.100	101.92
137	0.842	0.002	0.000	0.045	0.100	0.011	0.027	101.92
149	0.618	0.000	0.042	0.203	0.097	0.039	0.054	101.95
150	0.107	0.321	0.202	0.300	0.069	0.000	0.100	102.06
126	0.564	0.257	0.043	0.000	0.100	0.036	0.065	102.07
109	0.107	0.321	0.202	0.300	0.069	0.000	0.100	102.08
136	0.600	0.000	0.000	0.300	0.100	0.000	0.100	102.18
97	0.346	0.387	0.174	0.009	0.080	0.003	0.021	102.34
86	0.444	0.100	0.134	0.227	0.092	0.004	0.000	102.41
90	0.210	0.251	0.250	0.139	0.100	0.050	0.100	102.44
88	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.46
117	0.193	0.136	0.250	0.300	0.100	0.022	0.054	102.61
142	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.68
106	0.292	0.500	0.000	0.099	0.078	0.032	0.000	102.78
132	0.000	0.435	0.212	0.239	0.076	0.039	0.041	102.88
143	0.413	0.328	0.000	0.166	0.093	0.000	0.069	103.01
130	0.400	0.500	0.000	0.000	0.100	0.000	0.092	103.29
96	0.278	0.326	0.197	0.078	0.100	0.022	0.000	103.40
129	0.092	0.500	0.027	0.300	0.081	0.000	0.000	103.94
99	0.100	0.500	0.250	0.000	0.100	0.050	0.000	104.04
131	0.111	0.457	0.078	0.238	0.100	0.016	0.100	104.35
125	0.078	0.472	0.000	0.300	0.100	0.050	0.000	104.46
140	0.000	0.500	0.250	0.151	0.100	0.000	0.015	104.58

Table 17.0
Phase I **Motor Alkylate Blends**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED FOR 0 % SUPER ALKYLATE

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
124	1.000	0.000	0.000	0.000	0.000	0.000	0.051	92.16
92	0.700	0.000	0.250	0.000	0.000	0.050	0.100	93.41
119	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.44
91	0.650	0.000	0.000	0.300	0.000	0.050	0.000	94.94
127	0.729	0.000	0.197	0.051	0.022	0.002	0.000	95.05
123	0.753	0.000	0.056	0.178	0.000	0.013	0.100	95.09
113	0.871	0.000	0.053	0.000	0.041	0.036	0.000	96.50
84	0.871	0.000	0.053	0.000	0.041	0.036	0.000	96.88
145	0.505	0.000	0.245	0.169	0.073	0.008	0.078	100.80
95	0.693	0.000	0.183	0.010	0.086	0.027	0.100	100.88
141	0.860	0.000	0.000	0.000	0.090	0.050	0.100	101.02
116	0.314	0.000	0.250	0.300	0.086	0.050	0.000	101.84
108	0.650	0.000	0.250	0.000	0.100	0.000	0.033	101.86
149	0.618	0.000	0.042	0.203	0.097	0.039	0.054	101.95
136	0.600	0.000	0.000	0.300	0.100	0.000	0.100	102.18

Table 18.0
Phase I **Motor Alkylate Blends**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED FOR 0% SUPER ALKYLATE, 0% M-Toluidine, 0% MMT

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
119	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.44
91	0.650	0.000	0.000	0.300	0.000	0.050	0.000	94.94

Table 19.0
Phase I **Super Alkylate Blends No. 151 - 202**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED BY MON

Blend No.	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	**MON**
178	0.700	0.250	0.000	0.000	0.050	0.000	98.10
180	0.531	0.250	0.210	0.000	0.009	0.033	98.70
193	0.400	0.250	0.300	0.000	0.050	0.100	98.72
176	0.531	0.250	0.210	0.000	0.009	0.033	99.24
194	0.750	0.250	0.000	0.000	0.000	0.100	99.41
179	0.640	0.174	0.142	0.000	0.045	0.079	100.04

182	0.426	0.216	0.300	0.024	0.035	0.000	100.26
153	0.700	0.000	0.300	0.000	0.000	0.000	100.34
169	0.630	0.250	0.068	0.018	0.034	0.100	100.34
152	0.607	0.083	0.288	0.000	0.023	0.075	100.44
183	0.848	0.071	0.081	0.000	0.000	0.068	100.63
165	0.937	0.000	0.032	0.000	0.032	0.031	100.64
196	0.471	0.250	0.188	0.041	0.050	0.047	100.76
167	0.493	0.186	0.300	0.021	0.000	0.099	100.78
159	0.810	0.156	0.000	0.017	0.017	0.052	100.82
188	0.671	0.054	0.212	0.017	0.046	0.007	100.87
184	0.650	0.000	0.300	0.000	0.050	0.100	101.01
160	0.718	0.172	0.081	0.020	0.008	0.000	101.06
197	0.867	0.063	0.000	0.020	0.050	0.100	101.06
164	0.774	0.000	0.196	0.018	0.012	0.100	101.30
171	0.463	0.127	0.299	0.060	0.050	0.095	101.82
199	0.393	0.250	0.270	0.070	0.017	0.100	101.92
173	0.650	0.125	0.150	0.050	0.025	0.050	101.99
177	0.650	0.125	0.150	0.050	0.025	0.050	102.04
198	0.650	0.125	0.150	0.050	0.025	0.050	102.04
161	0.965	0.000	0.000	0.035	0.000	0.017	102.09
201	0.619	0.000	0.300	0.050	0.031	0.047	102.10
158	0.650	0.125	0.150	0.050	0.025	0.050	102.11
166	0.650	0.238	0.056	0.057	0.000	0.054	102.12
162	0.659	0.059	0.228	0.055	0.000	0.044	102.22
170	0.710	0.185	0.000	0.067	0.039	0.055	102.68
172	0.804	0.053	0.052	0.056	0.036	0.000	103.08
175	0.561	0.115	0.242	0.073	0.009	0.000	103.25
155	0.482	0.208	0.187	0.085	0.038	0.000	103.32
185	0.766	0.000	0.116	0.068	0.050	0.074	103.42
189	0.828	0.055	0.025	0.079	0.013	0.100	103.46
156	0.828	0.055	0.025	0.079	0.013	0.100	103.50
163	0.438	0.146	0.300	0.100	0.017	0.049	103.50
187	0.303	0.250	0.300	0.100	0.047	0.060	103.50
157	0.600	0.250	0.000	0.100	0.050	0.100	103.95
195	0.438	0.146	0.300	0.100	0.017	0.049	104.02
186	0.540	0.194	0.166	0.100	0.000	0.100	104.21
151	0.350	0.250	0.300	0.100	0.000	0.000	104.38
190	0.603	0.042	0.217	0.100	0.038	0.100	104.39
192	0.659	0.116	0.075	0.100	0.050	0.040	104.46
200	0.583	0.250	0.047	0.100	0.020	0.033	104.58
174	0.550	0.000	0.300	0.100	0.050	0.000	104.70
168	0.600	0.000	0.300	0.100	0.000	0.100	104.72
191	0.855	0.000	0.000	0.100	0.045	0.039	104.91
202	0.550	0.000	0.300	0.100	0.050	0.000	104.92
181	0.764	0.000	0.126	0.100	0.010	0.025	105.06
154	0.773	0.128	0.000	0.100	0.000	0.000	105.69

Table 20.0
Phase I **Super Alkylate Blends**
Component Volume Fractions & Motor Octane Number Results [10]
SORTED FOR 0% M-Toluidine, 0% MMT

Blend No.	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	g/gal MMT	MON
178	0.700	0.250	0.000	0.000	0.050	0.000	98.10
153	0.700	0.000	0.300	0.000	0.000	0.000	100.34

6.4.3.3. Blend Component Trends

Effect of blend components on fuel MON for the aviation alkylate blends 1–75 is assessed by the following graphics of Figures 18.0 through 23.0 which indicate trends relative to the influence of the individual blend components on fuel MON. The indicated trend lines reflect a simple first order linear correlation. A more in depth analysis of the effect of blend components is provided by the Appendix C Statistical Analysis performed by ConocoPhillips. [24]

As indicated by the following graphics, the components *meta*-Toluidine and super alkylate tended to have a greater influence on resulting blend MON than the other components.

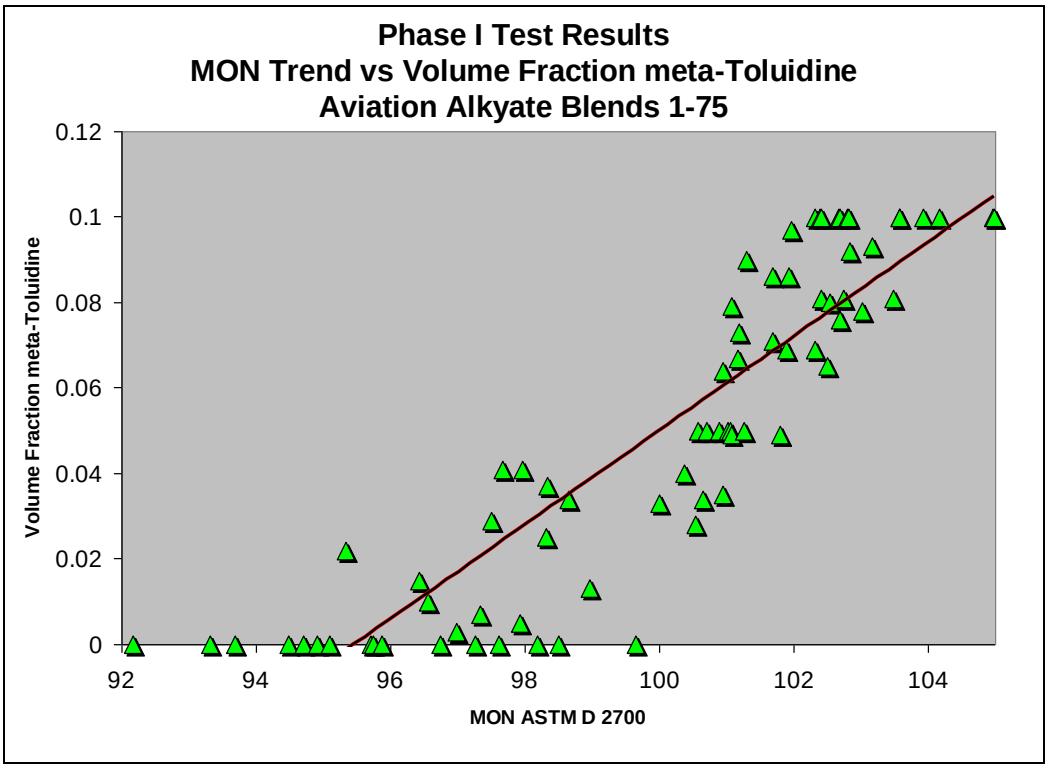

Figure 18.0 - Phase I, MON Trend vs *meta*-Toluidine Volume Fraction

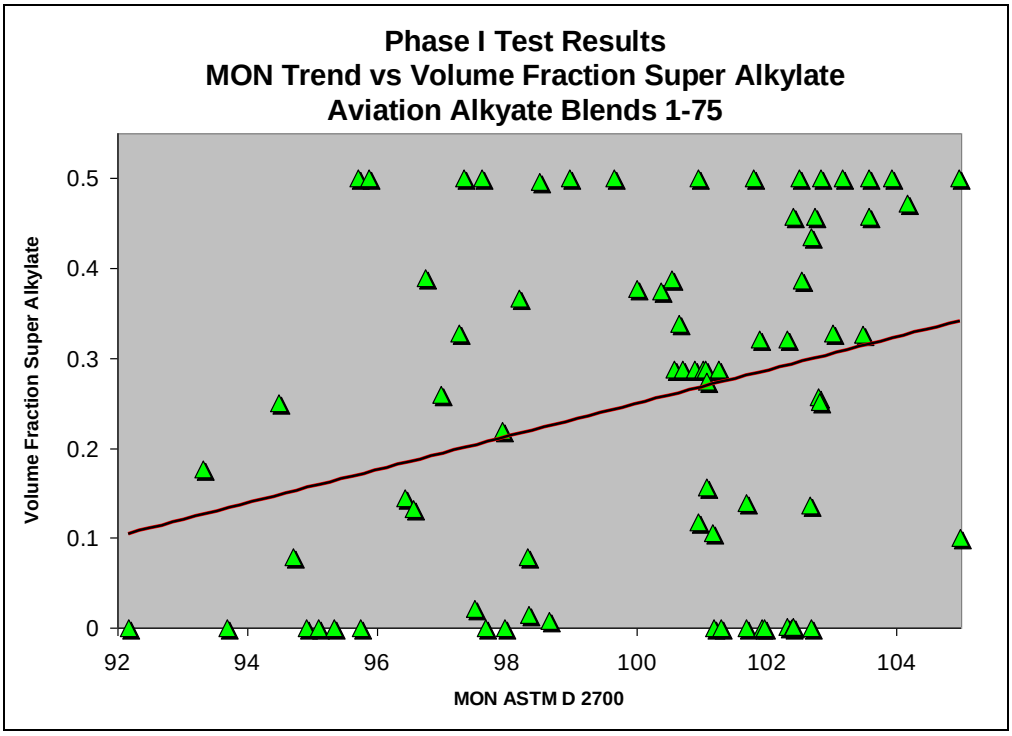

Figure 19.0 - Phase I, MON Trend vs Super Alkylate Volume Fraction

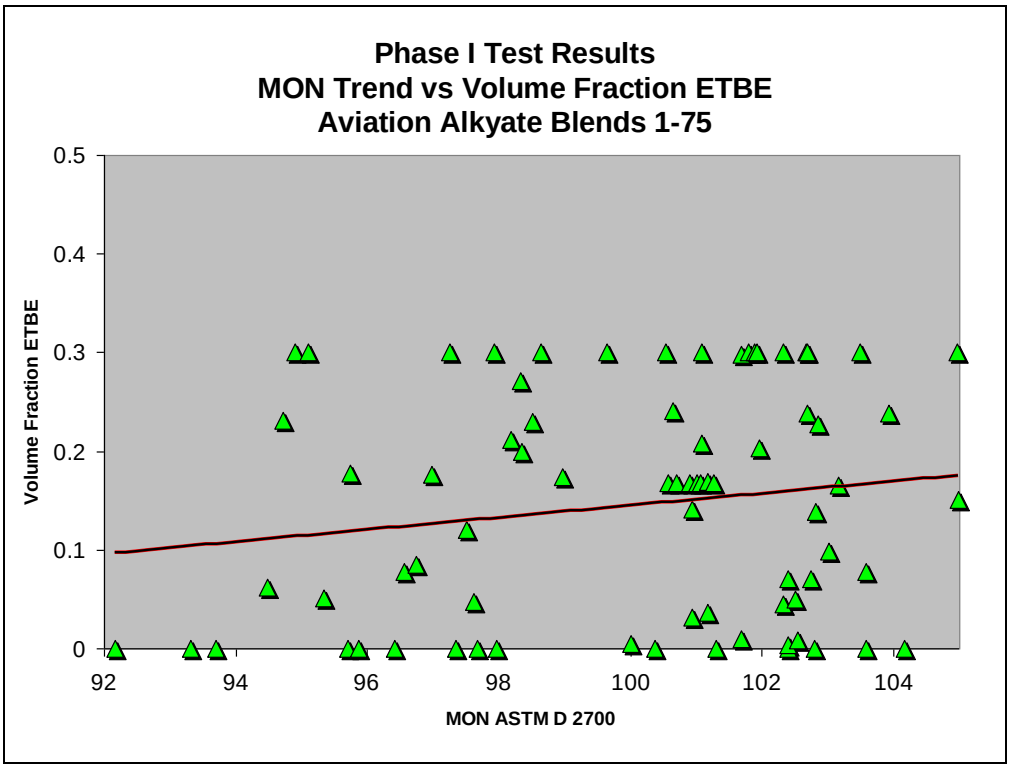

Figure 20.0 - Phase I, MON Trend vs ETBE Volume Fraction

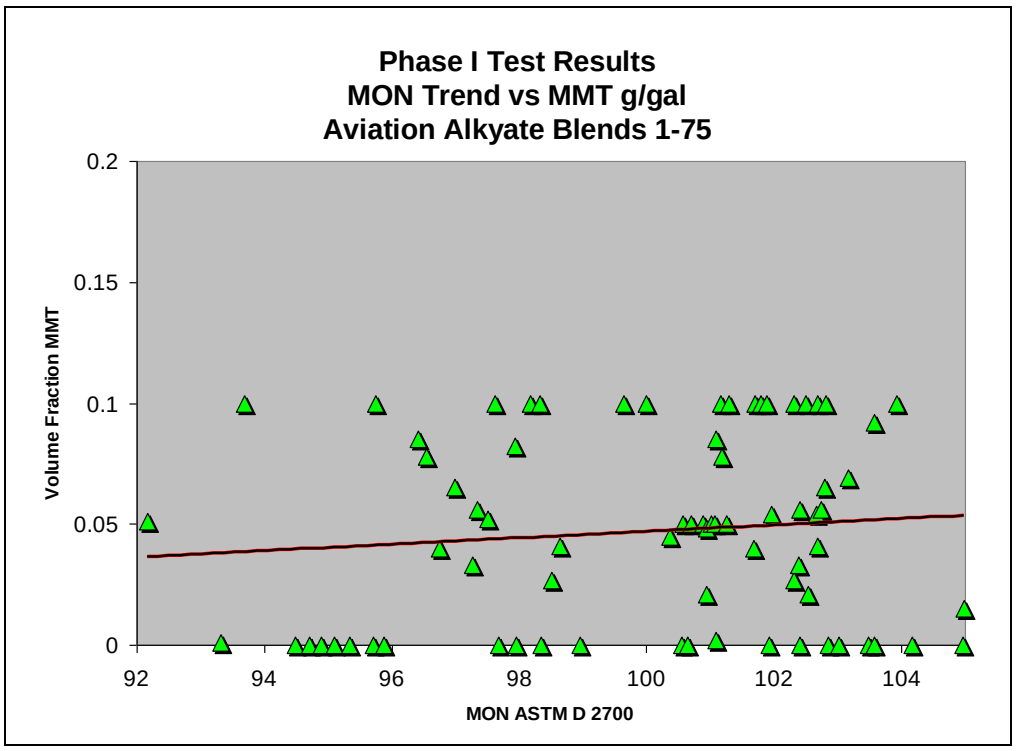

Figure 21.0 - Phase I, MON Trend vs MMT g/gal

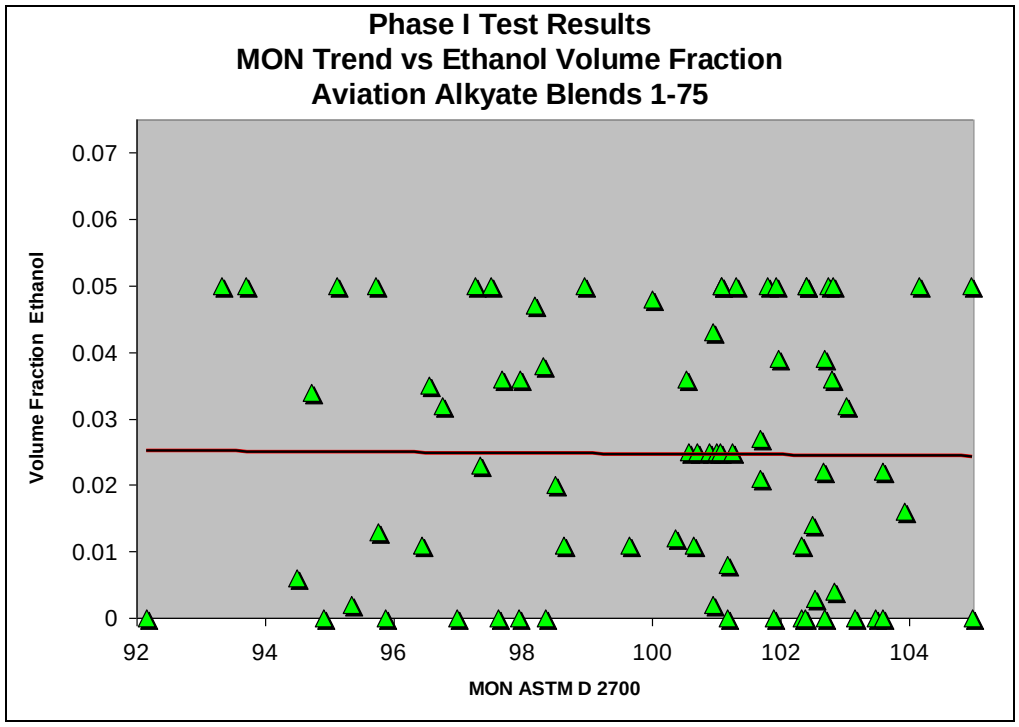

Figure 22.0 - Phase I, MON Trend vs Ethanol Volume Fraction

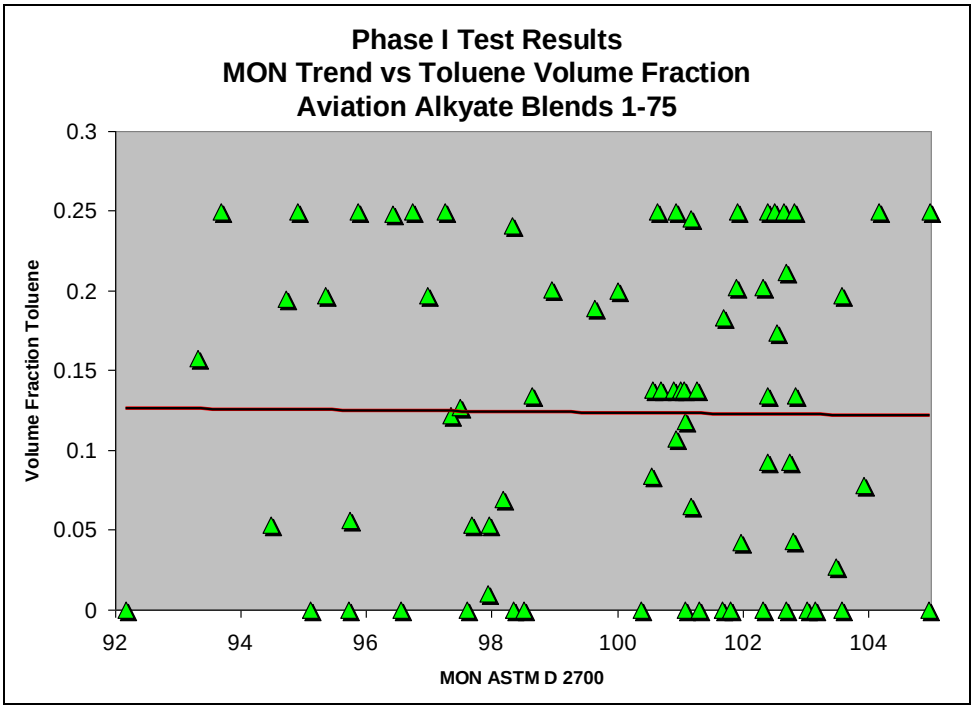

Figure 23.0 - Phase I, MON Trend vs Toluene Volume Fraction

6.4.3.4. Statistical Analysis

Multiple regression analyses of composition variables against MON test results were conducted by ConocoPhillips on the three matrices. A set of equations was developed that predicts MON from the test mixture composition for each of the three matrices. A separate equation was developed for each of the three matrices – aviation, motor, and super alkylate. The regression coefficients which are contained on page 4 of Appendix A are summarized in the following Table 21.0. Results of the statistical analysis were presented at the SAE General Aviation Conference in April 2002; a copy of this presentation is included as Appendix C of this report.

Table 21.0
Data Analysis Regression Coefficients [10]
Phase I Research MON Test 202 Blends

	Variable	Regression Coefficients		
		Aviation Alkylate	Motor Alkylate	Super Alkylate
1	Aviation Alkylate (AVALK)	92.000	NA	NA
2	Motor Alkylate (MOALK)	NA	91.367	NA
3	Super Alkylate (SUALK)	99.499	99.702	100.480
4	Toluene (TOL)	92.697	92.340	94.428
5	ETBE (ETBE)	101.131	101.393	100.646
6	*meta*-Toluidine (mT)	-195.428	-166.555	151.466
7	Ethanol (ETNOL)	95.240	95.701	94.269
8	AvAlky x Manganese	21.138	NA	NA

9	MoALky x Manganese	NA	21.81	NA
10	SuAlky x Manganese	13.653	14.244	7.437
11	*m*-Toluidine x Manganese	-184.508	-187.174	-123.838
12	AvAlky x *m*-Toluidine	434.984	NA	NA
13	MoAlky x *m*-Toluidine	NA	402.424	NA
14	SuAlky x *m*-Toluidine	393.428	359.464	NS
15	Toluene x *m*-Toluidine	441.070	407.982	36.398
16	ETBE x *m*-Toluidine	357.430	328.772	-21.965
17	Ethanol x *m*-Toluidine	353.220	302.538	NS
NA = not applicable to this matrix NS = found to be not significant for the matrix Composition = volume fraction except g/gal for Manganese (MMT)				

Using the above regression coefficients, the equation for predicting MON for the aviation alkylate matrix is presented as follows where the value for each blend component is the proportional volume fraction (expressed as 0.XXX) except the Manganese term is g/gal. The MON equations for the motor alkylate matrix and the super alkylate matrix are similarly derived.

AVIATION ALKYLATE MON MODEL

MON_{AVALK} = *(AVALK X 92) + (SUALK X 99.499) + (TOL x 92.697) + (ETBE x 101.131) – (mT x 195.428) + (ETNOL x 95.240) + (AVLALK x Mn x 21.138) + (SUALK X MMT X 13.653) – (mT x MMT x 184.508) + (AVALK x mT X 434.984) + (SUALK x mT x 393.428) + (TOL x mT x 441.070) + (ETBE x mT x 357.43) + (ETNOL x mT x 353.22)*

MOTOR ALKYLATE MON MODEL

MON_{MOALK} = *(MOALK X 91.367) + (SUALK X 99.702) + (TOL x 92.340) + (ETBE x 101.393) – (mT x 166.555) + (ETNOL x 95.701) + (MOLALK x MMT x 21.81) + (SUALK X MN X 14.244) – (mT x MMT x 187.174) + (MOALK x mT X 402.424) + (SUALK x mT x 359.464) + (TOL x mT x 407.982) + (ETBE x mT x 328.772) + (ETNOL x mT x 302.538)*

SUPER ALKYLATE MON MODEL

MON_{SUALK} = *(SUALK X 100.480) + (TOL x 94.428) + (ETBE x 100.646) + (mT x 151.466) + (ETNOL x 95.269) + (SA X MMT X 7.437) – (mT x MMT x 123.838) + (TOL x mT x 36.398) - (ETBE x mT x 21.965)*

6.4.4. Conclusions

Conclusions and observations relative to MON performance of the Phase I Test Matrix are summarized as follows. The reader is directed to the Appendix A Report, reference (10), for a thorough description of test fuels and test results. See also Appendix C for conclusions and analyses relative to alkylate and component effectiveness. The purpose of this report is to provide a summary of the related testing and to highlight significant conclusions and findings within the scope of the design experiment.

- Best performing alkylates ranked from best to least were #1 super alkylate, #2 aviation alkylate, and #3 motor alkylate [(24)]
- Phase I test results indicated *m*-Toluidine and Super Alkylate when used as a blend component offer significant potential for improving MON performance with respect to the components investigated. Toluene and Ethanol offer little to no benefit relative to MON. Effectiveness of ETBE and MMT appears to be linked to the specific base alkylate.
- The additive *m*-Toluidine was observed to be one of the most effective additives relative to effect on MON.
- The compound Super Alkylate was observed to provide a positive effect as an octane enhancer. Super Alkylate when blended as an additive with Aviation Alkylate and Motor Alkylate exhibited a positive affect on MON performance
- Higher MMT concentrations had a positive effect on MON ratings with Aviation and Motor Alkylates, but the reverse was observed when blended with Super Alkylate
- Higher ETBE concentrations exhibited modest improvements in MON performance when blended with Motor and Aviation Alkylates, but resulted in little to no improvement when blended with Super Alkylate
- Higher Toluene concentrations had little impact on MON performance when blended with Motor and Aviation Alkylates and yielded a negative MON response when blended with Super Alkylate
- Ethanol had no impact on MON performance when blended with Aviation, Motor, or Super Alkylates
- Higher *m*-Toluidine concentrations resulted in a significant positive effect on MON performance when blended with Aviation, Motor, or Super Alkylate.
- Certain blends yielded MON values in the 100–104 range; however, other properties require further assessment relative to compliance with ASTM D 910. Whereas the focus of the Phase I research was engine octane satisfaction, properties such as vapor pressure, freeze point, heat content, and distillation were not controlled as part of the experiment and were not evaluated for agreement with ASTM D 910 AVGAS specification.
- Highest Aviation Alkylate MON without super alkylate, *m*-Toluidine, and MMT was 94.9–95.1 MON (See Table 15.0)
- Highest Motor Alkylate MON without super alkylate, *m*-Toluidine, and MMT was 94.4–94.9 MON (See Table 18.0)
- Highest Super Alkylate MON without MMT without *m*-Toluidine and without MMT was 98.1–100.3 MON (See Table 20.0)

- Equations derived from statistical modeling of MON test results provide a reasonably accurate modeling tool for use in predicting MON performance for the range of blend components and concentrations investigated.

6.5. PHASE II Results – Full Scale Engine Tests 30 UL Blends

6.5.1. Background

Following completion of the Phase I laboratory MON screening research in April of 2001, options were evaluated for continuation of CRC research of UL AVGAS alternatives. A Phase II research plan evolved which provided for full scale engine testing of a group of unleaded fuels formulated based upon the Phase I test results. Significant to the Phase II plan was utilization of the Phase I mathematical models to predict MON performance of the test blends. Aspects of the Phase II research plan were discussed and defined during the August 2001 meeting[19] of the UL AVGAS Task Group with research plans finalized during the November 2001 meeting[20].

NOTE……Phase II Research provided for full scale engine testing of 30 unleaded fuel blends. Test criteria was fuel knock performance in representative critical engines.

6.5.2. Research Plan

The Phase II Research Project was implemented as an industry collaborative effort with organization, planning, and implementation continuing to follow the Phase I practices. Objective of the Phase II Research was to conduct full scale engine testing of unleaded fuel blends derived from the Phase I test results. Base fuels, blend components, and formulation boundaries were defined as shown in Table 22.0. The resulting Phase II research plan provided for full scale engine testing at both the FAA William J. Hughes Technical Center's AFETF and at Cessna Aircraft using a group of 30 unleaded fuel blends. The Phase II test matrix was designed around 15 aviation alkylate blends and 15 motor alkylate blends, each containing specific concentrations of six different octane boosting components. The 30 blends were designed to bracket a range of 97-105 MON using the mathematical models derived from the Phase I MON screening tests. Each blend was prepared as a single batch, which was then split into two parcels that were furnished to the two engine test facilities as anonymous blends, identified only by a blend number.

Table 22.0
CRC Phase II Unleaded AVGAS Test Matrix
Base Fuels & Blend Components [20]
Full Scale Engine Tests, 30 UL Blends

BLEND COMPONENT	***BASE FUEL***	
	(A) Aviation Alkylate	***(B) Motor Alkylate***
Super Alkylate % vol	0 - 50%	0 - 50%
Toluene % vol	0 - 25%	0 - 25%
ETBE % vol	0 - 30%	0 - 30%

m-Toluidine % vol	0 - 10%	0 - 10%
Ethanol % vol	0 - 5%	0 - 5%
Manganese, g Mn/gal	0 - 0.1	0 - 0.1

Notes :
① Blend fractions are % volume unless shown otherwise
② Above test matrix was finalized & agreed upon during November 13, 2000 meeting. [20]
③ Test Method – Full scale engine testing to determine blend knock performance
④ Participants – Dixie Services, ChevronTexaco, Ethyl, ExxonMobil, Air BP, Cessna, ChevronTexaco, FAA Technical Center, Lyondell Chemical, Ultramar Diamond Shamrock, ConocoPhillips, AvPower
⑤ 8 aviation alkylate blends without MMT
7 aviation alkylate blends with MMT
8 motor alkylate blends without MMT
7 motor alkylate blends with MMT

6.5.2.1. Blend Components

The Phase II test matrix was structured using two base fuel components ***AVIATION ALKYLATE*** and ***MOTOR ALKYLATE*** which are described in the Appendix A report[10] and in Section 6.4.2.1 of this report.

Six different blend components were selected for the Phase II test matrix with the objective of evaluating their contribution to octane enhancement of the resulting blend. These components which are classified as saturated hydrocarbons, aromatic hydrocarbons, ethers, alcohols, aromatic amines, and organometallic manganese compounds are described in the Appendix A report[10] and in Section 6.4.2.1 of this report. These components are the same as used in the Phase I laboratory MON screening test with the exception that the super alkylate compound is used as a blend component in Phase II rather than a base fuel as evaluated in Phase I.

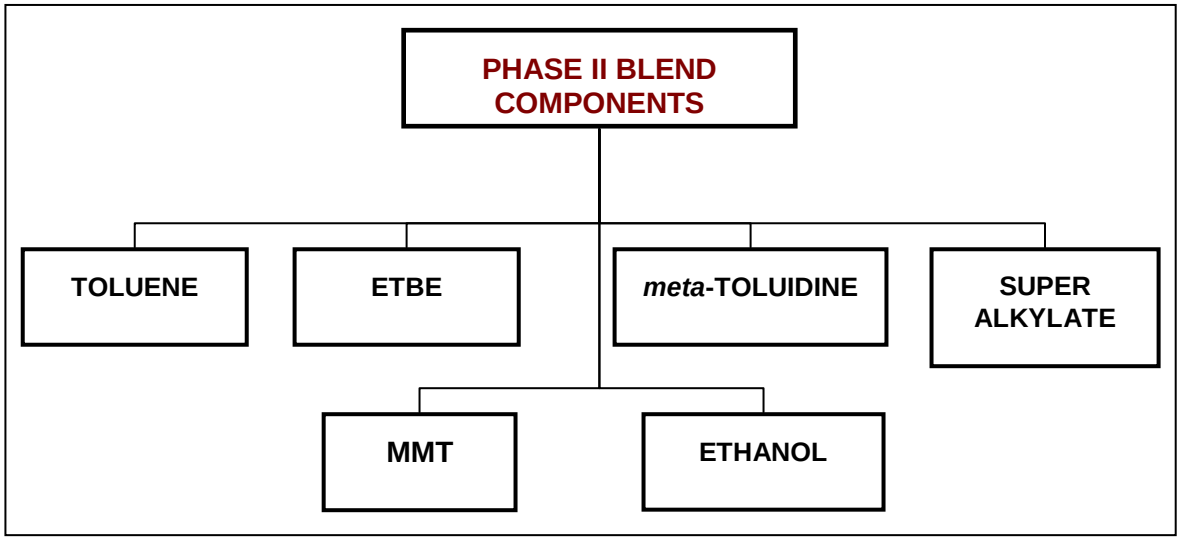

Figure 24.0 - Phase II Blend Components

6.5.2.2. Matrix Design

The Phase II test matrix was not planned as a designed experiment but rather was structured around the objective of evaluating the knock performance in a full scale engine of a group of unleaded fuels derived from the Phase I results. Blends were selected using the mathematical models derived from Phase I statistical analysis. Design guidelines included a MON range of 97 to 105 in increments of 2 MON points with three or more different formulations for each MON rating. Additionally, it was specified that the test matrix provide for evaluation of blends with and without the metal additive MMT. The resulting test matrix as derived by ConocoPhillips provided for 30 unleaded blends consisting of 15 aviation alkylate blends (7 blends with MMT, 8 blends without MMT) and 15 motor alkylate blends (7 blends with MMT, 8 blends without MMT). The resulting test matrix is shown in Tables 24.0 and 25.0.

6.5.2.3. Logistics Plan

Reflecting the industry/government collaborative research arrangement implemented during the Phase I research project and continuing throughout the CRC UL AVGAS research described within this report, Phase II logistics were defined early in the research planning stage with each member organization providing a fuel, component, or service as summarized in the Table 23.0 Logistics Plan. A single independent laboratory, Dixie Services, was retained by the Task Group to formulate the blends and to conduct the specified component and blend property testing. Funding for laboratory blending and related property tests including purchase of select compounds was provided by the FAA Technical Center. Full scale engine testing was performed by the two member organizations FAA Technical Center's AFETF and Cessna Aircraft with each providing a suitable test engine representative of the existing fleet.

Table 23.0
CRC UL AVGAS Phase II Logistics Plan

Task Group Member	Component, Material, Service Provided
Cessna Aircraft	ETBE Engine Testing, Test Engine
ChevronTexaco	Motor Alkylate
ConocoPhillips	Aviation Alkylate Design Experiment, Statistical Analysis
Dixie Services	Formulation of Super Alkylate, Component Physical Property Tests, Matrix Blending, & Blend D 910 Property Tests
Ethyl Corp.	MMT (Manganese Hytech 3062)
ExxonMobil	*meta*-Toluidine
FAA Tech Center AFETF	Funding for blending & property tests Engine Testing, Test Engine
Ultramar Diamond Shamrock	Toluene

6.5.3. Laboratory Test Results

Results of laboratory analyses of Phase II blends and components are contained in the Appendix A Laboratory Analysis Report. The following sections summarize the laboratory test results including Phase II blend formulations, blend ASTM D 910 properties, blend component properties, predicted blend MON ratings, observed MON values, comparison of predicted versus blend MON values, and the results of blend homogeneity tests.

6.5.3.1. Blend Formulations

Blend formulations which were derived from the Table 22.0 Test Matrix boundaries are presented as follows in Tables 24.0 and 25.0. Note that the MON values shown in Tables 24.0 and 25.0 represent predicted values calculated from the Phase I regression models. Descriptor AV indicates aviation alkylate blends without MMT; AM indicates aviation alkylate blends with MMT; MO indicates motor alkylate blends without MMT; and MM indicates motor alkylate blends with MMT.

Table 24.0
Phase II **Aviation Alkylate Blends**
Component **Volume Fractions** & **Calculated** Motor Octane Number [10]

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta* - Toluidine	Ethanol	g/gal MMT	**Calculated MON**
AV1	0.0730	0.3272	0.2500	0.2997	0.0000	0.0501	0	97.5
AV2	0.0402	0.3998	0.2500	0.2977	0.0103	0.0000	0	99.0
AV3	0.0000	0.5000	0.2502	0.1898	0.0600	0.0000	0	102.9
AV4	0.4002	0.4997	0.0000	0.0000	0.1000	0.0000	0	104.1
AV5	0.0000	0.4698	0.2501	0.2499	0.0302	0.0000	0	100.9
AV6	0.0000	0.3500	0.2501	0.2999	0.1001	0.0000	0	104.3
AV7	0.0000	0.4997	0.2501	0.1502	0.1000	0.0000	0	104.6
AV8	0.2916	0.4997	0.0000	0.0985	0.0784	0.0318	0	103.2
AM1	0.3324	0.2876	0.1376	0.1675	0.0500	0.0248	0.0500	100.9
AM2	0.8602	0.0000	0.0000	0.0000	0.0897	0.0501	0.1000	101.7
AM3	0.8695	0.0000	0.0000	0.0705	0.0250	0.0350	0.1000	97.3
AM4	0.6001	0.0000	0.0000	0.2998	0.1000	0.0000	0.0500	102.5
AM5	0.8000	0.0000	0.1248	0.0000	0.0552	0.0199	0.0500	99.2
AM6	0.3549	0.4995	0.1404	0.0000	0.0052	0.0000	0.0500	97.1
AM7	0.2500	0.4998	0.0000	0.2001	0.0000	0.0501	0.1000	99.0

Notes:
① MON shown is predicted MON computed using Phase I regression models of Section 6.4.3.3
② Blend Label assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. See Exhibit VI of Appendix A for corresponding mass fractions. [10]

Table 25.0
Phase II **Motor Alkylate Blends**
Component **Volume Fractions** & **Calculated** Motor Octane Number [10]

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta* - Toluidine	Ethanol	g/gal MMT	**Calculated MON**
MO1	0.2501	0.4501	0.0000	0.2998	0.0000	0.0000	0	98.1
MO2	0.0613	0.5001	0.2014	0.1742	0.0129	0.0501	0	99.0
MO3	0.1926	0.1358	0.2501	0.2999	0.1001	0.0216	0	103.4
MO4	0.0000	0.4251	0.2501	0.2998	0.0250	0.0000	0	100.6
MO5	0.0780	0.4718	0.0000	0.2999	0.1001	0.0501	0	104.2
MO6	0.9400	0.0000	0.0147	0.0000	0.0453	0.0000	0	97.1

MO7	0.0000	0.4342	0.2114	0.2393	0.0650	0.0501	0	102.9
MO8	0.0000	0.4997	0.2496	0.1507	0.1000	0.0000	0	104.6
MM1	0.4001	0.4999	0.0000	0.0000	0.1001	0.0000	0.0920	103.6
MM2	0.6999	0.0000	0.2401	0.0000	0.0599	0.0000	0.1000	99.1
MM3	0.1108	0.4575	0.0776	0.2379	0.1000	0.0162	0.1000	103.3
MM4	0.3327	0.2877	0.1377	0.1675	0.0501	0.0243	0.0500	100.7
MM5	0.2260	0.4998	0.2511	0.0000	0.0000	0.0232	0.1000	97.0
MM6	0.5000	0.0997	0.1002	0.2349	0.0151	0.0501	0.0520	97.0
MM7	0.8602	0.0000	0.0000	0.0000	0.0896	0.0501	0.1000	101.1

Notes:
① MON shown is predicted MON computed using Phase I regression models of Section 6.4.3.3
② Blend Label assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. See Exhibit VI of Appendix A for corresponding mass fractions. (10)

6.5.3.2. Blend ASTM D 910 Properties

Each of the 30 unleaded blends was tested for the properties specified in ASTM D 910 for 100LL grade aviation gasoline except for sulfur content, tetraethyl lead, color, and electrical conductivity. Purpose of the ASTM D 910 property tests was to identify those properties which were either within or outside compliance with the ASTM D 910 specification. Results of D 910 properties tests are tabulated in Exhibit VIII of Appendix A report for each of the 30 blends. (10) Tables 26.0 and 27.0 summarize the blend property test results for the AV1 – AV8 (non MMT) aviation alkylate blends and MO1 – MO8 (non MMT) motor alkylate blends; properties non-compliant with ASTM D 910 are highlighted in yellow in each of the tables. Refer to Exhibit VIII of Appendix A for properties of the blends containing MMT.

It is significant that many of the blends exhibited vapor pressures which were non-compliant with ASTM D 910 thus indicating the need for further adjustment of fuel blends and properties in order to meet the 38-49 kPa vapor pressure limits. Vapor pressure of aviation gasoline is a critical property relative to flight safety with most small aircraft fuel systems highly evolved to handle the vapor pressure characteristics of current 100LL AVGAS. Similarly, the freezing point of some blends did not meet the D 910 requirement of -58°C. Only one of the 30 blends was observed to meet the minimum net heat of combustion specification of 43.5 MJ/kg. . With respect to MON, three of the 16 AV and MO blends exhibited MON values below the ASTM D 910 min spec 99.5 MON. Nine of the 14 AM and MM blends (containing MMT) yielded MON values compliant with ASTM D 910.

As discussed in the Appendix A laboratory report, whereas the subject “blends were formulated to explore the relationship between detonation characteristics and classes of blending components without regard to other properties, it is not unexpected that most of the fuels fail to meet Grade 100LL requirements, notably volatility (vapor pressure, distillation), heat of combustion, and freeze point. Exploration and refinement of these properties remains the subject of future research.” (10)

Table 26.0
Phase II Blend Properties [10]
Aviation Alkylate Blends Without MMT
(Highlighted values indicate non-compliance with ASTM D 910)

ASTM Test Method	AV1	AV2	AV3	AV4	AV5	AV6	AV7	AV8	100LL Spec
Motor Octane Number	97.0	99.8	103.4	104.4	101.2	105.2	105.6	103.4	99.5 min
Supercharge Rating Perf No.	136.6	146.1	>161	>161	152.5	>161	>161	>161	130 min
Density, 15 ° kg/m^3	762.1	760.2	770.3	736.2	764.0	789.5	780.7	729.5	
Vapor Pressure, 38 ° kPa	24.8	18.7	14.6	22.1	16.6	15.4	13.3	27.0	38-49
Freezing Point °C	<-70	-41nh	<-70	+19nh	-47	<-70	<-70	-33nh	-58 max
Heat of Combustion, MJ/kg	40.184	40.783	41.080	43.162	40.960	39.962	40.982	42.032	43.5 min
Copper Corrosion	1b	1a	1a	1b	1a	1a	1a	1a	1 max
Potential residue, 5 h, 100°C									
Precipitate, mg/100mL	0.6	0.3	0.4	0.3	<0.1	<0.1	<0.1	<0.1	3 max
Potential Gum, mg/100mL	4	3	6	5	4	6	7	5	6 max
Water reaction, interface	1b	1b	1b	1b	1b	1b	1b	1b	
Separation rating	2	2	2	2	2	2	2	2	
Volume Change, mL	3	0	0	0	0	0	0	2	± 2 max
Distillation, % evaporated °C									
IBP	67.5	79.5	86.5	53.5	82.5	81.5	87.5	62.5	
5	72.5	85.0	91.5	64.5	87.5	87.5	92.5	70.0	
10	75.0	88.5	92.5	73.0	90.0	89.5	94.5	76.0	75 max
15	77.5	88.5	93.5	76.5	91.0	90.5	95.5	81.5	
20	80.0	90.0	94.5	79.5	91.5	91.5	96.5	87.0	
30	87.0	91.5	95.5	84.0	93.5	92.5	97.5	93.5	
40	91.0	93.0	97.5	87.5	94.5	94.5	99.5	96.5	75 min
50	93.5	94.5	100.0	91.0	96.5	97.5	101.5	98.5	105 max
60	96.0	97.0	101.5	85.5	98.5	100.5	104.5	100.5	
70	98.5	99.5	104.5	101.0	101	104.5	107.5	104.5	
80	101.5	103.0	109.5	109	104.5	112.5	114.5	109.5	
85	103.5	105.5	115.0	119.0	107.5	121.0	124.0	116.0	
90	106.0	109.5	127.0	163.0	113.5	161.0	169.0	155.0	135 max
95	111.0	122.0	187.0	192.0	150.0	195.0	195.0	195.0	
End	156.5	178.0	197.5	199.5	189.5	198.0	198.0	197.5	170 max
Sum of 10% + 50%	168.5	183.0	192.5	164.0	186.5	187.0	195.5	174.5	135 min
Recovery	98.6	98.9	99.1	97.9	98.5	99.0	99.1	99.0	97 min
Residue	1.3	1.0	0.8	0.7	0.8	0.8	0.8	0.8	1.5 max
Loss	0.1	0.1	0.1	1.4	0.7	0.2	0.1	0.2	

Notes:
① Extracted from Exhibit VIII, Appendix A.

Table 27.0
Phase II Blend Properties [10]
Motor Alkylate Blends Without MMT
(Highlighted values indicate non-compliance with ASTM D 910)

ASTM Test Method	MO1	MO2	MO3	MO4	MO5	MO6	MO7	MO8	100LL Spec
Motor Octane Number	98.1	99.2	103.6	101.0	104.6	96.7	102.3	105.0	99.5 min
Supercharge Rating Perf No.	114.1	123.1	152.5	131.2	156.6	121.8	149.4	>161	130 min
Density, 15 ° kg/m^3	711.2	750.9	790.9	765.1	750.3	711.2	773.3	780.6	
Vapor Pressure, 38 ° kPa	30.7	24.9	26.4	17.4	25.5	48.9	21.2	14.5	38-49
Freezing Point °C	<-70	<-70	<-70	<-70	<-70	+4 nh	<-70	<-70	-58 max
Heat of Combustion, MJ/kg	41.835	40.909	39.376	40.607	39.706	43.849	39.864	40.899	43.5 min
Copper Corrosion	1a	1b	1a	1b	1a	1b	1a	1a	1 max
Potential residue, 5 h, 100°C									
Precipitate, mg/100mL	0.2	0.3	0.1	<0.1	1.2	0.3	0.3	<0.1	3 max
Potential Gum, mg/100mL	2	<1	9	2	6	9	5	8	6 max
Water reaction, interface	1b	2	2	1b	1b	1b	2	1b	
Separation rating	2	2	2	2	2	1	2	1	
Volume Change, mL	3	0	1	0	3	0	3	0	± 2 max
Distillation, % evaporated °C									
IBP	59.0	67.5	58.0	81.0	66.0	38.0	70.0	96.5	
5	73.5	72.0	70.5	88.0	70.5	55.5	76.5	92.0	
10	79.0	75.0	77.5	89.5	73.0	65.5	78.0	93.5	75 max
15	81.0	79.0	81.5	90.0	75.0	73.5	80.0	94.5	
20	83.0	84.0	84.5	91.0	77.5	80.0	83.0	95.5	
30	86.0	91.0	89.0	92.0	82.0	90.5	89.0	97.5	
40	89.0	94.5	93.0	93.5	88.5	97.5	93.0	99.5	75 min
50	90.5	96.5	97.0	95.0	91.5	102.0	96.0	100.5	105 max
60	93.0	98.5	100.5	97.5	96.0	106.0	99.0	103.5	
70	96.5	100.0	104.5	100.0	100.0	110.5	102.5	112.0	
80	100.5	103.0	113.5	104.0	106.5	120.5	108.5	115.5	
85	103.5	105.0	123.0	107.0	116.0	129.5	113.0	125.5	
90	109.0	110.0	163.5	112.5	175.0	152.5	126.5	174.5	135 max
95	132.5	135.5	193.5	127.5	195.5	182.5	188.5	196.0	
End	181.0	184.5	204.0	191.5	198.0	199.5	198.0	198.0	170 max
Sum of 10% + 50%	169.5	171.5	174.5	184.5	164.5	167.5	174.0	194.0	135 min
Recovery	98.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	97 min
Residue	1.3	0.3	0.4	0.9	0.7	0.4	0.6	0.8	1.5 max
Loss	0.7	0.7	0.6	0.1	0.3	0.6	0.4	0.2	

Notes:
① Extracted from Exhibit VIII, Appendix A.

6.5.3.3. Blend Component Properties

Phase II blend component physical and chemical properties were determined by the applicable ASTM test method and are summarized in Table 28.0 which is extracted from Exhibit IV of the Appendix A Dixie Services Laboratory Report. [10] The ETBE analysis was conducted to test method ASTM D 5441 (MTBE gas chromatography method), but calibrated for impurities typical of ETBE.

Table 28.0
Phase II Blend **Component** Properties [10]
[Extracted from Exhibit IV, Appendix A]

ASTM Test Method	Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	Ethanol	*meta* - Toluidine
D 4052 Relative Density, 15.56ºC	0.6917	0.6912	0.6996	0.8710	0.7465	0.7939	0.9925
API Gravityº	72.9	73.0	70.5	30.8	57.9	46.6	10.9
D 5191 Vapor Press, DVPE, psi	5.70	7.76	1.81	0.90	4.41	2.20	< 0.10
D 2700 Motor Octane Number	91.1	89.7	99.7	108.3	98.2	88.6	NA
D 2622 Sulfur Content, mass %	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	NA
E 1064 Water Content, mass %					0.0486	0.332	NA
D 2360 Toluene Content, mass %	NA	NA	NA	99.88	NA	NA	NA
D 5441* ETBE Content, mass %	NA	NA	NA	NA	96.64	NA	NA
D 5501 Ethanol Content, mass %	NA	NA	NA	NA	NA	99.61	NA
D 850 Distillation Range, °C	NA	NA	NA	0.5	NA	NA	NA
D 86 Distillation, % evaporated °C							
IBP	40.0	43.0	97.0		68.0		
5	61.0	51.0	98.0		70.0		
10	75.0	60.0	98.0		71.0		
20	84.5	75.0	98.5		72.0		
30	91.5	87.0	99.0		73.0		
40	95.5	95.0	99.5		73.0		
50	98.0	99.0	100.0	110.6	73.5	78.0(lit.)	203-4(lit.)
60	100.5	103.0	100.5		73.5		
70	103.0	107.0	102.0		74.0		
80	106.0	113.5	103.5		74.5		
90	113.0	128.0	111.5		76.0		
95	125.0	157.5	161.5		78.5		
End	151.5	193.5	187.0		101.5		
Recovery	97.9	98.0	99.0		99.0		
Residue	0.9	1.0	0.2		0.5		
Loss	1.2	1.0	0.8		0.5		

6.5.3.4. Blend MON Predicted vs Test

An important work product derived from the Phase I research was a series of mathematical models (generated from regression analyses) which were shown to provide a reasonably accurate empirical tool for prediction of MON performance of related blends over the selected range of composition. The blend predicted MON values listed in Tables 24.0 and 25.0 were calculated using the Phase I regression models. Note that nine of the Phase II blends were exact duplicates of Phase I blends.

Table 29.0 provides a comparison of predicted MON versus observed test values for the 30 UL blends and is the same as Exhibit IX of Appendix A. ASTM D 910 testing of the Phase II blends yielded MON values for each of the 30 UL blends which are listed in the far right hand column of Table 29.0. The middle column lists the predicted MON values while the MON values for the nine replicate blends are noted in the left hand column. As shown in Table 29.0, the correlation between predicted and measured MON values is encouraging, thus indicating the validity of the regression models and associated methodology. The correlation is also illustrated graphically by Figure 25.0 which is reproduced from Exhibit IX of Appendix A. [10]

Table 29.0
Comparison of MON Predicted vs Test [10]
Phase II 30 UL Blends

	Blend No.	MON Phase I Matrix Test Results	MON Phase II Predicted ①	MON Phase II Test Results ②
1	AV1	-	97.5	97.0
2	AV2	-	99.0	99.8
3	AV3	-	102.9	103.4
4	AV4	-	104.1	104.4
5	AV5	-	100.9	101.2
6	AV6	-	104.3	105.2
7	AV7	-	104.6	105.6
8	AV8	103.0	103.2	103.4
9	MO1	-	98.1	98.1
10	MO2	99.2	99.0	99.2
11	MO3	-	103.4	103.6
12	MO4	-	100.6	101.0
13	MO5	104.5	104.2	104.6
14	MO6	-	97.1	96.7
15	MO7	-	102.9	102.3
16	MO8	-	104.6	105.0
17	AM1	100.9	100.9	101.0
18	AM2	101.3	101.7	101.6
19	AM3	-	97.3	96.4
20	AM4	-	102.5	102.9
21	AM5	-	99.2	99.6
22	AM6	-	97.1	96.6
23	AM7	-	99.0	99.6
24	MM1	103.3	103.6	103.8
25	MM2	-	99.1	99.4
26	MM3	104.4	103.3	104.0
27	MM4	100.8	100.7	100.7
28	MM5	-	97.0	96.8
29	MM6	-	97.0	96.2
30	MM7	101.0	101.1	100.9

Notes:
① Predicted using Phase I regression models. See Tables 24 & 25 of this report.
② Determined from ASTM D 2700 test; see Tables 26 & 27 of this report.

NOTE……Phase II Research results validated the Phase I regression models as being a reasonable predictor of blend MON property for the applicable group of blend components and concentrations.

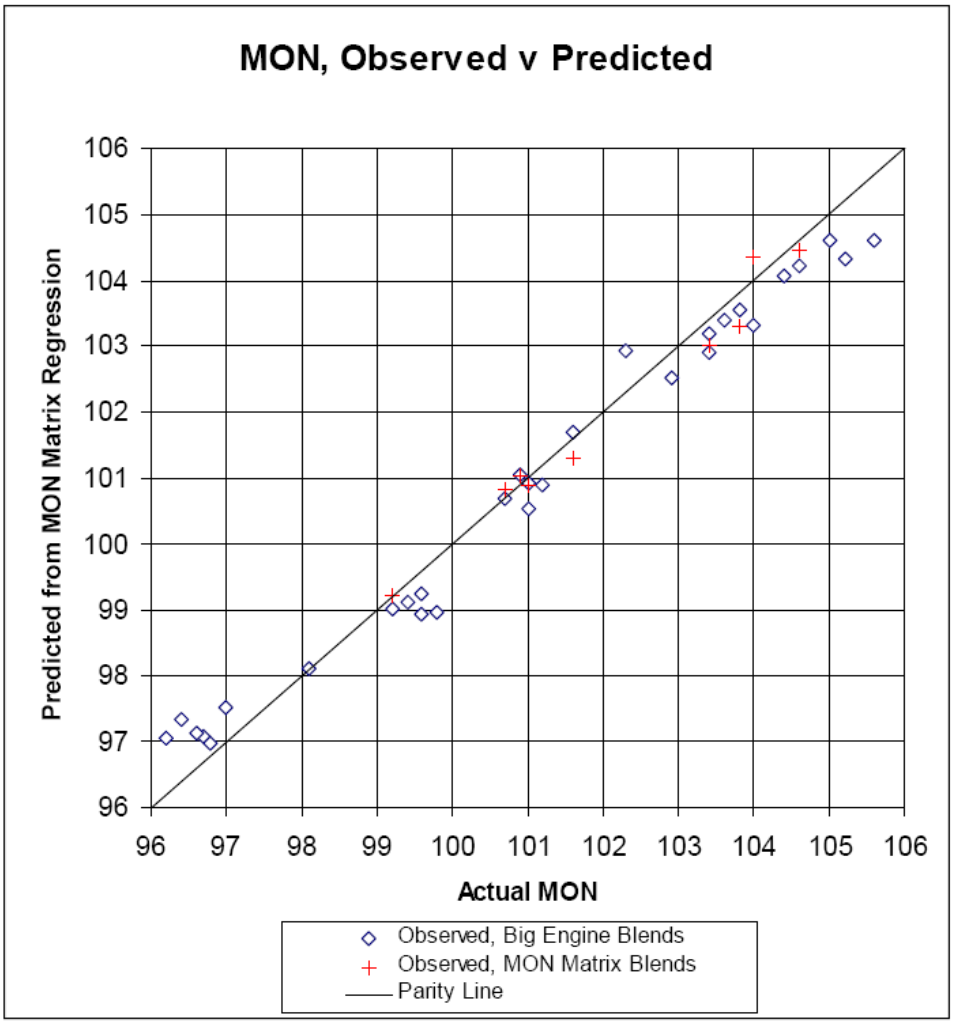

Figure 25.0 – D 2700 MON Observed Test Results vs Predicted MON [10]

6.5.3.5. Mixture Homogeneity Temperature Test

Based upon observations during mixing and handling of the Phase I blends, a supplemental study was performed by Dixie Services during the Phase II research project to investigate the effect of temperature on mixture homogeneity. It was observed that the compound *meta*-Toluidine exhibited a tendency to separate at higher volume fractions from the mixture with increasing cold temperature; it was also observed that this tendency was reduced when combined with other additives.[19] Phase I mixtures were evaluated for homogeneity temperature by conducting the following experiment at cold temperatures. Results of the homogeneity temperature experiment are included in Appendix D of this report.

1. Place ca. 17 mL fuel in 16 X 130 mm test tube with screw cap.
2. Chill specimens overnight in the coldest air chamber of a cloud/pour point bath.
3. If a chilled specimen remains homogeneous at the bath temperature, record the bath temperature as the homogeneity temperature of the sample and remove the sample from the test set.
4. Allow the non-homogeneous specimens to return to room temperature. Mix well to restore uniformity. Move the specimens to the next warmer air chamber of the cloud/pour point bath and allow to equilibrate overnight.
5. Repeat steps 3 and 4 as required to characterize all samples.

6.5.4. Engine Test Results

Objective of the Phase II research project was to evaluate the knock performance of the unleaded fuel blends in full scale piston aircraft engines representative of the general aviation fleet. Objectives included correlation of blend MON with engine octane requirement. A total of 30 unleaded fuel blends consisting of 15 aviation alkylate blends and 15 motor alkylate blends as described in Tables 24.0 and 25.0 were evaluated for knock performance by parallel engine test programs at both the FAA Technical Center's AFETF and at Cessna Aircraft. Engine testing was performed during calendar year 2002 with full test reports subsequently published by both the FAA Technical Center[12] and Cessna Aircraft[13]. Although test methods and engines differed between the two test resources, results and conclusions are generally consistent and complimentary as described in the following sections 6.5.4.1 through 6.5.4.2. Differences in the test methods and test setup were mitigated since the full scale engine test methods provided for a comparative analysis between each of the 30 unleaded blends using a minimum specification 100LL as a baseline fuel. A comparison between the two test facilities and associated test methods is shown in the following Table 30.0.

Table 30.0
Comparison Between FAA & Cessna Test Methods

Method	FAA AFETF	Cessna Test Facility
Test Engine	Six cylinder 540 CID rated at 300 BHP	Four cylinder 360 CID rated at 200 BHP
Engine CR	8.7:1	9.0:1
Load Method	Dynamometer	Propeller, Fixed Pitch
Engine Torque Measurement	Dynamometer Load Cell	Torquemeter
Fuel Flow	Mass Fuel Flow	Volumetric Fuel Flow
Inlet Air Relative Humidity	Controlled to < 5%	Not controlled but documented
Inlet Air Temperature	103º ± 3ºF	230º ± 2ºF
CHT Hottest	Maintained at 475º ± 3ºF	Allowed to increase during lean out to max
Power Metric	Observed Brake Horsepower	BMEP calculated on basis of observed BHP

NOTE……Phase II full scale engine tests provided for a comparative analysis between the 30 experimental unleaded blends and a Baseline 100LL based upon measured engine knock response.

6.5.4.1. FAA Technical Center Test Results

Full scale engine detonation testing of the 30 unleaded experimental blends listed in Tables 24.0 and 25.0 was completed in September 2002 at the FAA Aviation Fuels & Engine Test Facility located at the FAA William J. Hughes Technical Center in Atlantic City, New Jersey. Results of these tests are documented in FAA Report No. DOT/FAA/AR-04/25 dated September 2004. [(12)] This report may be accessed at http://actlibrary.tc.faa.gov by searching keyword "avgas". A description of the IO-540-K test engine and the associated FAA Technical Center test methods, test equipment, and associated procedures are presented in Sections 6.3.3 – 6.3.5 of this report. The objective of the full scale engine tests was to compare the knock performance of the unleaded fuel blends against a baseline minimum specification 100LL fuel and to explore correlation of blend MON with engine octane requirement.

The FAA AFETF test method consisted of conducting a mixture lean out curve at 100% [2700 RPM WOT], 85% [2600 RPM], 75% [2450 RPM], and 65% [2350 RPM] power settings [while holding manifold pressure and engine speed constant] for each fuel blend including the baseline 100LL fuel. Each mixture lean out curve was performed by incrementally manually leaning the fuel flow in 5% increments from a pre-determined rich value to the point where either limiting detonation was encountered or the engine became unstable. Each of the six cylinders was monitored continuously for indications of detonation as indicated by combustion pressure patterns using the instrumented cylinder head technology described in Section 6.3.4.1 and in the FAA Test Results Report[(12)] . In excess of 148 mixture lean out curves were conducted. A description of the aircraft piston engine mixture lean out test procedure and its utility is discussed in Section 6.3.5.1 of this report; the mixture lean out curve provides a basis for consistently and comparatively evaluating engine knock and mixture characteristics for multiple fuels as a function of fuel/air ratio.

Results of the FAA AFETF mixture lean out curves are shown graphically in the following Figures 26.0 through 33.0 which are extracted from the FAA Test Results Report[(12)]. The diagonal lines shown on each of the mixture lean out curves indicates onset of combustion knock for each fuel blend for power settings of 100% 85%, 75%, and 65%. The diagonal line for the baseline 100LL fuel is color coded bold red. Those fuels noted by a diagonal line to the right of the "RED" 100LL diagonal line performed worst than the 100LL baseline fuel. Those fuels noted by a diagonal line to the left of the "RED" 100LL diagonal line performed better than the 100LL baseline fuel. Fuel blends which knock at a fuel flow richer than the 100LL baseline are viewed negatively since they would require significant changes to existing aircraft and engines with a negative impact on energy consumption. Fuel blends which are characterized by knock at a fuel flow leaner than the baseline fuel provide increased knock margin.

Note that the FAA Test Results Report[(12)] contains an exceptionally large amount of data which offers the potential for further analysis for effect of blend formulations on engine characteristics such as BSFC, fuel/air ratio, BHP at best power, and EGT. Comparative analysis of BHP, BSFC, and EGT for the blends tested is addressed within the FAA Test Results Report. This summary research report focuses primarily on engine octane response and correlation with blend MON rating.

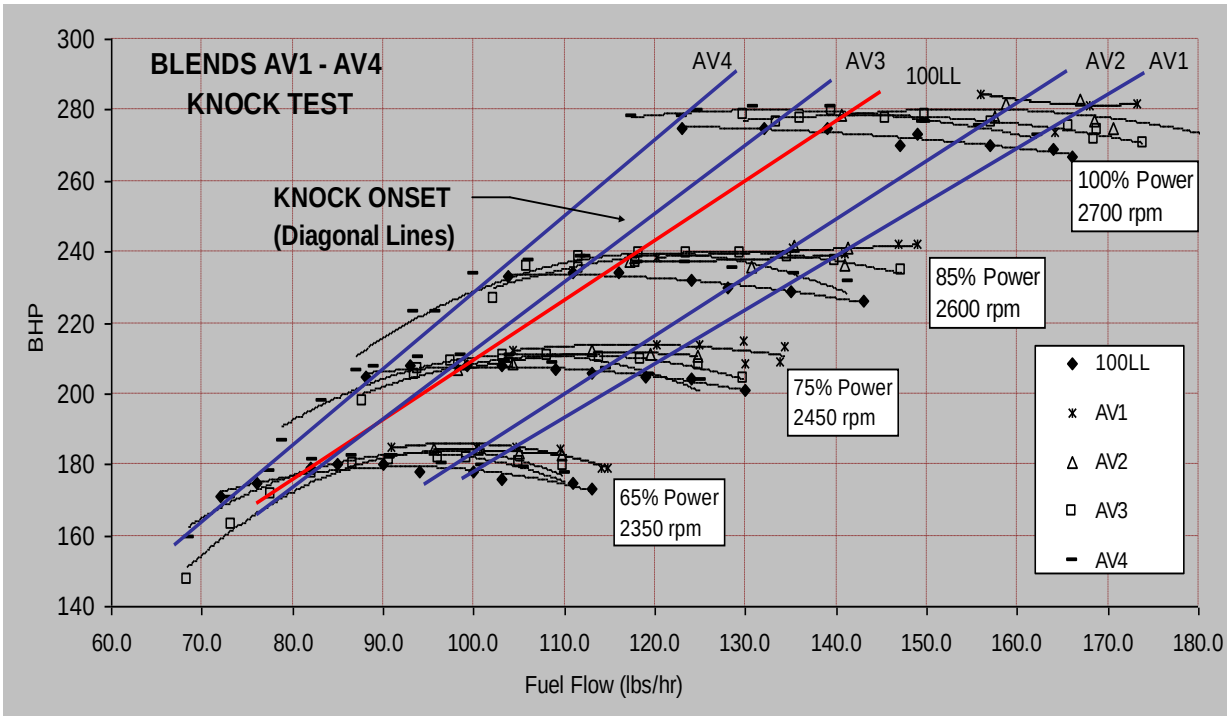

Figure 26.0 – FAA Knock Test, Mixture Lean Out, Blends AV1-AV4 [12]

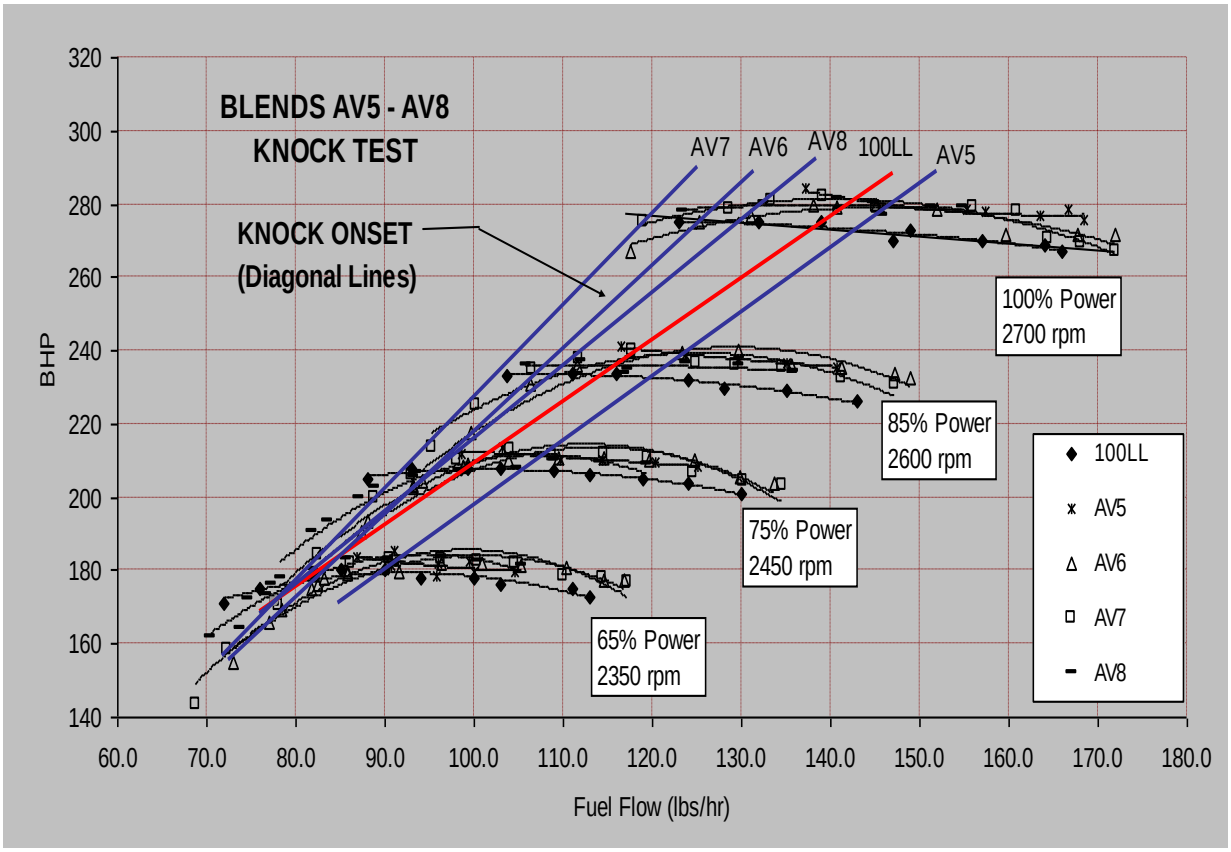

Figure 27.0 – FAA Knock Test, Mixture Lean Out, Blends AV5-AV8 [12]

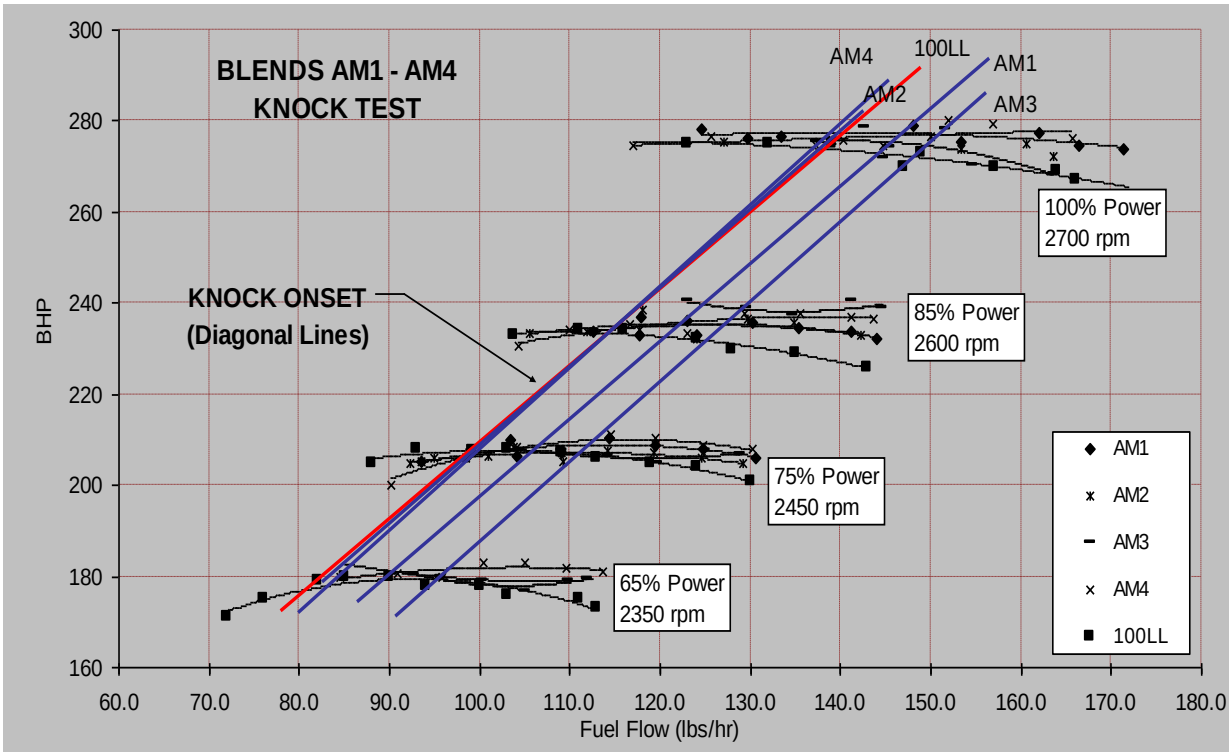

Figure 28.0 – FAA Knock Test, Blends AM1 – AM4 [12]

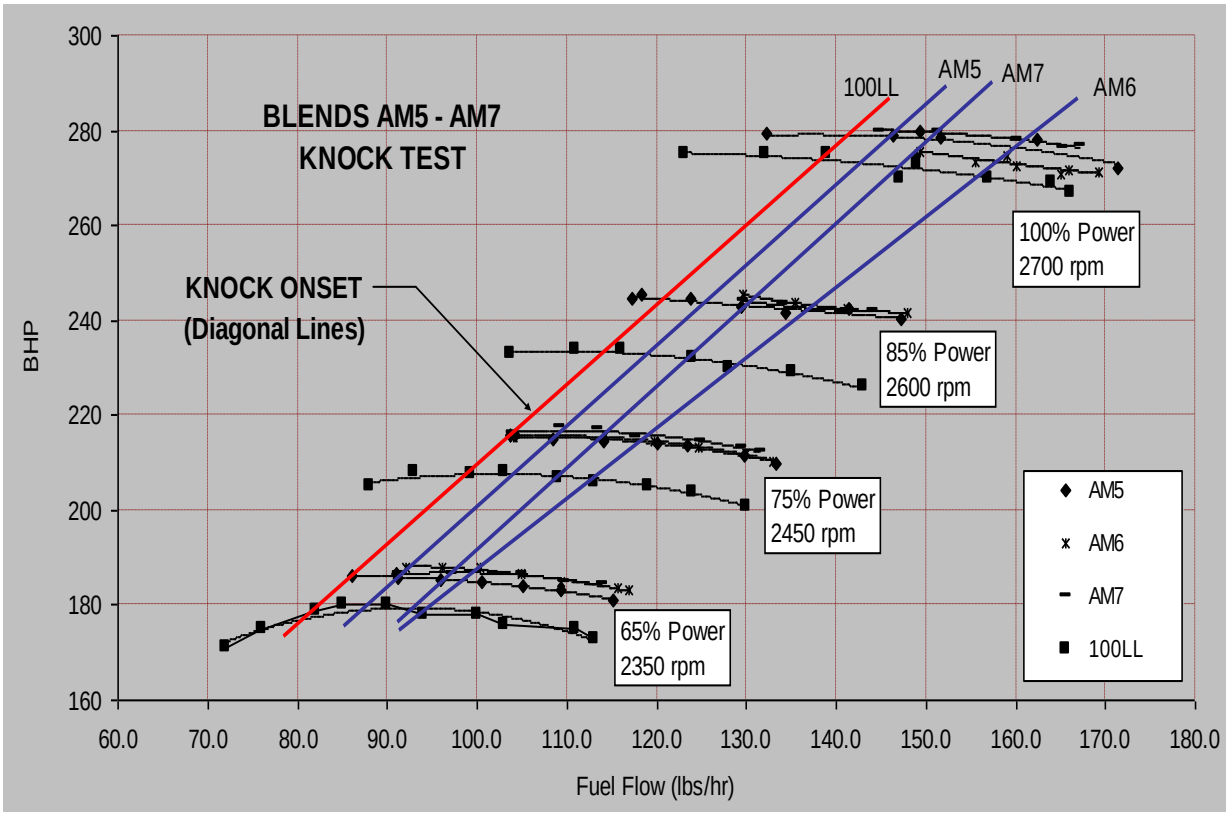

Figure 29.0 – FAA Knock Test, Blends AM5 – AM7 [12]

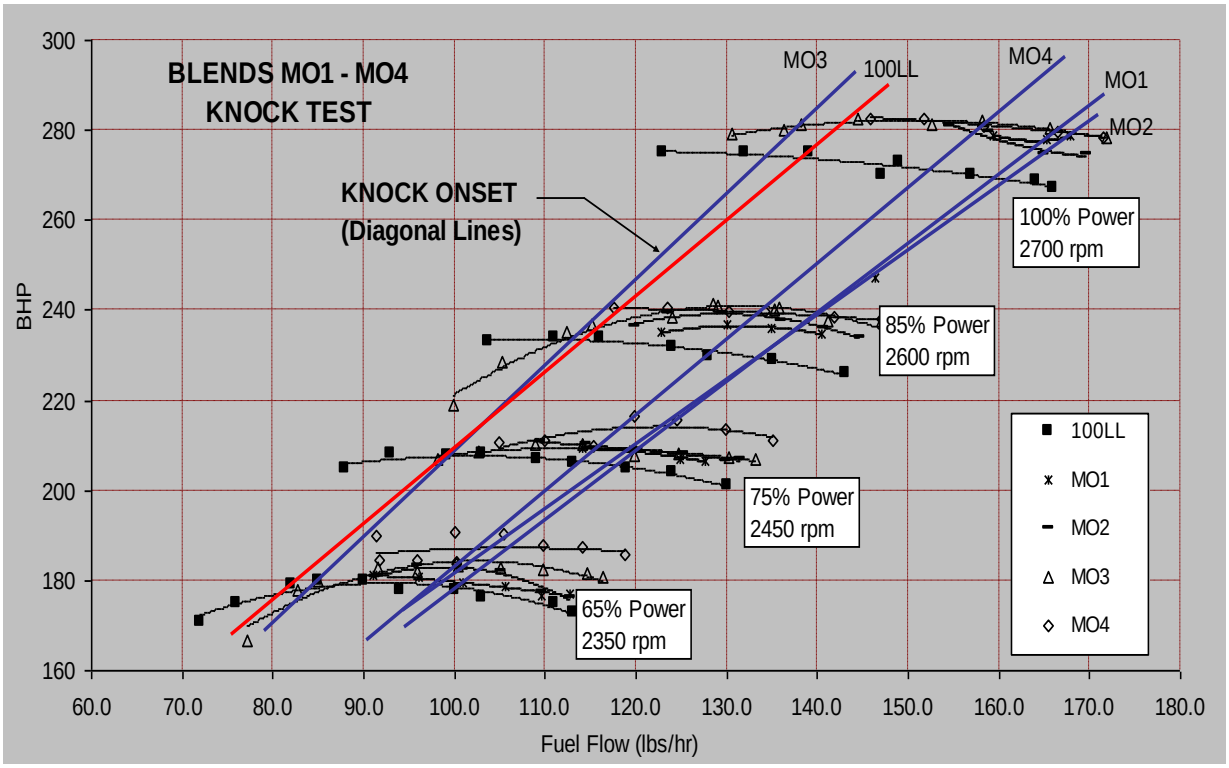

Figure 30.0 – FAA Knock Test, Blends MO1 – MO4 [12]

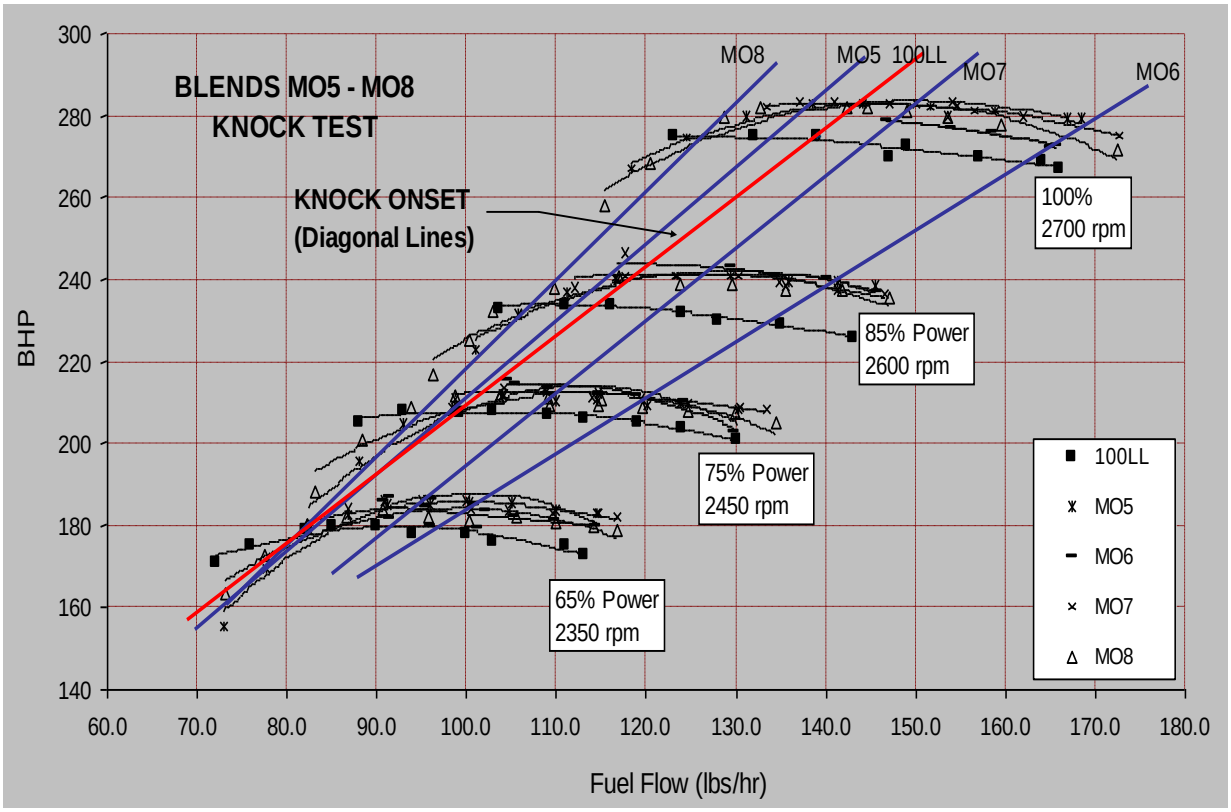

Figure 31.0 – FAA Knock Test, Blends MO5 – MO8 [12]

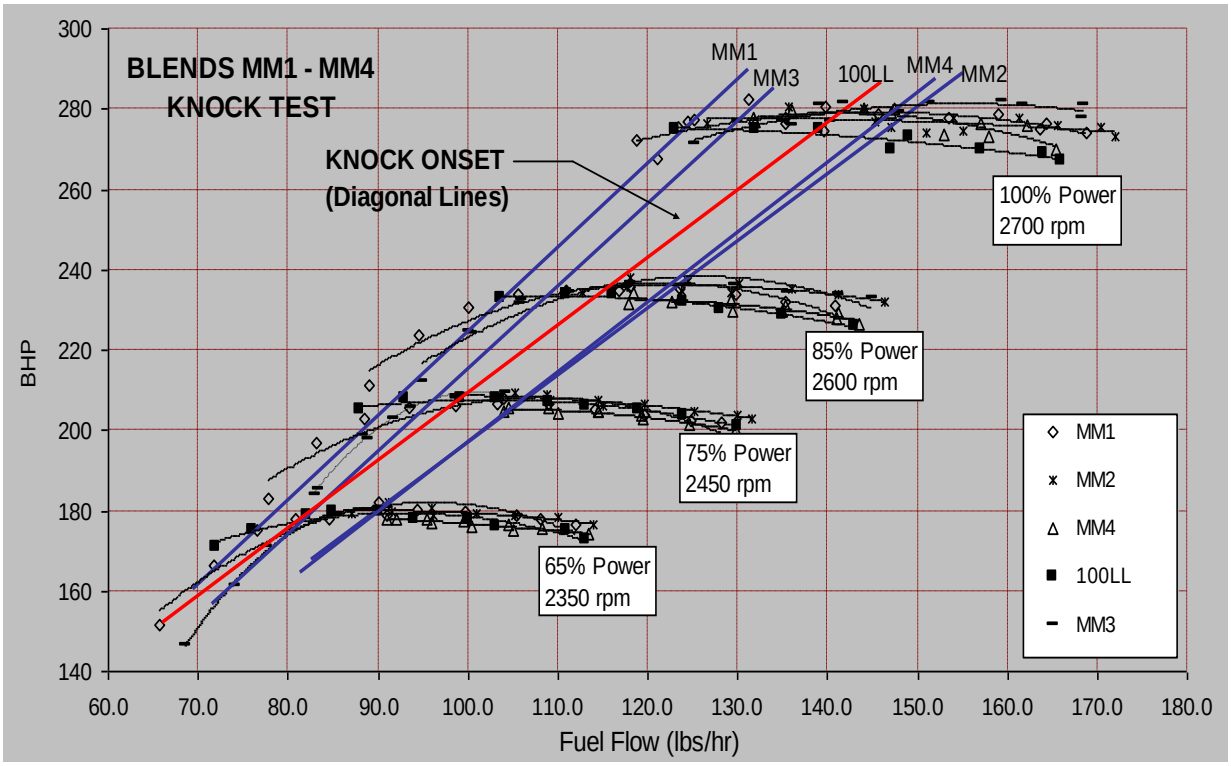

Figure 32.0 – FAA Knock Test, Blends MM1 – MM4 [12]

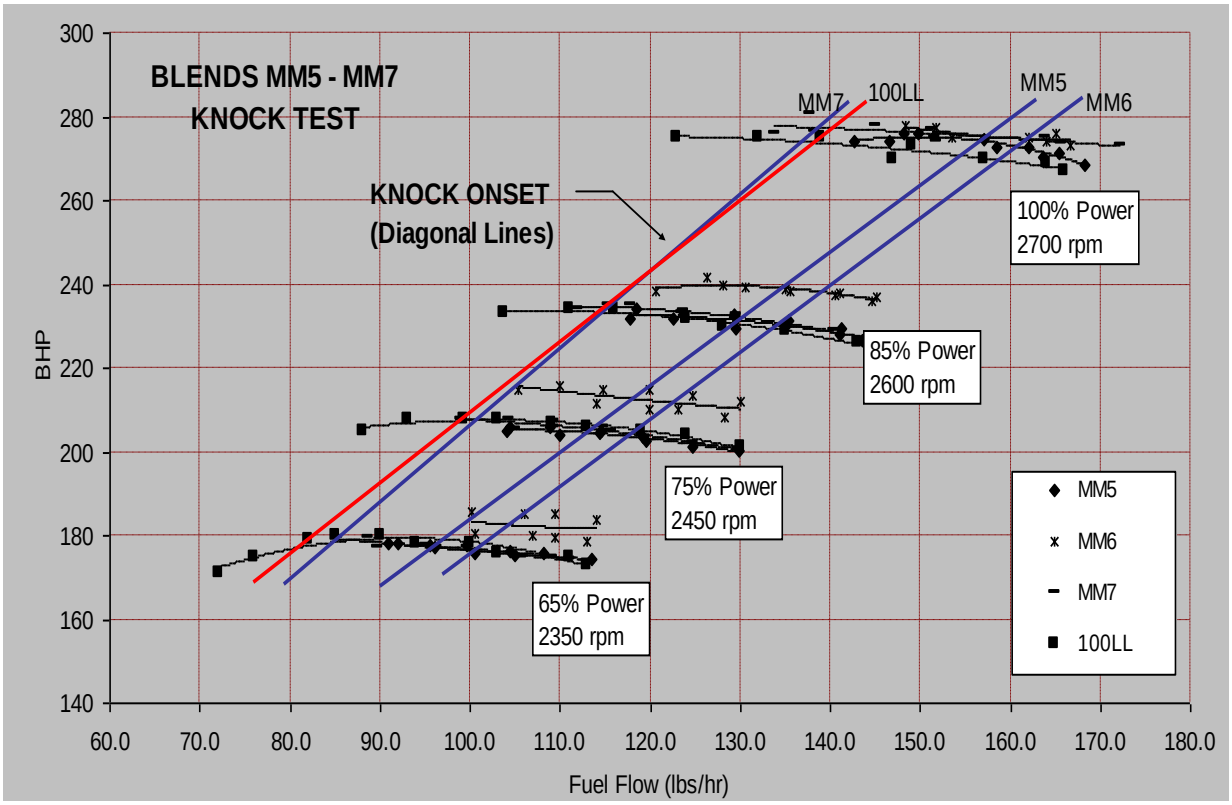

Figure 33.0 – FAA Knock Test, Blends MM5 – MM7 [12]

Figures 34.0 through 37.0 illustrate relative ranking of the blends within each of the four groups (AV, AM, MO, MM) using the data from the detonation lean out curves; these figures compare the observed fuel flow at onset of detonation for each of the blends with the baseline 100LL fuel. For example, blend AV1 encountered knock at 168 lbs/hr fuel flow which is 20.9% richer than the 139 lbs/hr fuel flow at knock onset for the 100LL baseline fuel. On the other hand, the best performing blend AV7 did not encounter knock until the fuel flow was leaned to 119 lbs/hr, 14.3% leaner than the 100LL baseline fuel flow.

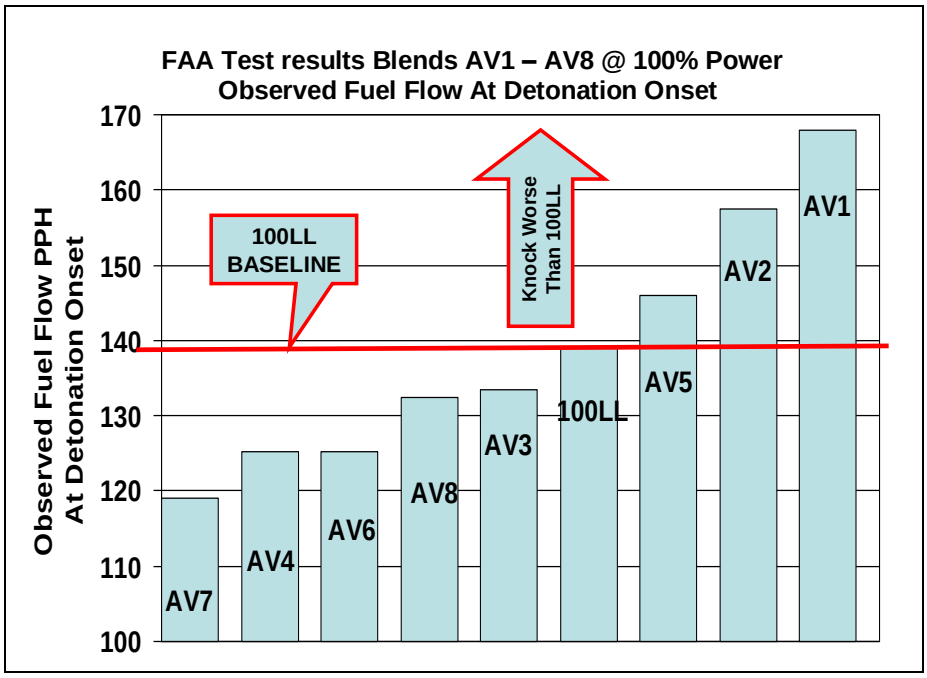

Figure 34.0 – Relative Ranking Blends AV1 – AV8, FAA Test

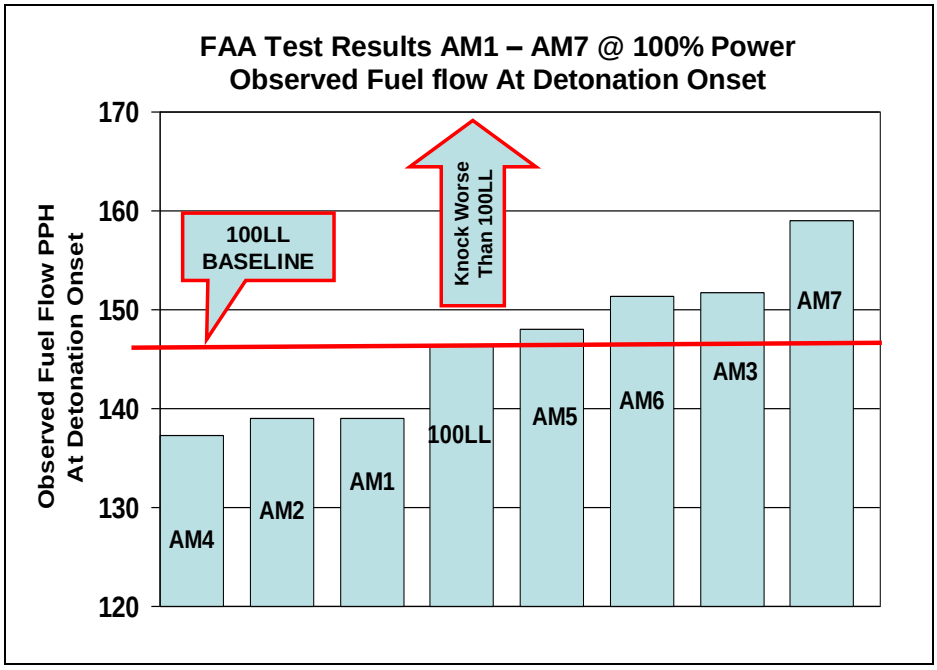

Figure 35.0 – Relative Ranking Blends AM1 – AM7, FAA Test

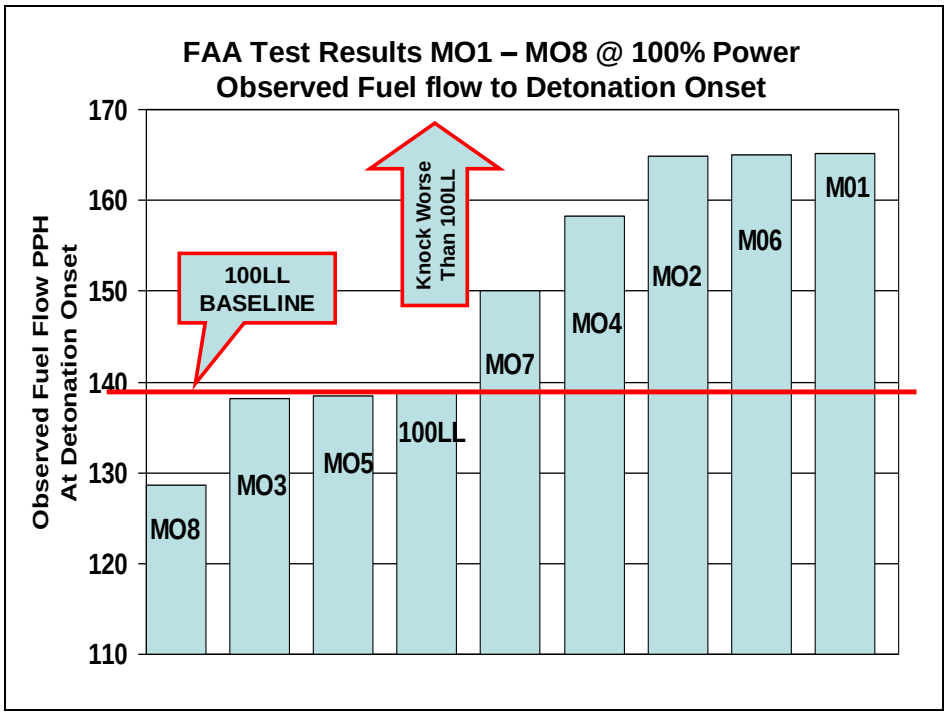

Figure 36.0 – Relative Ranking Blends MO1 – MO8, FAA Test

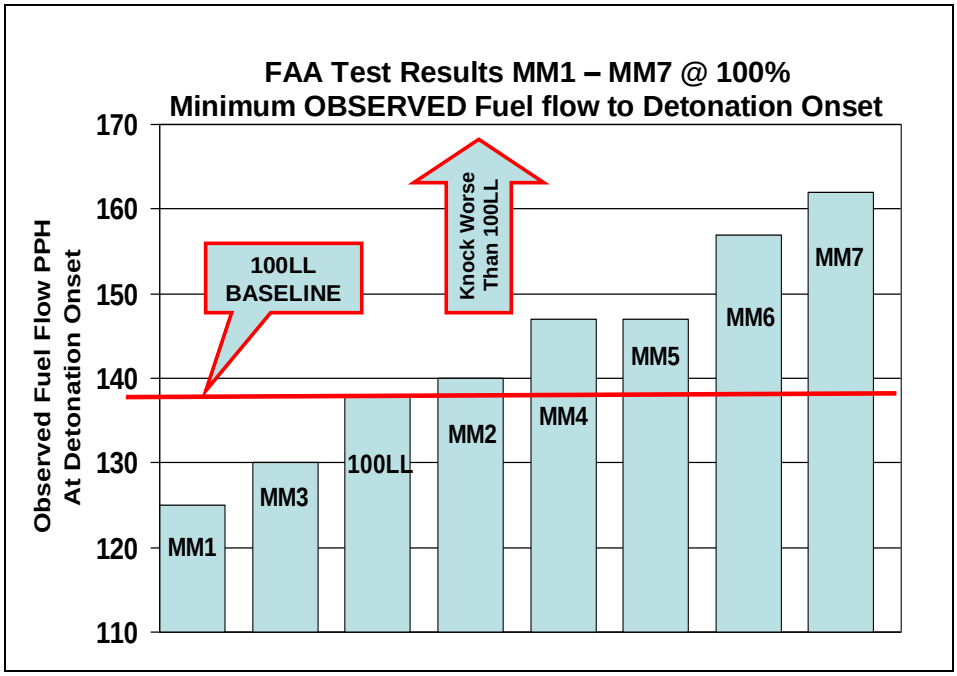

Figure 37.0 – Relative Ranking Blends MM1 – MM7, FAA Test

The following Tables 31.0 and 32.0 provide a tabular ranking of the blends for the aviation and motor alkylate groups respectively with blend formulations repeated for reference. The ranking is based upon observed fuel flow at knock onset with blends ranked from the best performing blends at the top of the list to the worst performing blends at the bottom of the list; the ranking is extracted from the previous Figures 26.0 through 33.0. Those color highlighted blends listed above 100LL provided an octane response as good as or better than the 100LL baseline. Those blends listed below 100LL provided an octane response worse than the baseline 100LL with the octane response becoming progressively worse from top to bottom. Significant observations are summarized as follows.

- As indicated in the far right hand columns of Tables 31.0 and 32.0, those blends with a higher MON rating tended to correlate well with the relative octane performance of the blend as measured in the full scale engine.
- Similarly, those blends with a rating lower than 100 MON provided poor octane response in the engine with detonation occurring at mixtures rich of the baseline 100LL fuel flow
- The ASTM D 2700 MON rating of the fuel agrees well with the calculated/predicted value, reference Section 6.5.3.4 for both the aviation and motor alkylate groups
- Generally, Tables 31.0 and 32.0 indicate that under the conditions of the test, an unleaded fuel with an MON rating of at least 101 was required to satisfy the octane requirement of the test engine to a similar or better level than the 100LL base fuel. Exceptions were blends AV5, MO4, and MO7 which fell below expectations.

Table 31.0
Phase II FAA Test Results Aviation Alkylate Blends
Ranking by Blend Number Based Upon Engine Onset of Knock [12]
[Knock Performance Ranked From Best at Top to Worst at Bottom]

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta* – Toluidine	Ethanol	g/gal MMT	Calc MON	D2700 MON	D909 PN
Aviation Alkylate Blends Without MMT										
AV7	0.0000	0.4997	0.2501	0.1502	0.1000	0.0000	0	104.6	105.6	>161
AV6	0.0000	0.3500	0.2501	0.2999	0.1001	0.0000	0	104.3	105.2	>161
AV4	0.4002	0.4997	0.0000	0.0000	0.1000	0.0000	0	104.1	104.4	>161
AV8	0.2916	0.4997	0.0000	0.0985	0.0784	0.0318	0	103.2	103.4	>161
AV3	0.0000	0.5000	0.2502	0.1898	0.0600	0.0000	0	102.9	103.4	>161
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
AV5	0.0000	0.4698	0.2501	0.2499	0.0302	0.0000	0	100.9	101.2	152.5
AV2	0.0402	0.3998	0.2500	0.2977	0.0103	0.0000	0	99.0	99.8	146.1
AV1	0.0730	0.3272	0.2500	0.2997	0.0000	0.0501	0	97.5	97.0	136.6
Aviation Alkylate Blends With MMT										
AM4	0.6001	0.0000	0.0000	0.2998	0.1000	0.0000	0.0500	102.5	102.9	155.6
AM2	0.8602	0.0000	0.0000	0.0000	0.0897	0.0501	0.1000	101.7	101.6	160.3
AM1	0.3324	0.2876	0.1376	0.1675	0.0500	0.0248	0.0500	100.9	101.0	146.6
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
AM5	0.8000	0.0000	0.1248	0.0000	0.0552	0.0199	0.0500	99.2	99.6	140.1
AM6	0.3549	0.4995	0.1404	0.0000	0.0052	0.0000	0.0500	97.1	96.6	122.4
AM3	0.8695	0.0000	0.0000	0.0705	0.0250	0.0350	0.1000	97.3	96.4	127.8
AM7	0.2500	0.4998	0.0000	0.2001	0.0000	0.0501	0.1000	99.0	99.6	129.6

Notes:
① Calc MON shown is predicted MON computed using Phase I regression models of Section 6.4.3.3
② Blend No. assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. Compositional data, MON, & PN taken from Exhibits VII & VIII of Appendix A. [10]
③ Ranking by knock on-set extracted from FAA Test Results Report. [12]
④ Highlighted blends are those providing knock response equivalent to or better than 100LL

Table 32.0
Phase II FAA Test Results Motor Alkylate Blends
Ranking by Blend Number Based Upon Engine Onset of Knock [12]
[Knock Performance Ranked From Best at Top to at Bottom]

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta* - Toluidine	Ethanol	g/gal MMT	Calc MON	D2700 MON	D909 PN
Motor Alkylate Blends Without MMT										
MO8	0.0000	0.4997	0.2496	0.1507	0.1000	0.0000	0	104.6	105.0	>161
MO3	0.1926	0.1358	0.2501	0.2999	0.1001	0.0216	0	103.4	103.6	152.5
MO5	0.0780	0.4718	0.0000	0.2999	0.1001	0.0501	0	104.2	104.6	156.6
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
MO7	0.0000	0.4342	0.2114	0.2393	0.0650	0.0501	0	102.9	102.3	149.4
MO4	0.0000	0.4251	0.2501	0.2998	0.0250	0.0000	0	100.6	101.0	131.2
MO2	0.0613	0.5001	0.2014	0.1742	0.0129	0.0501	0	99.0	99.2	123.1
MO6	0.9400	0.0000	0.0147	0.0000	0.0453	0.0000	0	97.1	96.7	121.8
MO1	0.2501	0.4501	0.0000	0.2998	0.0000	0.0000	0	98.1	98.1	114.1
Motor Alkylate Blends With MMT										
MM1	0.4001	0.4999	0.0000	0.0000	0.1001	0.0000	0.0920	103.6	103.8	>161
MM3	0.1108	0.4575	0.0776	0.2379	0.1000	0.0162	0.1000	103.3	104.0	>161
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
MM2	0.6999	0.0000	0.2401	0.0000	0.0599	0.0000	0.1000	99.1	99.4	151.1
MM4	0.3327	0.2877	0.1377	0.1675	0.0501	0.0243	0.0500	100.7	100.7	144.2
MM5	0.2260	0.4998	0.2511	0.0000	0.0000	0.0232	0.1000	97.0	96.8	132.5
MM6	0.5000	0.0997	0.1002	0.2349	0.0151	0.0501	0.0520	97.0	96.2	121.8
MM7	0.8602	0.0000	0.0000	0.0000	0.0896	0.0501	0.1000	101.1	100.9	156.8

Notes:
① Calc MON shown is predicted MON computed using Phase I regression models of Section 6.4.3.3
② Blend No. assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. Compositional data, MON, & PN taken from Exhibit VII & VIII of Appendix A. [10]
③ Ranking by knock on-set extracted from FAA Test Results Report. [12]
④ Highlited blends are those providing knock response equivalent to or better than 100LL

6.5.4.2. Cessna Aircraft Test Results

A parallel engine test program using an identical group of the Phase II unleaded blends was carried out by Cessna Aircraft concurrently with the FAA tests. Full scale engine detonation testing of the 30 unleaded experimental blends listed in Tables 24.0 and 25.0 was also completed in September 2002 at Cessna's Test Facility located at Cessna Aircraft in Wichita Kansas. Results of these tests are documented in Cessna's Report "Cessna Evaluation of CRC Fuel Matrix Blends dated December 2005. [13] A copy of this report is on file at the Coordinating Research Council. A description of the IO-320-X test engine and the associated Cessna test methods, test equipment, and associated procedures are presented in Sections 6.3.3 – 6.3.5 of

this report. The objective of the full scale engine tests was to compare the knock performance of the unleaded fuel blends against a baseline minimum specification 100LL fuel and to explore correlation of blend MON with engine octane requirement

As discussed in Section 6.3.5.3, the Cessna knock test procedure involved setting the power level using the engine throttle and leaning the fuel flow in increments of 3-5% fuel flow beginning at or near the full rich setting and continuing to lean until heavy knock or until detonation free operation re-emerged on the lean side of best power while maintaining 230°F ±2°F induction air temperature at the inlet of the engine throttle body. CHT were not controlled but were allowed to respond naturally to change in fuel mixture. Induction air relative humidity was not controlled but was documented for the ambient air conditions for each test. Cessna testing of each unleaded fuel was performed at three separate power settings which were established by setting manifold pressure (27 MAP, 25.5 MAP, & 24 MAP) using the engine throttle with the fixed pitch propeller loading the engine at the resulting engine speed.

Whereas the Cessna test method relied upon a fix pitch propeller to load the engine, the resulting engine performance followed the classical propeller load curve (Section 6.3.5.3, Figure 15.0) as fuel flow was leaned during the fuel detonation test. To accommodate the multiple variables of BHP and RPM, engine loading was characterized in terms of BMEP using the equation of Figure 16.0; see also Figure 2A, Section A of reference 13.

Each of the four cylinders was monitored continuously for indications of detonation using the instrumented cylinder head technology described in Section 6.3.5.3 and in the Cessna Report[13]. In excess of 11 mixture lean out curves were conducted. Note that the Cessna tests conducted lean outs at three separate power settings whereas the FAA tests involved lean out curves at four separate power settings.

Results of the Cessna mixture lean out curves are shown graphically in the following Figures 37.0 through 44.0 which are extracted from the Cessna Test Results Report[12]. The diagonal lines shown on each of the mixture lean out curves indicates the “fuel flow at onset of combustion knock” for each fuel blend including the baseline 100LL as the fuel flow is varied for the three different power settings. Those fuels noted by a diagonal line to the right of the 100LL diagonal line performed worst than the 100LL baseline fuel. Those fuels noted by a diagonal line to the left of the 100LL diagonal line performed better than the 100LL baseline fuel. Fuel blends which knock at a fuel flow richer than the 100LL baseline are viewed negatively since they would require significant changes to existing aircraft and engines with a negative impact on energy consumption. Fuel blends which are characterized by knock at a fuel flow leaner than the baseline fuel provide increased knock margin.

Note that the Cessna lean out curves are plotted in terms of BMEP versus volumetric fuel flow whereas the FAA lean out curves depict BHP versus mass fuel flow. Many small aircraft have fuel gages which indicate volumetric flow in gals/hr.

Similar to the FAA Phase II report, the Cessna Test Results Report[13] contains an enormous amount of data which offers the potential for further analysis for effect of blend formulations on engine characteristics such as BSFC, fuel/air ratio, BHP at best power, and EGT. Comparative analysis of BHP, BSFC, EGT, and CHT for the blends tested is addressed within the Cessna Test Results Report. This summary research report focuses primarily on engine octane response and correlation with blend MON rating.

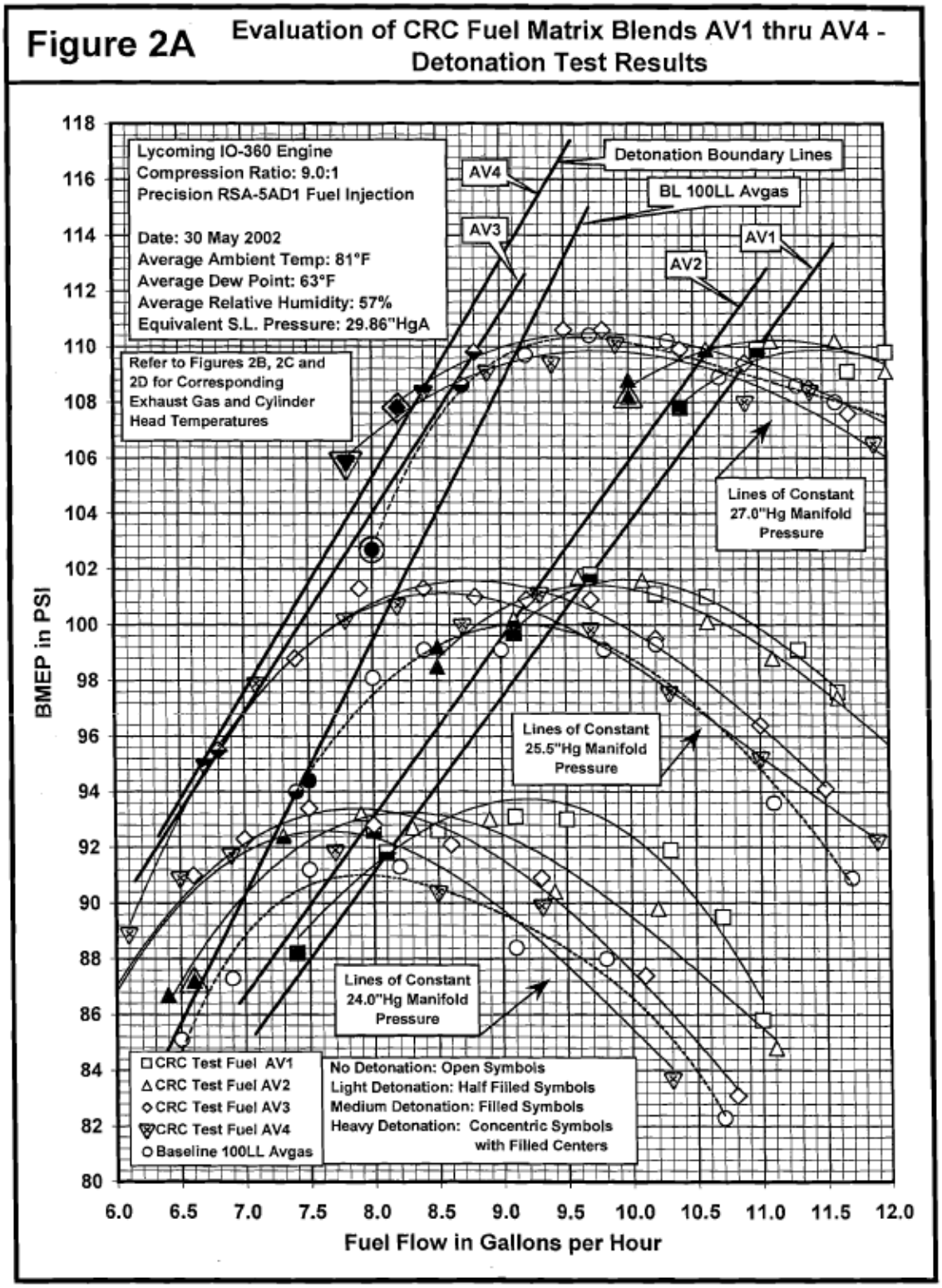

Figure 38.0 – Cessna Knock Test, Mixture Lean Out, Blends AV1-AV4 [13]

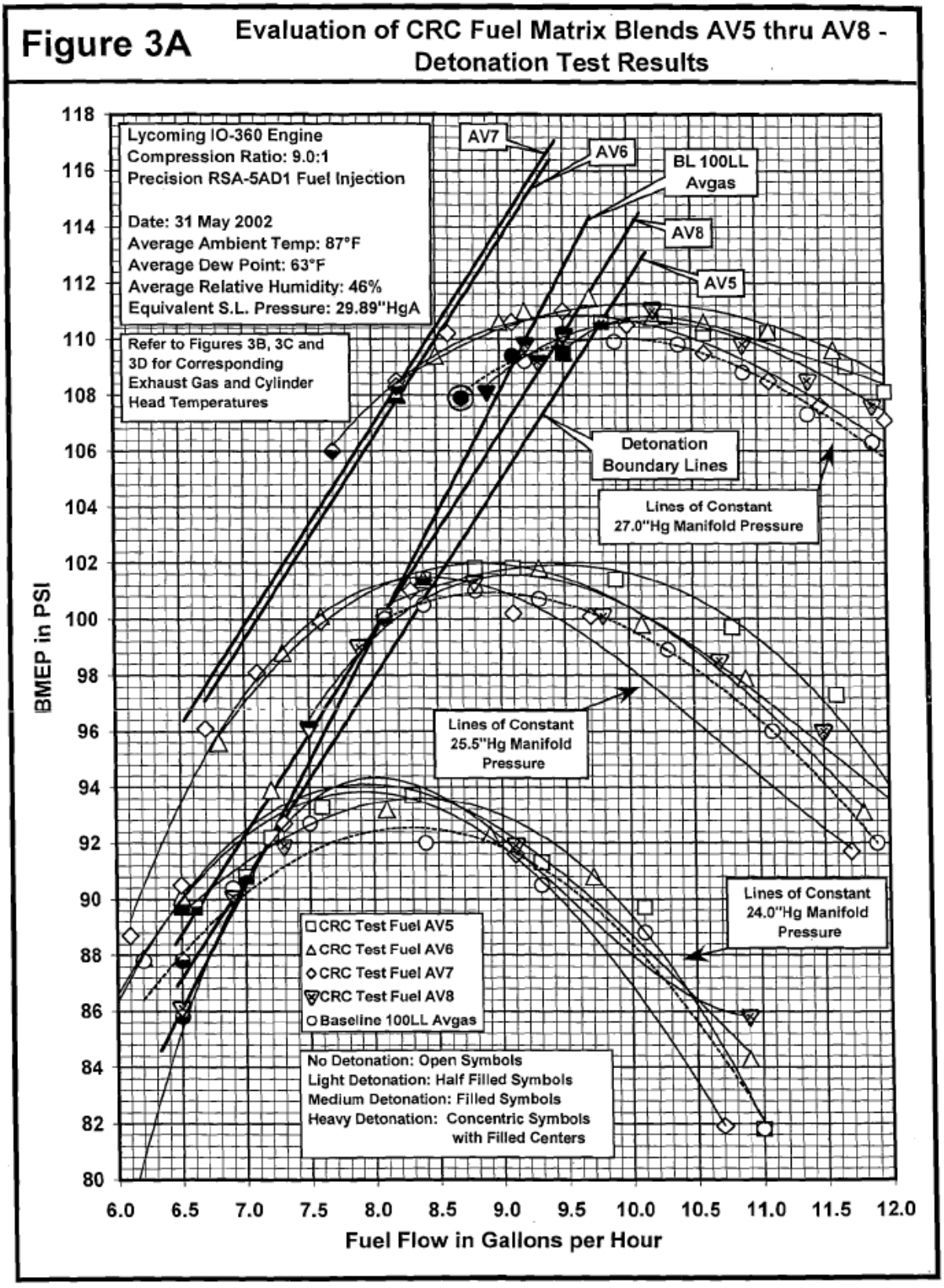

Figure 39.0 – Cessna Knock Test, Mixture Lean Out, Blends AV5-AV8 [13]

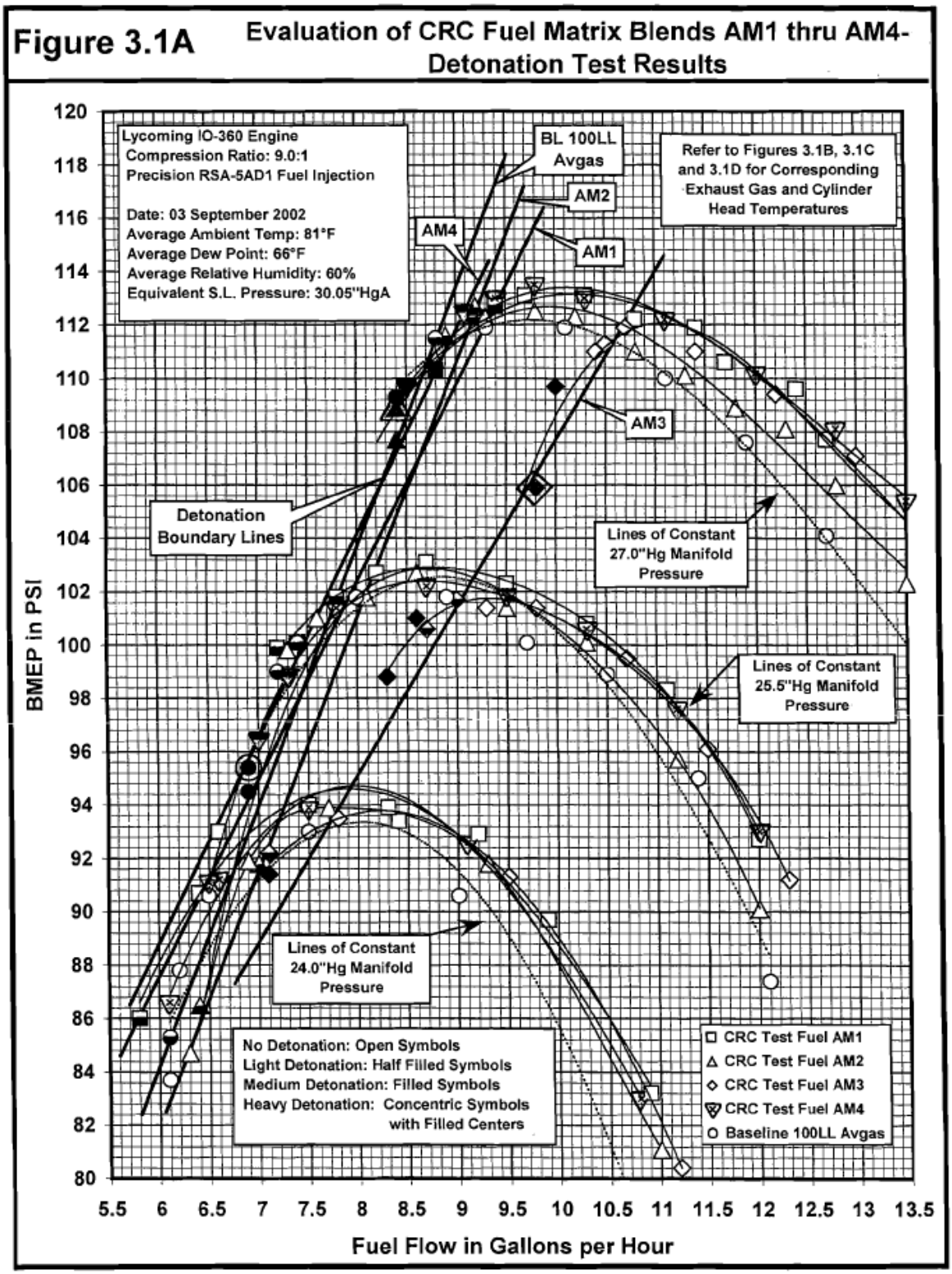

Figure 40.0 – Cessna Knock Test, Mixture Lean Out, Blends AM1-AM4 [13]

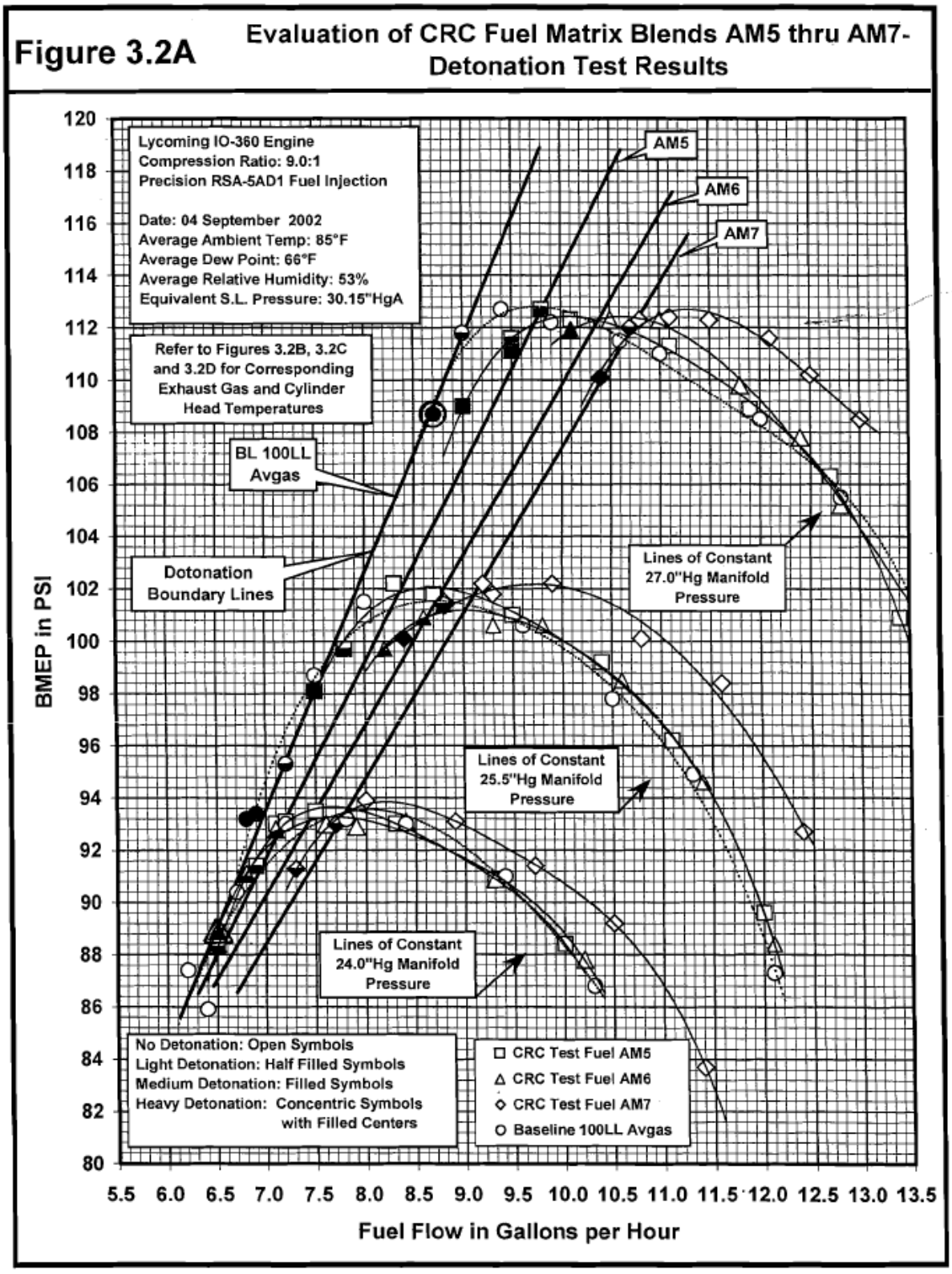

Figure 41.0 – Cessna Knock Test, Mixture Lean Out, Blends AM5-AM7 [13]

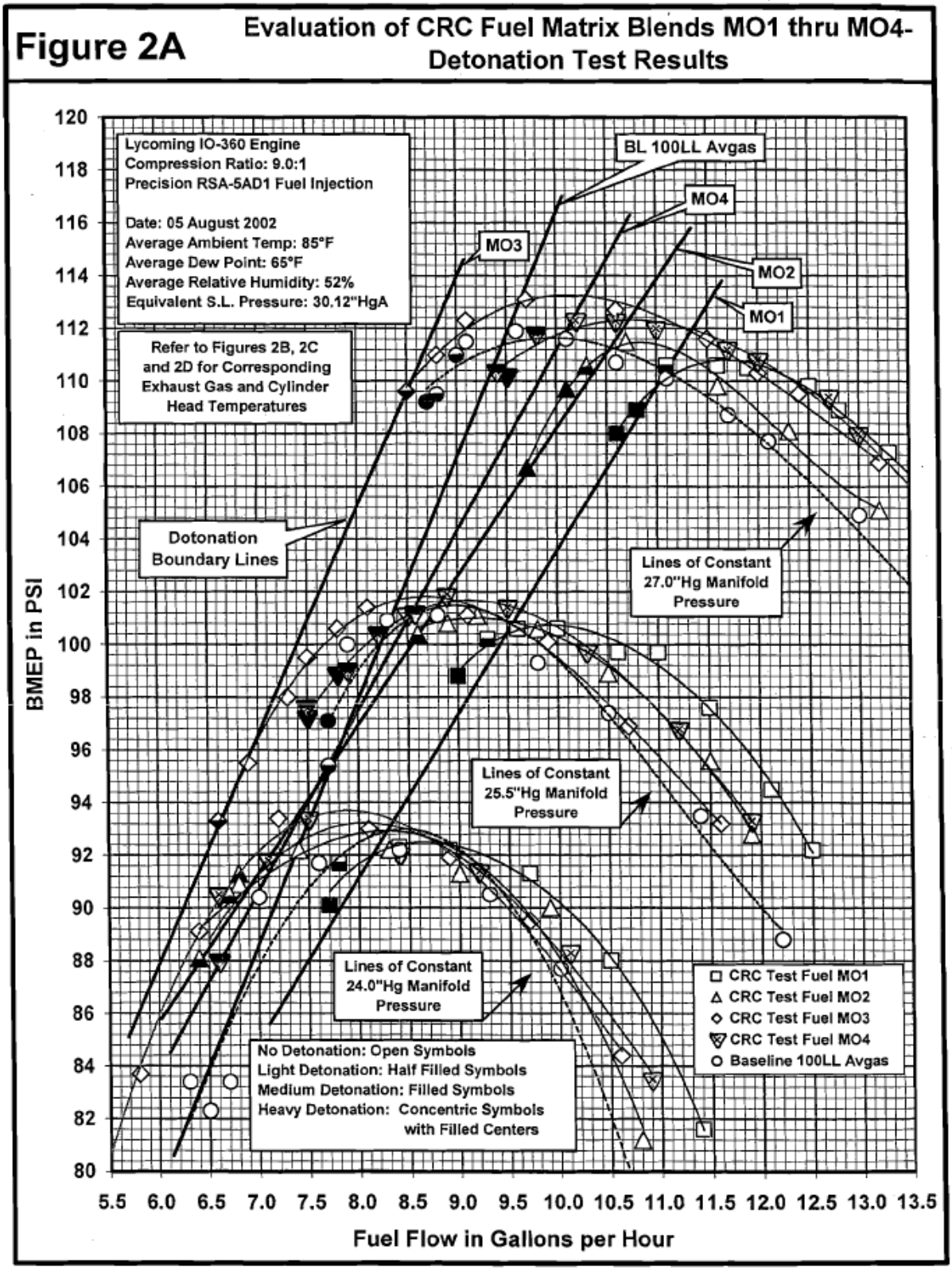

Figure 42.0 – Cessna Knock Test, Mixture Lean Out, Blends MO1-MO4 [13]

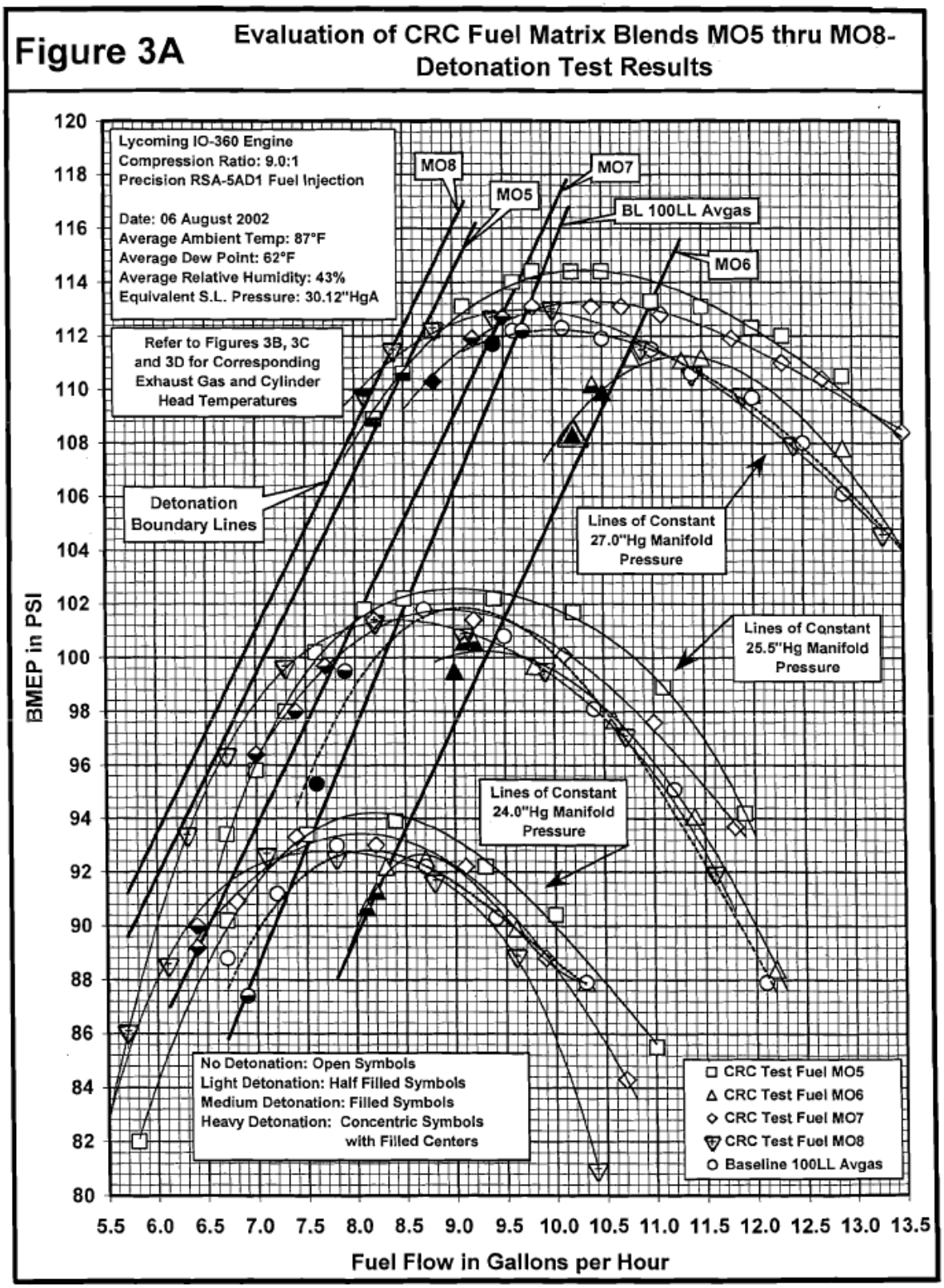

Figure 43.0 – Cessna Knock Test, Mixture Lean Out, Blends MO5-MO8 [13]

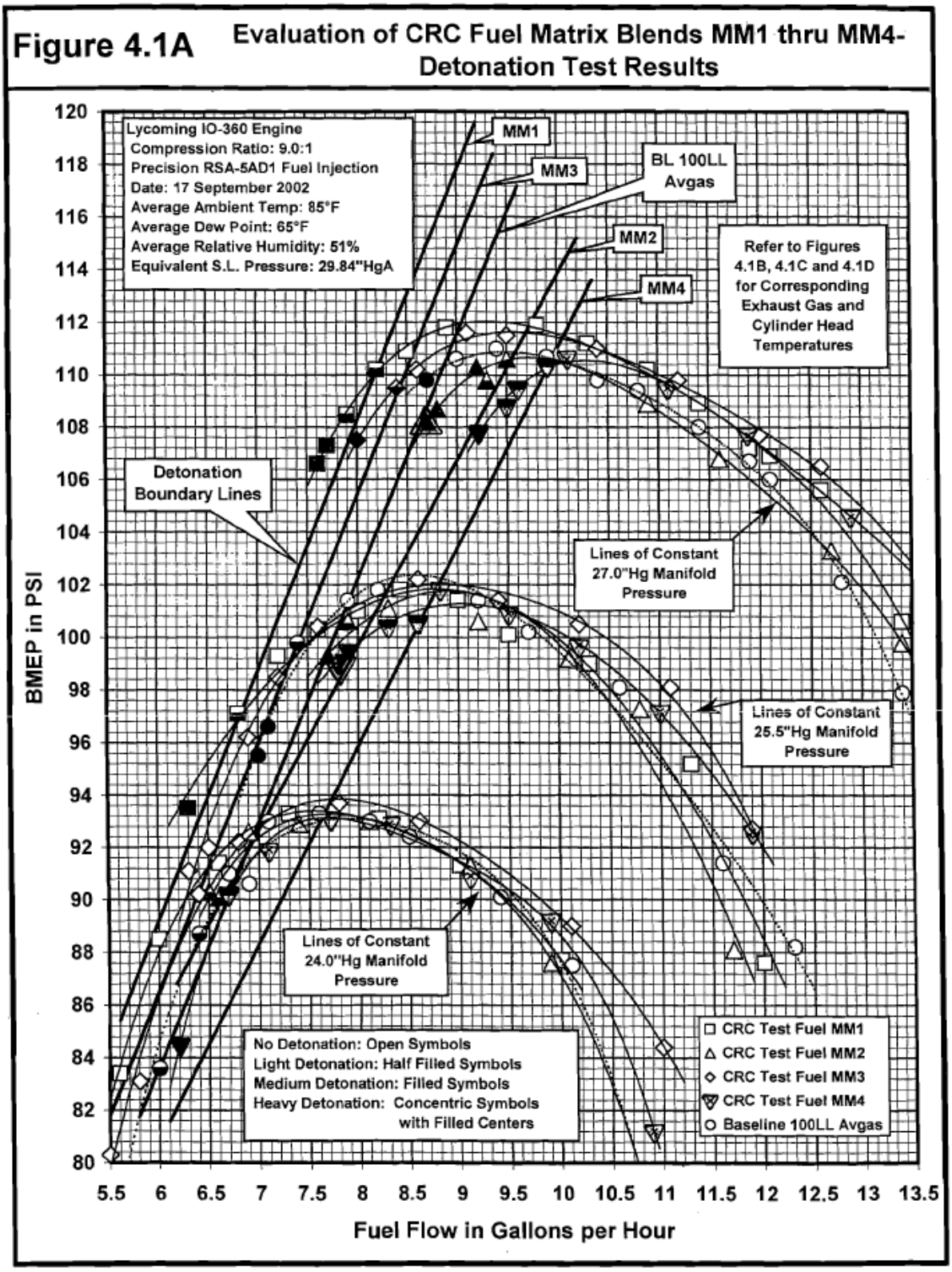

Figure 44.0 – Cessna Knock Test, Mixture Lean Out, Blends MM1-MM4 [13]

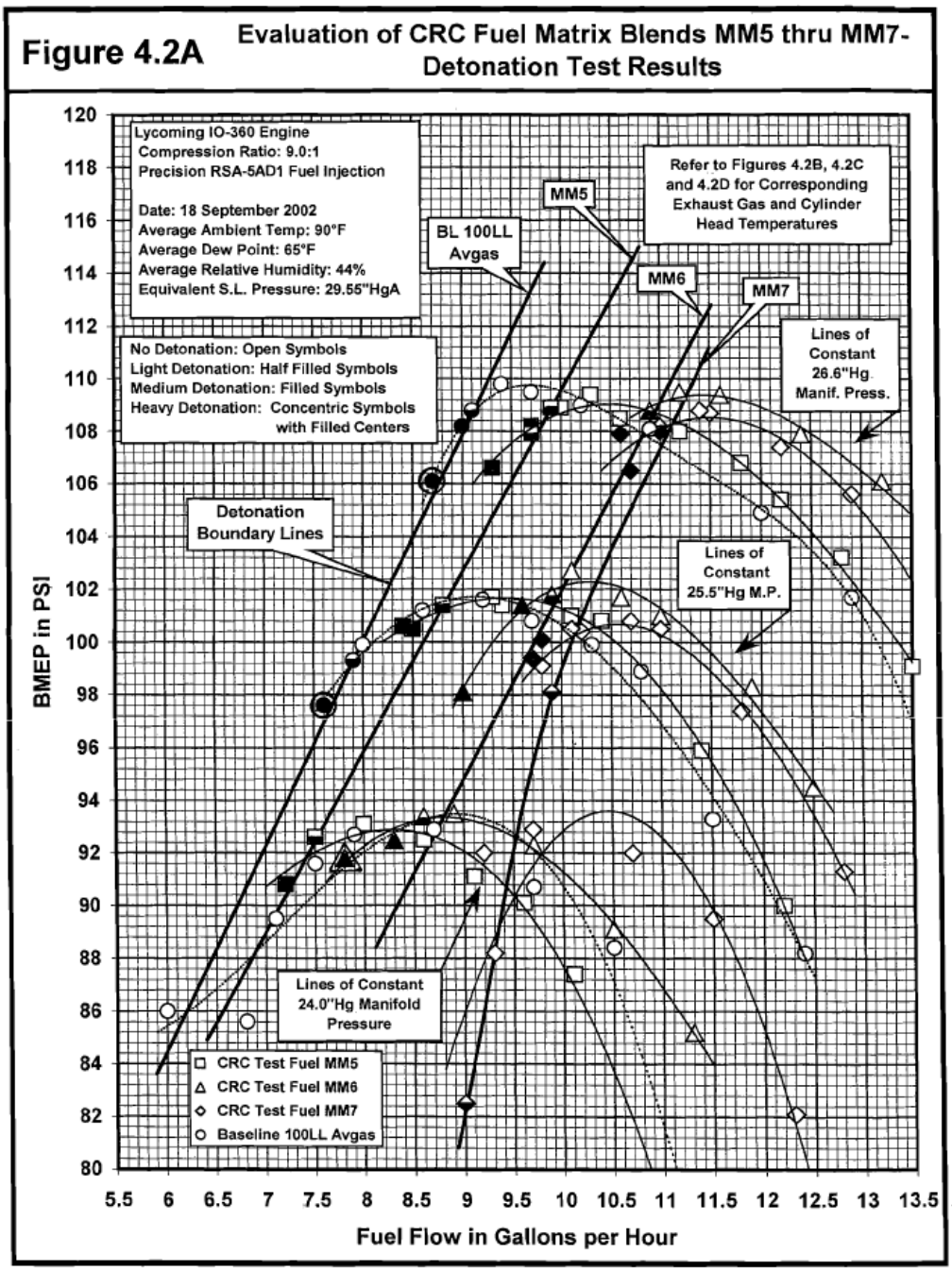

Figure 45.0 – Cessna Knock Test, Mixture Lean Out, Blends MM5-MM7 [13]

The following Figures 46.0 through 49.0 illustrate relative ranking of the blends tested by Cessna for each of the four groups (AV, AM, MO, MM) using the data from the lean out curves; these figures compare the observed volumetric fuel flow at onset of detonation for each of the blends with the baseline 100LL fuel and are based upon the data contained within the Cessna Test Results Report[13]. For example, blend AV1 encountered knock at 10.7 gals/hr fuel flow which is 19.4% richer than the 8.96 gals/hr fuel flow at knock onset for the 100LL baseline fuel. The best performing blend AV7 did not encounter knock until the fuel flow was leaned to 7.92 gals/hr, 13.4% leaner than the 100LL baseline fuel flow.

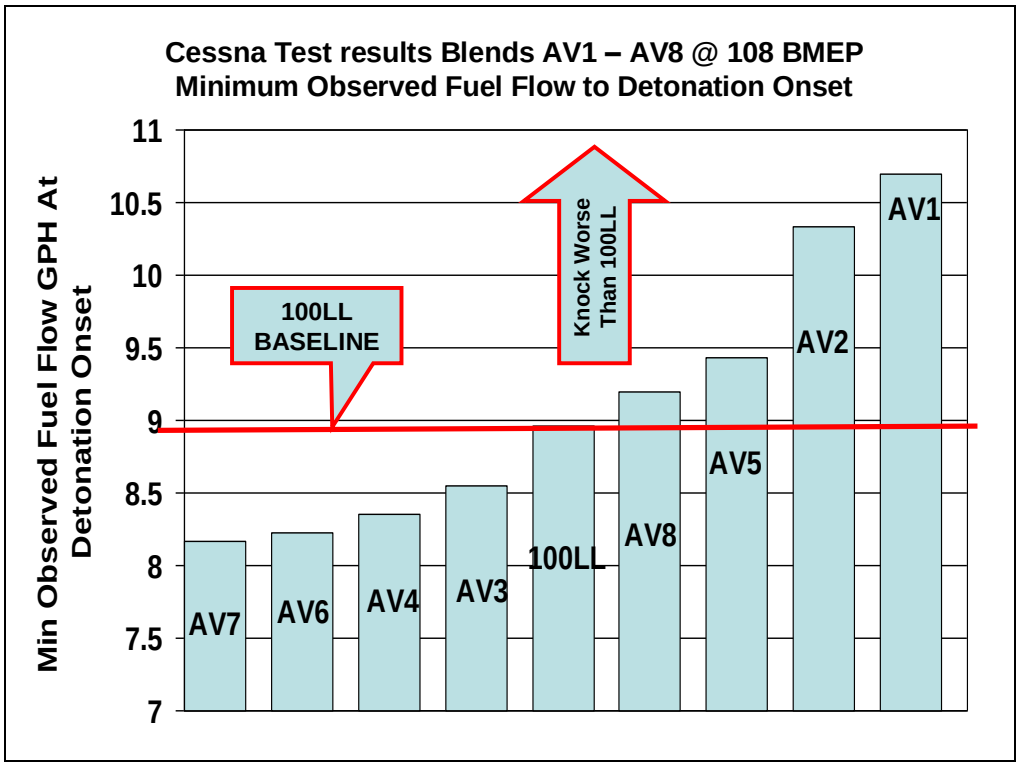

Figure 46.0 – Relative Ranking Blends AV1 – AV8, Cessna Test

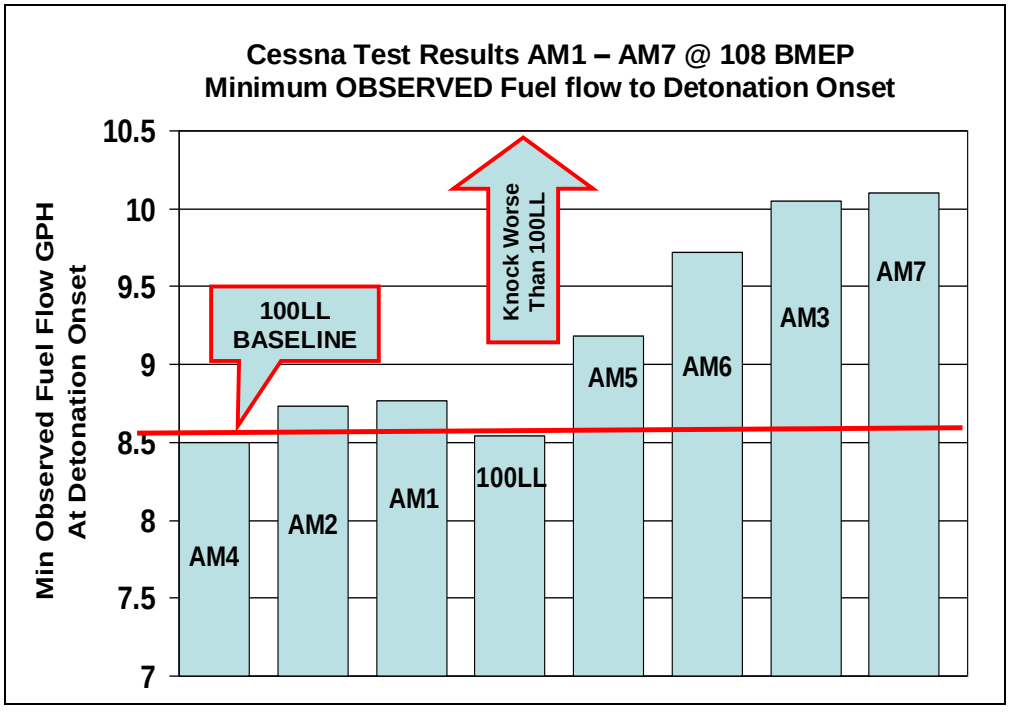

Figure 47.0 – Relative Ranking Blends AM1 – AM7, Cessna Test

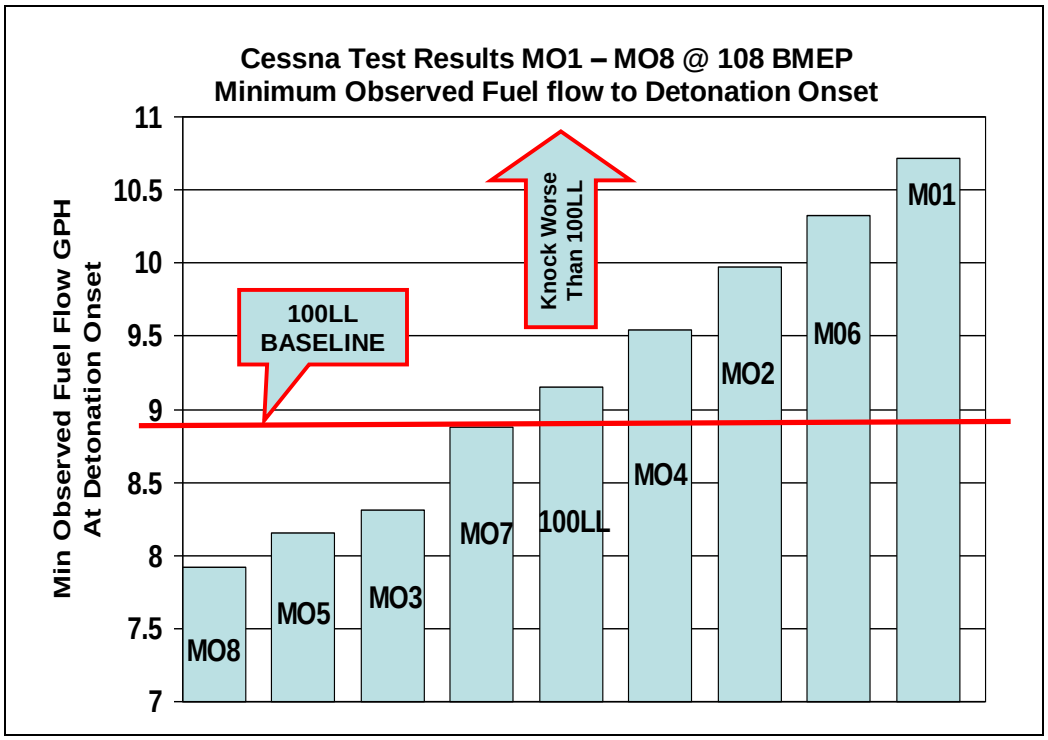

Figure 48.0 – Relative Ranking Blends MO1 – MO8, Cessna Test

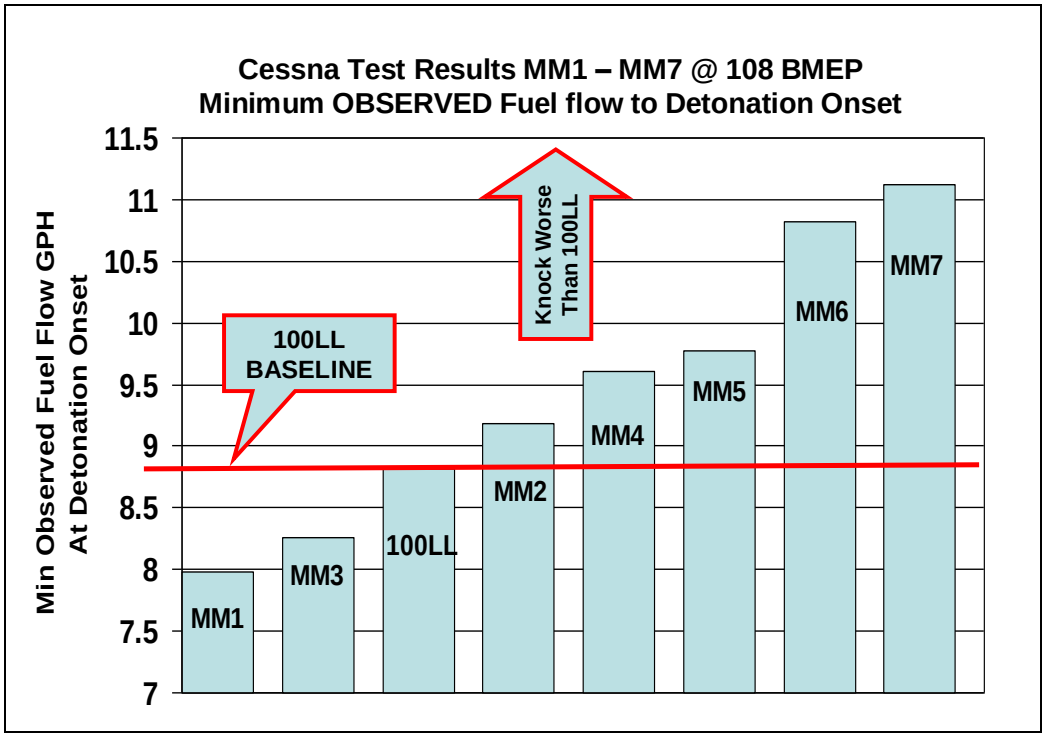

Figure 49.0 – Relative Ranking Blends MM1 – MM7, Cessna Test

The following Tables 33.0 and 34.0 provide a tabular ranking of the blends for the aviation and motor alkylate groups respectively as tested by Cessna with blend formulations again repeated for reference. The ranking is based upon observed fuel flow at knock onset with blends ranked from the best performing blends at the top of the list to the worst performing blends at the bottom of the list; the ranking is extracted from the previous Figures 46.0 through 49.0. Consistent with the FAA test results, those color highlighted blends listed above 100LL provided an octane response as good as or better than the 100LL baseline. Those blends listed below 100LL provided an octane response worse than the baseline 100LL with the octane response becoming progressively worse from top to bottom. Significant observations for the Cessna detonation tests of the Phase II blends are summarized as follows.

- As indicated in the far right hand columns of Tables 33.0 and 34.0, those blends with a higher MON rating correlate well with the relative octane performance of the blend as measured in the full scale engine [same as observed for FAA test results]
- Similarly, those blends with a rating lower than 100 MON provided poor octane response in the engine with detonation occurring at mixtures rich of the baseline 100LL fuel flow [same as observed for FAA test results]
- The ASTM D 2700 MON rating of the fuel agrees well with the calculated/predicted value, reference Section 6.5.3.4 for both the aviation and motor alkylate groups
- Generally, Tables 33.0 and 34.0 indicate that under the conditions of the test, an unleaded fuel with an MON rating of over 102 was required to satisfy the octane requirement of the test engine to a similar or better level than the 100LL base fuel. An exception was blend AV8, MON 103.4, which fell below expectations.

Table 33.0
Phase II Cessna Test Results Aviation Alkylate Blends
Ranking by Blend Number Based Upon Engine Onset of Knock [13]
[Knock Performance Ranked From Best at Top to Worst at Bottom]

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta* - Toluidine	Ethanol	g/gal MMT	Calc MON	D2700 MON	D909 PN
Aviation Alkylate Blends Without MMT										
AV7	0.0000	0.4997	0.2501	0.1502	0.1000	0.0000	0	104.6	105.6	>161
AV6	0.0000	0.3500	0.2501	0.2999	0.1001	0.0000	0	104.3	105.2	>161
AV4	0.4002	0.4997	0.0000	0.0000	0.1000	0.0000	0	104.1	104.4	>161
AV3	0.0000	0.5000	0.2502	0.1898	0.0600	0.0000	0	102.9	103.4	>161
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
AV8	0.2916	0.4997	0.0000	0.0985	0.0784	0.0318	0	103.2	103.4	>161
AV5	0.0000	0.4698	0.2501	0.2499	0.0302	0.0000	0	100.9	101.2	152.5
AV2	0.0402	0.3998	0.2500	0.2977	0.0103	0.0000	0	99.0	99.8	146.1
AV1	0.0730	0.3272	0.2500	0.2997	0.0000	0.0501	0	97.5	97.0	136.6
Aviation Alkylate Blends With MMT										
AM4	0.6001	0.0000	0.0000	0.2998	0.1000	0.0000	0.0500	102.5	102.9	155.6
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
AM2	0.8602	0.0000	0.0000	0.0000	0.0897	0.0501	0.1000	101.7	101.6	160.3
AM1	0.3324	0.2876	0.1376	0.1675	0.0500	0.0248	0.0500	100.9	101.0	146.6
AM5	0.8000	0.0000	0.1248	0.0000	0.0552	0.0199	0.0500	99.2	99.6	140.1
AM6	0.3549	0.4995	0.1404	0.0000	0.0052	0.0000	0.0500	97.1	96.6	122.4
AM3	0.8695	0.0000	0.0000	0.0705	0.0250	0.0350	0.1000	97.3	96.4	127.8
AM7	0.2500	0.4998	0.0000	0.2001	0.0000	0.0501	0.1000	99.0	99.6	129.6

Notes:
① Calc MON shown is predicted MON computed using Phase I regression models of Section 6.4.3.3
② Blend Label assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. Compositional data, MON, & PN taken from Exhibit VII & VIII of Appendix A. [10]
③ Ranking by knock on-set extracted from Cessna Test Results Report. [13]
④ Highlighted blends are those providing engine knock response equivalent to or better than 100LL

Table 34.0
Phase II Cessna Test Results Motor Alkylate Blends
Ranking by Blend Number Based Upon Engine Onset of Knock [13]
[Knock Performance Ranked From Best at Top to at Bottom]

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta* – Toluidine	Ethanol	g/gal MMT	Calc MON	D2700 MON	D909 PN
Motor Alkylate Blends Without MMT										
MO8	0.0000	0.4997	0.2496	0.1507	0.1000	0.0000	0	104.6	105.0	>161
MO5	0.0780	0.4718	0.0000	0.2999	0.1001	0.0501	0	104.2	104.6	156.6
MO3	0.1926	0.1358	0.2501	0.2999	0.1001	0.0216	0	103.4	103.6	152.5
MO7	0.0000	0.4342	0.2114	0.2393	0.0650	0.0501	0	102.9	102.3	149.4
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
MO4	0.0000	0.4251	0.2501	0.2998	0.0250	0.0000	0	100.6	101.0	131.2
MO2	0.0613	0.5001	0.2014	0.1742	0.0129	0.0501	0	99.0	99.2	123.1
MO6	0.9400	0.0000	0.0147	0.0000	0.0453	0.0000	0	97.1	96.7	121.8
MO1	0.2501	0.4501	0.0000	0.2998	0.0000	0.0000	0	98.1	98.1	114.1
Motor Alkylate Blends With MMT										
MM1	0.4001	0.4999	0.0000	0.0000	0.1001	0.0000	0.0920	103.6	103.8	>161
MM3	0.1108	0.4575	0.0776	0.2379	0.1000	0.0162	0.1000	103.3	104.0	>161
100LL	NA	NA	NA	NA	NA	NA	NA	NA	100.3	-
MM2	0.6999	0.0000	0.2401	0.0000	0.0599	0.0000	0.1000	99.1	99.4	151.1
MM4	0.3327	0.2877	0.1377	0.1675	0.0501	0.0243	0.0500	100.7	100.7	144.2
MM5	0.2260	0.4998	0.2511	0.0000	0.0000	0.0232	0.1000	97.0	96.8	132.5
MM6	0.5000	0.0997	0.1002	0.2349	0.0151	0.0501	0.0520	97.0	96.2	121.8
MM7	0.8602	0.0000	0.0000	0.0000	0.0896	0.0501	0.1000	101.1	100.9	156.8

Notes:
① Calc MON shown is predicted MON computed using Phase I regression models of Section 6.4.3.3
② Blend Label assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. Compositional data, MON, & PN taken from Exhibit VII & VIII of Appendix A. [10]
③ Ranking by knock on-set extracted from Cessna Test Results Report. [13]
④ Highlighted blends are those providing engine knock response equivalent to or better than 100LL

6.5.5. Comparison FAA & Cessna Test Results

Of significant interest during the Phase II full scale engine tests was correlation between the FAA test results and the Cessna test results in consideration of the differences in test set up, detonation test equipment, and test methods. The following Figures 50.0 through 53.0 provide a comparison between the FAA and Cessna test results by comparing the percent change in observed fuel flow at knock onset for each of the blends based upon the 100LL baseline fuel flow. Although test methods and engines differed between the two test resources, results and conclusions are generally consistent and complimentary.

As evident from Figures 50.0 – 53.0, the test results from the two test facilities tended to correlate with the two being in agreement with respect to the relative octane performance of the blends as compared to the 100LL baseline fuel. The exception was blends AV8, MO7, and MM7.

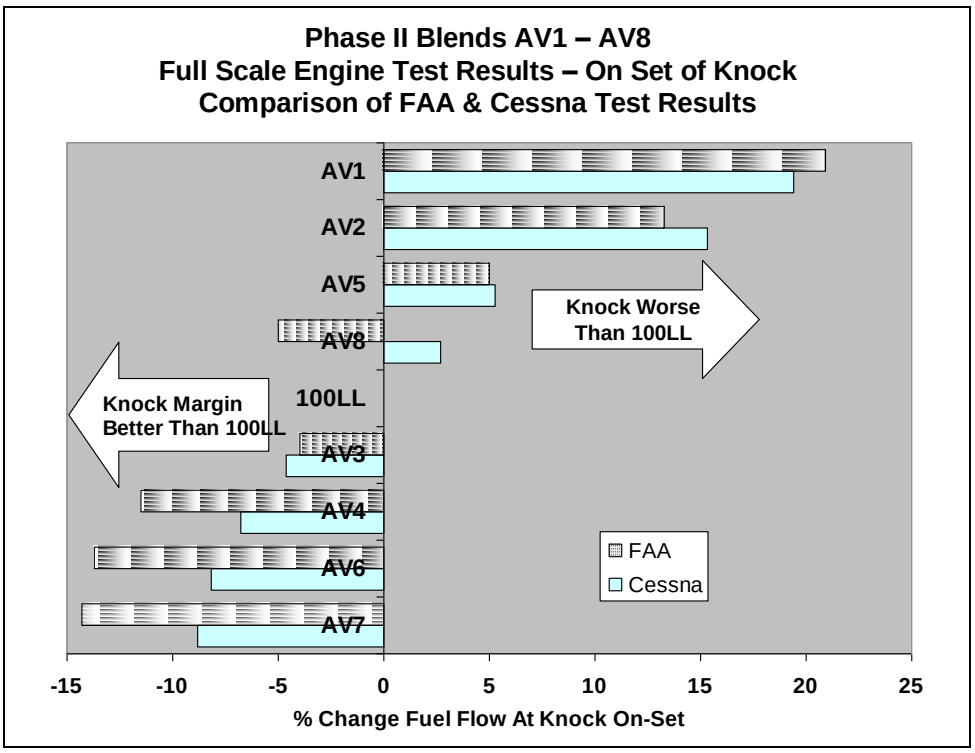

Figure 50.0 – Comparison FAA & Cessna Results AV1-AV8

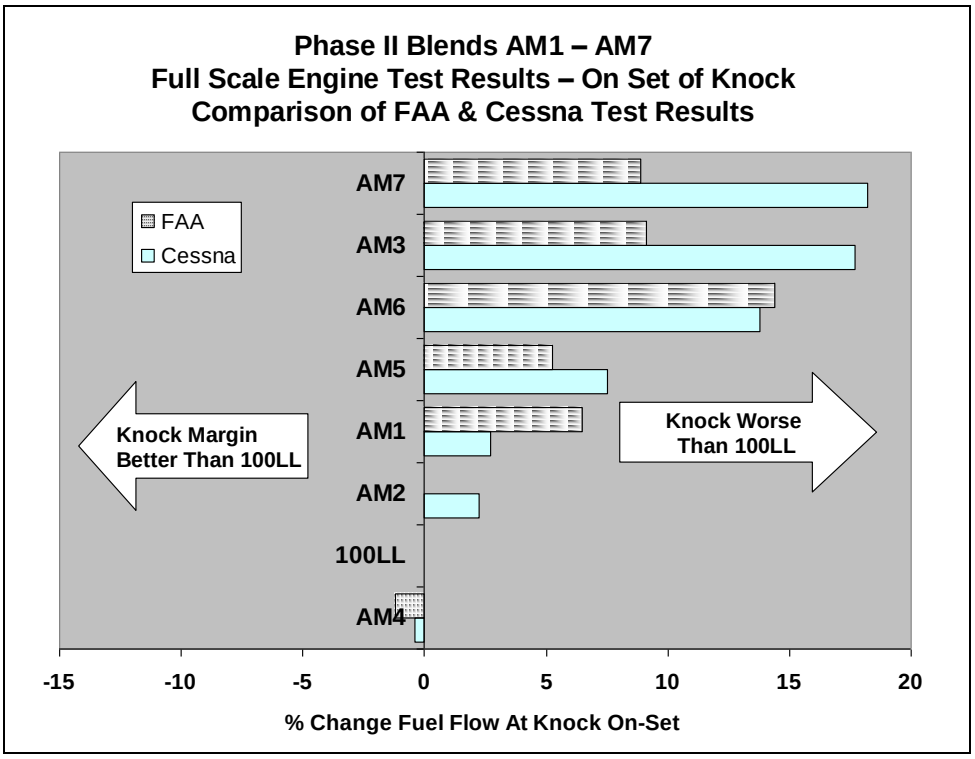

Figure 51.0 – Comparison FAA & Cessna Results AM1-AM7

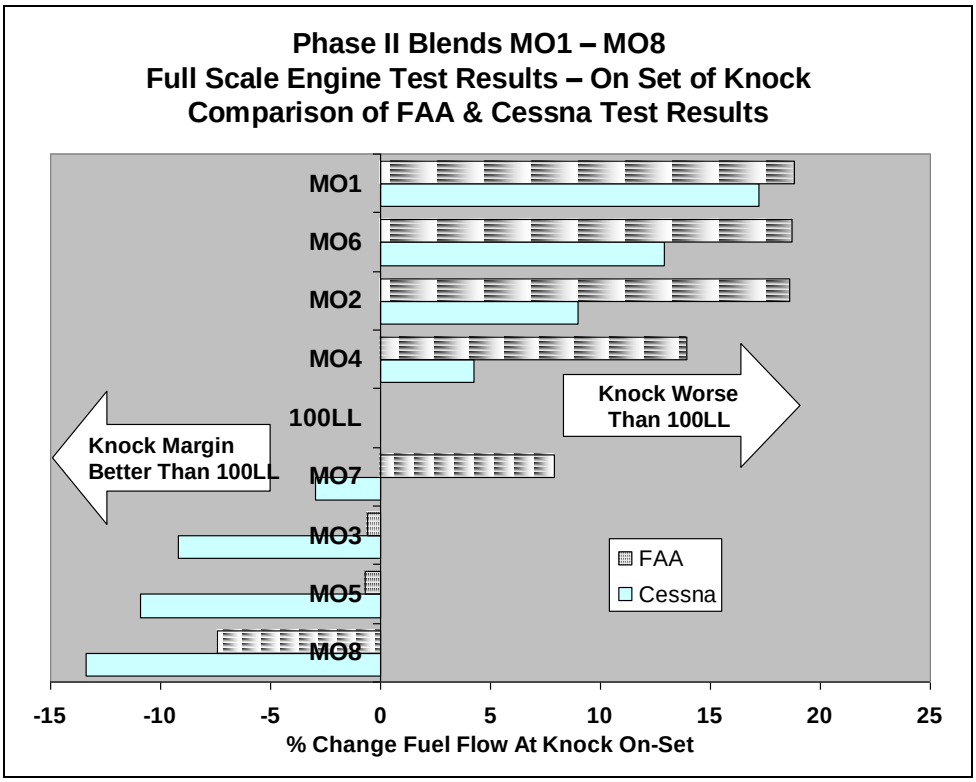

Figure 52.0 – Comparison FAA & Cessna Results MO1-MO8

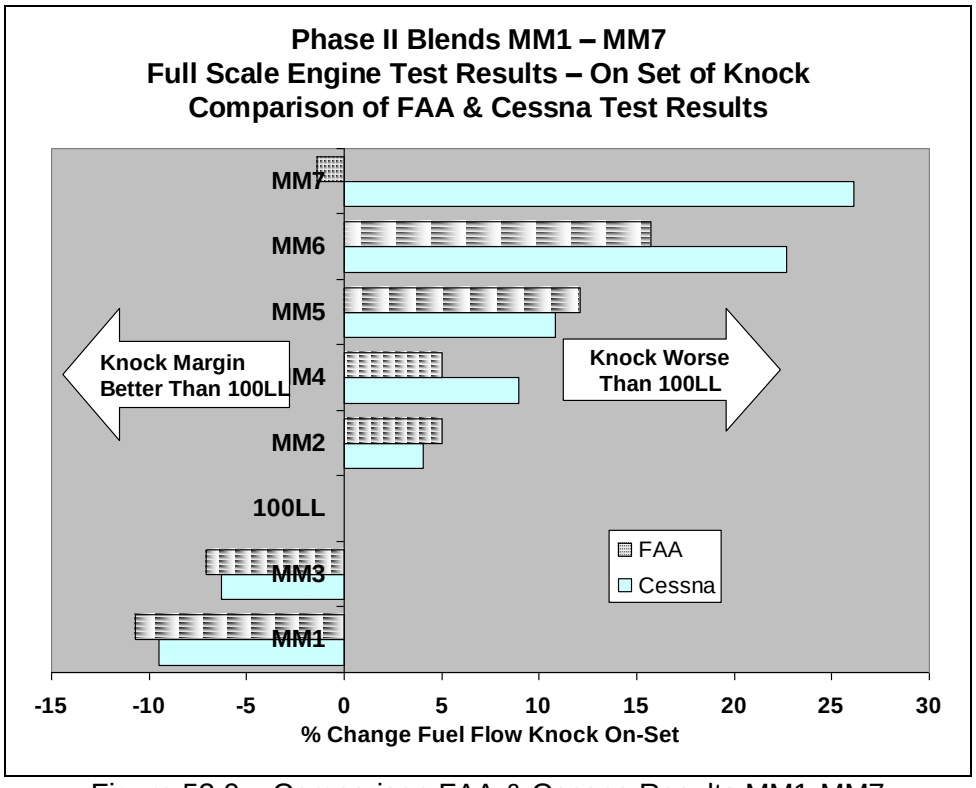

Figure 53.0 – Comparison FAA & Cessna Results MM1-MM7

6.5.6. Phase II Conclusions

Although test methods and engines differed between the FAA and Cessna test facilities, results and conclusions are generally consistent and complimentary relative to the observed positive octane response of the engine with those blends designated by higher MON ratings. Significant conclusions and observations relative to MON performance of the Phase II Test Matrix are summarized as follows. The reader is directed to the respective engine test report references (12) and (13) and the applicable laboratory test report reference (10) for a thorough and in depth assessment of conclusions and observations. The purpose of this report is to provide a summary of the related testing and to highlight significant conclusions and findings. The Phase II test results were not subjected to the same type of multiple linear regression analysis of the relationship between engine detonation characteristics and the type and concentration of blend components similar to that employed for the Phase I blends because the Phase II test matrix was not selected using designed experiment constraints.

Overall Test Results

- Blends with a higher MON rating tended to correlate well with the relative positive octane response as measured in the engine. Progressively higher MON rated fuels tended to provide greater positive octane margin. See summary in Figures 54.0 and 56.0.
- Blends with a lower MON rating tended to correlate with the relative negative or poor octane response as measured in the engine. Blends with progressively lower MON ratings tended to provide an increasingly negative octane margin.
- MON ratings predicted for the experimental blends agreed closely with the D 2700 measured ratings.
- Both FAA and Cessna results indicated that, under the test conditions, an unleaded fuel with a MON rating of at least 101 was required to give similar or better full size engine octane satisfaction when compared to the 100LL baseline fuel. Exceptions were blends AV5, MO7, MO4, and MM4 which offered good MON but did not always meet expectations.
- To further quantify this effect, MON was plotted against fuel flow at knock onset as illustrated by Figures 54.0 and 56.0. Both FAA and Cessna results indicated that, under the test conditions, an unleaded fuel must be approximately 2 MON higher to match the engine octane satisfaction of the leaded 100LL baseline fuel.
- Blends AV7, AV6, AV4, and AV3 [105.6 MON to 102.9 MON respectively] were the best performing blends for the aviation alkylate blends without MMT and were shown to provide knock margins better than the Baseline 100LL. Note that the AV blends tended to contain a relatively high percentage of super alkylate (35% to 50% v/v). FAA test results showed Blend AV8 provided a positive octane response; whereas the opposite was observed in the Cessna test.
- Blends MO8, MO5, MO3, and MO7 [104.6 MON to 102.9 MON respectively] were the best performing blends for the motor alkylate group without MMT based upon the Cessna test results; the FAA test results indicated the MO blends were generally less effective in extent of positive octane response. Similar to the AV blends, the MO blends M08, MO7, and MO5 tended to contain a relatively high percentage of super alkylate (34% to 50% v/v). Blend MO6 which contained 0.0 % super alkylate and was 94% motor alkylate had a D 2700 MON rating of 96.7 and was ranked among the poorer performing MO blends.

- Consistent with the Phase I test results, the components super alkylate and *m*-Toluidine were primary ingredients in most of those blends exhibiting an octane response greater than 100LL.
- As indicated by the laboratory ASTM D 910 analysis of blend properties, many of the blends exhibited vapor pressure and freezing point properties which were non-compliant with the ASTM D 910 specification. Further adjustment of these blends would be required in order to meet D 910 properties, potentially impacting MON.

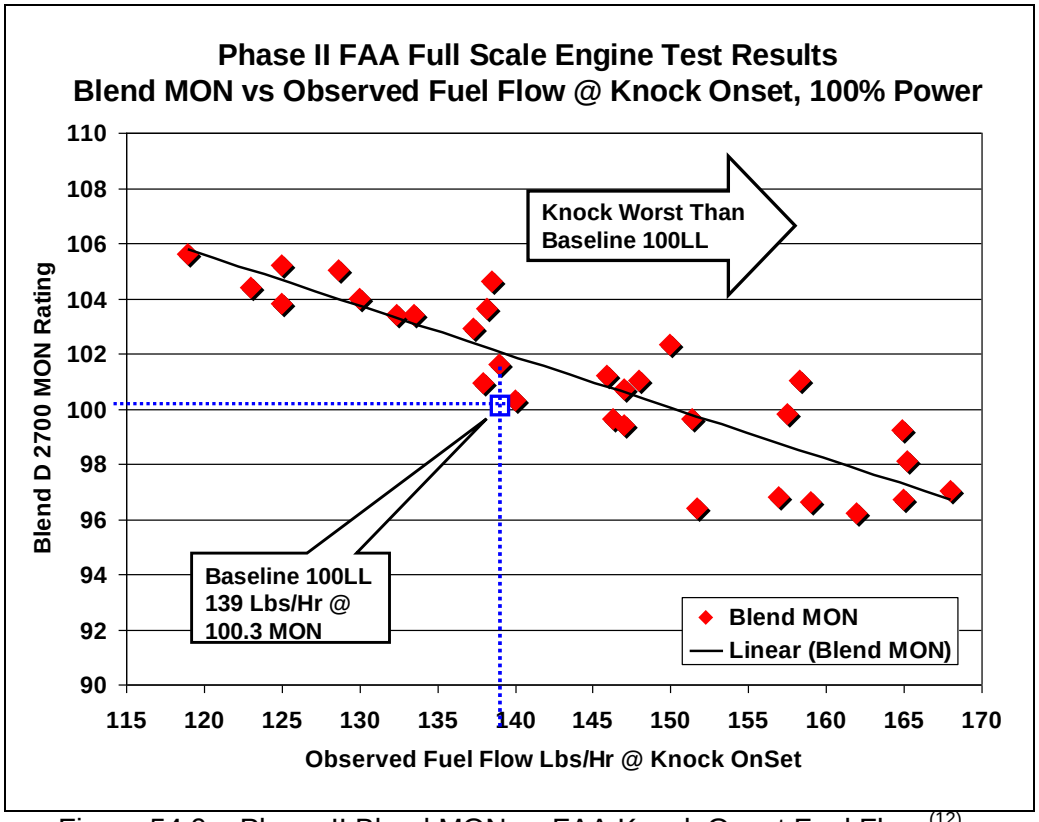

Figure 54.0 – Phase II Blend MON vs FAA Knock Onset Fuel Flow [12]

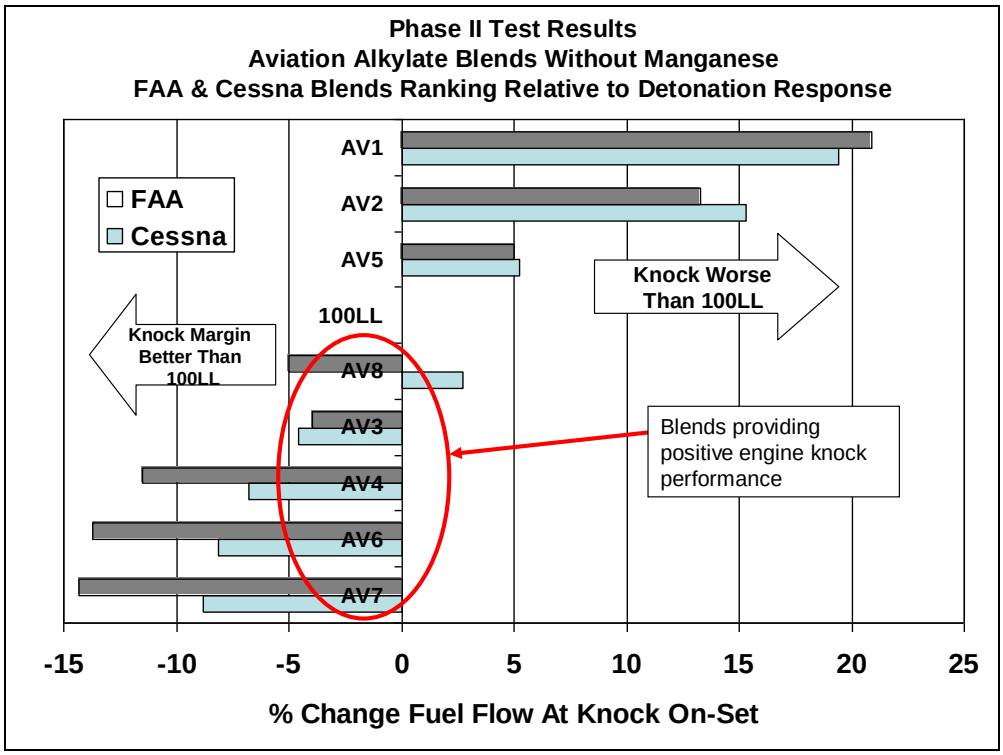

Figure 55.0 – Detonation Ranking of Av Alkylate Blends W/O MMT

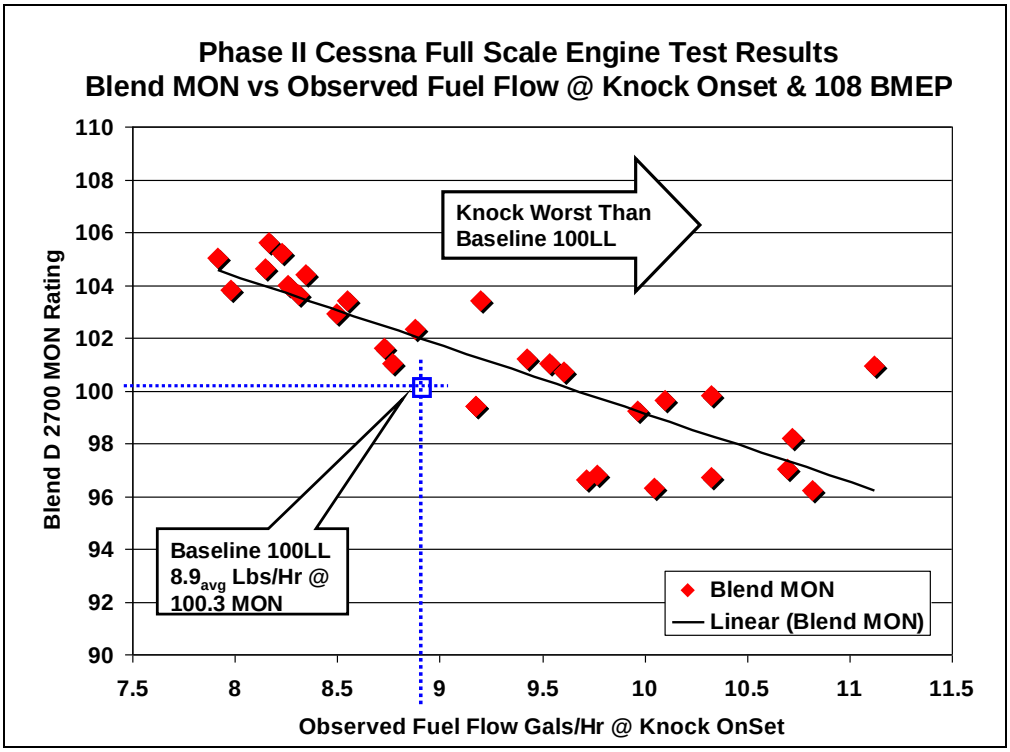

Figure 56.0 – Phase II Blend MON vs Cessna Knock Onset Fuel Flow [13]

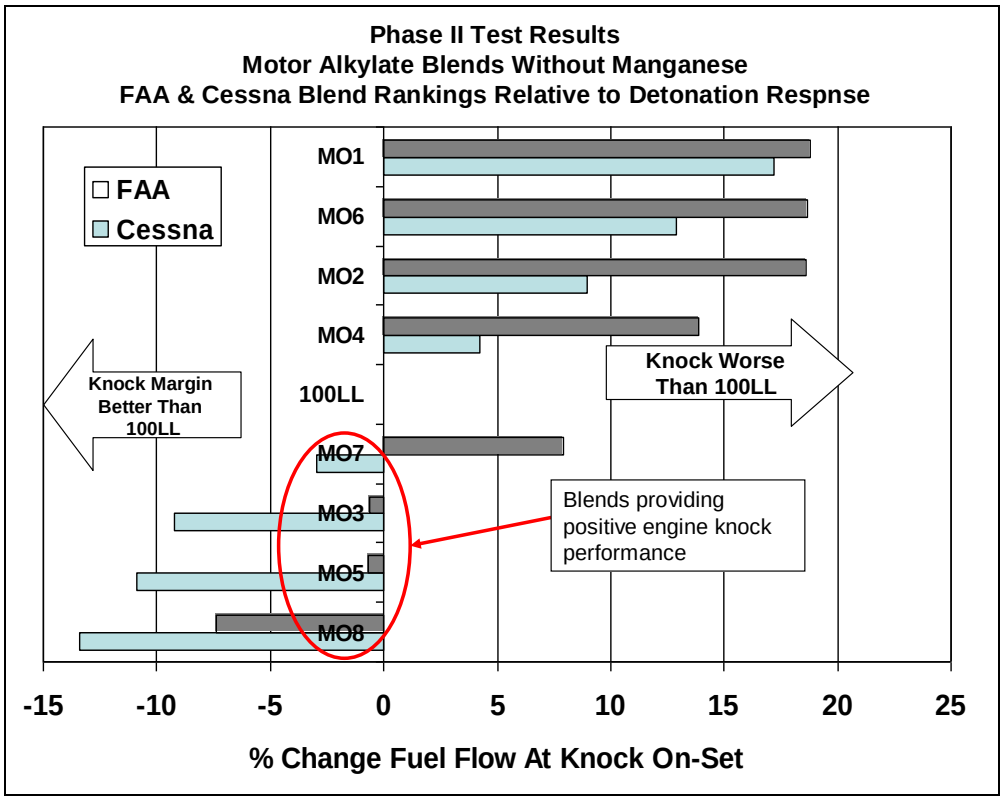

Figure 57.0 – Detonation Ranking of Motor Alkylate Blends W/O MMT

FAA Test Results

The following conclusions are extracted from the FAA test results report, reference 12.

- Engine knock performance tended to correlate with both the predicted MON and the D 2700 MON rating of the unleaded blends.
- Thirteen (13) of the thirty (30) unleaded blends provided knock performance equivalent to or better than the 100LL minimum spec AVGAS at a 100% power setting. All of the blends which performed better than the Baseline 100LL were characterized by higher MON and PN values. Five (5) of the unleaded blends that had higher MON values than the 100LL performed worst than the 100LL. Nine (9) of the blends that had higher PN than the Baseline 100LL performed worse than the 100LL. [12]
- Blends AV4 and AV7 were the best performing blends relative to anti-knock performance. Blend AV4 did not reach limiting knock at the 85%, 75%, or 65% power settings; blend AV7 did not reach limiting knock a the 100%, 75%, and 65% power settings. Blends AV6, MO5, and AM4 did not reach limiting knock at the 65% power setting.
- Blends AV1, AV2, AV6, MO1, MO3, MO4, MO5, and MO7 performed worst in the IO-540-K test engine than their MON or PN would indicate, while blends AM3, AM4, AM7, and MM6 performed better in the IO-540-K engine than their MON or PN would indicate.
- For all blends, the maximum power during leaning occurred at an average 98ºF rich of Peak EGT. For the blends that reached a peak EGT, the maximum power occurred at an average of 110ºF rich of Peak EGT. For the blends that developed limiting knock

and reached a Peak EGT, the knock limited mass fuel flow occurred at an average 65ºF lean of best power BHP and 23ºF rich of Peak EGT. The relevance is typical cruise operation in an aircraft where lean mixture is set based upon Peak EGT.

- While these tests addressed detonation characteristics only, eventually the full spectrum of aviation gasoline specifications for 100LL, as listed in ASTM D 910, will have to be addressed. Only blend MO6 met the minimum specification for net heat of combustion for the current 100LL aviation gasoline.
- For an unleaded fuel to provide full-scale engine knock performance equal to a leaded aviation gasoline, the unleaded fuel will need a higher MON and PN than the leaded aviation gasoline.
- The addition of MMT at levels of 0.100 g Mn/gal and less had a minimal effect on the blend knock performance.
- The study was inconclusive regarding the effect of manganese-based cylinder chamber deposits.

Cessna Test Results

The following conclusions are extracted from the Cessna test results report, reference 13.

- Detonation performance ranking [as measured in a full scale engine] of sixteen (16) aviation alkylate and motor alkylate test blends without manganese correlated with ASTM D 2700 MON ratings with exception of blend MO6.
- Detonation performance ranking [as measured in a full scale engine] of seven (7) aviation alkylate and motor alkylate test blends with manganese correlated with ASTM D 2700 MON ratings with exception of blend AM7.
- All aviation alkylate and motor alkylate blends ranked within a D 2700 reproducibility limit of 2.0 units.
- 13 of 16 AV and MO blends ranked within a D 2700 repeatability limit of 0.6 units.
- Test results indicated MMT imparts detonation characteristics that are influenced by the duration of engine exposure to such blends. Future fuels if containing MMT should be limited to those with concentrations of MMT proven to be capable of maintaining acceptable levels of combustion chamber and spark plug deposits
- High freezing point temperatures of some CRC Matrix blends represent a more critical issue than MON ratings.
- The Cessna report[13] included the following recommendations.

    1. The generally low vapor pressures, large volume percentage of high temperature boiling products and in many instances the high freezing point temperatures of the CRC Matrix Blends, renders of extreme importance that the specific heats of evaporation, the kinematic viscosities and corresponding densities over a temperature range be secured on all thirty (30) Matrix fuels while samples remain available.
    2. It is now possible to screen-out at least half of the CRC Matrix blends tested. Higher and more realistic volatility characteristics should be imparted to some or all surviving blends, and the following evaluations should be follow. Surviving blends should be tested for detonation characteristics on a carbureted engine.

Surviving blends should be evaluated for performance on both carbureted and fuel injected engines under ambient inlet conditions.

6.6. PHASE III Results – Full Scale Engine Tests 47 UL Blends

6.6.1. Background

Following completion of the Phase II full scale engine test program and subsequent analysis of test results, options for continuation of research of unleaded AVGAS alternatives were evaluated by the CRC Unleaded AVGAS Task Group, a working subcommittee of the CRC Unleaded AVGAS Development Group. The Task Group determined that the next research phase should better define the relationship between fuel composition and full scale engine detonation characteristics using designed experiment constraints while also seeking to improve the volatility characteristics of the fuels. It was further agreed that the emphasis should be on fuel blends capable of a MON rating of 100 and above with performance compared to 100LL leaded AVGAS. During the period of YR2005 through YR2006, a test plan was evolved which provided for continuation of the CRC research initiative based upon full scale engine tests at a single test facility using a matrix of 47 unleaded fuel blends derived from the prior research results. Full scale engine testing was resumed at the FAA Technical Center's Aviation Fuel & Engine Test Facility in YR2007 using the Lycoming IO-540-K test engine.

6.6.2. Research Plan

The Phase III Research Project was implemented as an industry collaborative effort with organization, planning, logistics, and implementation continuing to follow the methodologies successfully applied during the previous CRC UL AVGAS research projects. The objective of the Phase III Research was to conduct full scale engine testing of unleaded fuel blends derived from the Phase II test results with specific emphasis on further exploring the relationship between blend composition, volatility and engine octane response. Base fuels, blend components, and formulation boundaries comprising the basis of the research plan were defined as shown in the following Tables 35.0 and 36.0. Following a discussion of options and alternatives, it was agreed during the CRC UL AVGAS Task Group Meeting of November 10, 2005 [(21)] to proceed with implementation of the Phase III research plan based upon the August 18, 2005 Design Experiment proposed by ConocoPhillips.

The resulting Phase III research plan provided for resumption of full scale engine testing using a group of 47 unleaded fuels meeting the component and boundary design parameters of Tables 35.0 and 36.0. A single engine test facility, FAA William J. Hughes Technical Center, was use for the Phase III full scale engine testing. The group of 45 unleaded blends represented an unleaded experimental design matrix containing fractions of aviation alkylate, super alkylate, toluene, ethyl-*tert*-butyl ether (ETBE), *tert*-butylbenzene, and *meta*-toluidine as derived from the design experiment. All blends contained 5% *iso*-pentane to increase vapor pressure. Blend compositions bracketed a MON range of 97.6 to 106.3. Two additional blends (blend nos. 46 and 47) were designed as specific non-amine blends as shown in Table 36.0. All of the experimental blends were furnished to the engine test facility as anonymous blends, identified only by a blend number.

A single independent laboratory Dixie Services was designated by the Task Group to conduct the necessary blending and component property analyses to ensure consistency. Funding support for the laboratory analyses, testing, and purchase of certain blend components was provided by the FAA Technical Center.

Table 35.0 CRC Phase III Unleaded AVGAS Test Matrix Blend Components & Boundaries 45 UL Blends	
Blend Component	***Component Fraction Limits***
Aviation Alkylate	0 – 60%
Super Alkylate	0 – 50%
Toluene	0 – 20%
t-Butylbenzene	0 – 20%
m-Toluidine	3 – 12%
ETBE	0 – 30%
iso-Pentane	5%
Total Aromatics	30% Max
*Av alkylate + super alkylate + *iso*-Pentane	75% Max
*Av alkylate + *iso*-Pentane	65% Max
Notes: ① Blend fractions are % volume ②*Add *iso*-Pentane into alkylate totals to set the limits shown	

Table 36.0 CRC Phase III Unleaded AVGAS Test Matrix Blend Components & Boundaries Two Non-Amine Blends		
Blend Component	***Blend A***	***Blend B***
iso-Octane	81%	48%
iso-Pentane	9%	7%
Toluene	0%	0%
t-Butylbenzene	10%	15%
ETBE	0	30%
Notes: ① Blend fractions are % volume ②*Add *iso*-Pentane into alkylate totals to set the limits shown ③ Blends A and B became Test Blend No's 46 and 47		

NOTE……Phase III Research provided for full scale engine testing of 47 unleaded fuel blends. Test criteria was fuel knock performance in a representative critical engine.

6.6.2.1. Blend Components

The Phase III unleaded AVGAS test matrix consisted of 45 separate blends containing various amounts of aviation alkylate, super alkylate, toluene, ethyl-*tert*-butyl ether (ETBE), *tert*-butylbenzene, and *meta*-toluidine. Each of blends 1–45 contained 5% iso-pentane. Similar to Phase II, *meta*-toluidine and super alkylate were primary constituents in the Phase III test matrix with blends 1–45 containing 3–12 % volume *meta*-toluidine and 0–50% super alkylate. Components ETBE and toluene were also blend components in the Phase II research project. The Phase III components are described in Section 6.4.2.1 of this report with the exception the component *tert*-butyl benzene, which was not previously evaluated in Phases I and II, is described as follows.

> **"*tert*-Butyl Benzene"** – selected as an aromatic hydrocarbon based upon its octane improving performance.

Blend components were either furnished by Task Group member companies or were purchased with FAA Technical Center funding as shown by the Logistics Plan Table 37.0. Blend components were tested for selected chemical and physical properties which are documented in the Appendix B laboratory analysis report; see also Section 6.6.3.2 of this report.

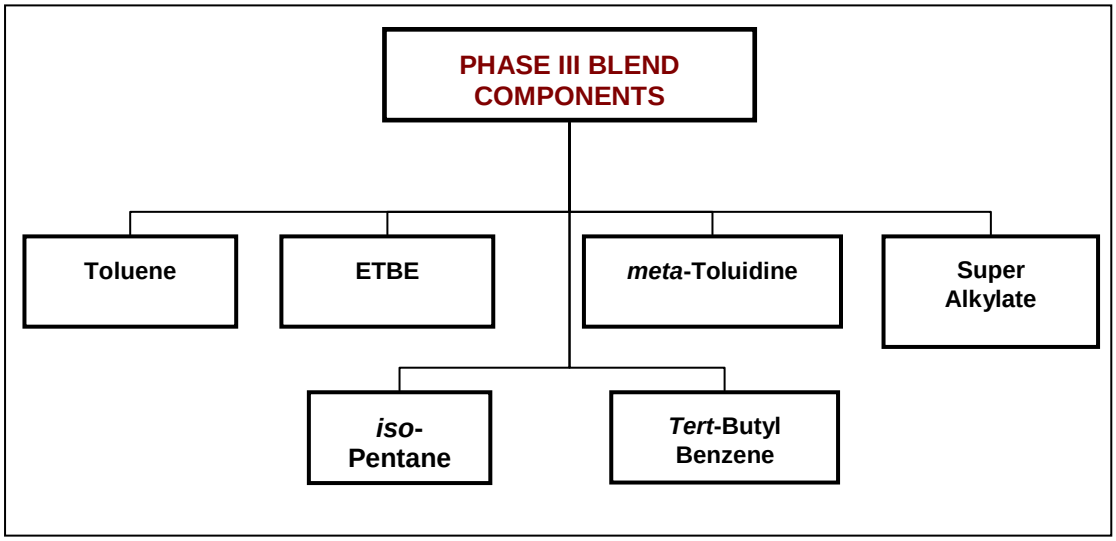

Figure 58.0 – Phase III Blend Components

6.6.2.2. Design Experiment

As with the prior Phase I program, the CRC UL AVGAS Phase III Research Project was planned and implemented as a designed experiment. The experimental design to evaluate the Phase III unleaded blends was again provided by ConocoPhillips Research Center statisticians based upon the components and blend constraints shown in the prior Table 35.0. The resulting experiment provided for a total of 45 unleaded blends to evaluate the interactions of the Table 35.0 components. Whereas all of the 45 blends were designed to contain 3–12 volume % *meta*-Toluidine, the decision was made to expand the matrix to include two additional specific non-amine blends which were included as Blend No's 46 and 47. [(11)] The resulting Phase III unleaded blend test matrix is shown in Table 38.0.

6.6.2.3. Logistics Plan

The Phase III Logistics Plan was implemented as a continuation of the Phase II approach with each member organization providing a fuel, component, or service as summarized in the Table 37.0 Phase III Logistics Plan. Continuing with the methods and practices successfully applied during the prior research phases, a single independent laboratory Dixie Services was retained by the CRC UL AVGAS Task Group to formulate the blends and to conduct the necessary blend and component laboratory testing. Funding for laboratory blending and property tests including purchase of specific compounds as discussed in the Appendix B Dixie Services Laboratory Report was provided by the FAA Technical Center's AFETF. In contrast to the previous Phase II which engaged multiple engine test resources, a single engine test facility was used for the Phase III full scale engine testing.

Table 37.0
Phase III Logistics Plan

	Component/Service	Source
1	Aviation Alkylate	ConocoPhillips
2	Super Alkylate	Purchased Through FAA AFETF
3	Toluene	Purchased Through FAA AFETF
4	*tert*-Butyl Benzene	Air BP
6	*meta*-Toluidine	ExxonMobil
5	ETBE	FAA AFETF
7	*iso*-Pentane	Purchased Through FAA Tech Center
8	Blend A (non-amine)	Air BP
9	Blend B (non-amine)	Air BP
10	100LL Baseline Min Spec	TBD
11	Blending and laboratory analysis	Dixie Services
12	Dynamometer Test Facility & Engine	FAA AFETF

6.6.3. Laboratory Test Results

Results of laboratory analyses of the Phase III blends and components are documented in the Appendix B Dixie Services Laboratory Analysis Report. The following sections summarize significant aspects of the Appendix B report, including Phase III blend formulations, specific blend ASTM properties, and blend component properties.

6.6.3.1. Blend Formulations

Blend formulations were derived as a design experiment based upon the Table 35.0 Phase III Blend Matrix Components and Boundaries. The following Tables 38.0 – 40.0 represent various rankings and sorts for the Phase III blend matrix.

- Table 38.0 – Phase III Blends 1 – 47 Sorted by Blend No.
- Table 39.0 – Phase III Blend Matrix MON, Sorted for 0% Super Alkylate
- Table 40.0 – Phase III Blend Matrix MON, Sorted for 0% Super Alkylate & meta-Toluidine < 5%
- Table 41.0 – Phase III Non-Amine Blends 46 & 47

Table 38.0
Phase III Matrix Test Blends
Component Volume Fractions & Motor Octane Number Results [11]
SORTED BY BLEND NO'S 1 - 47

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane	MON D 2700
1	0.4224	0.0000	0.0000	0.1995	0.0308	0.2973	0.0515	99.7
2	0.2689	0.2702	0.1016	0.1912	0.1180	0.0000	0.0501	104.8
3	0.0000	0.2299	0.1640	0.1359	0.1205	0.2997	0.0501	105.3
4	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501	103.9
5	0.0000	0.4998	0.0841	0.1569	0.0832	0.1260	0.0501	104.1
6	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.5020	106.0
7	0.1672	0.4997	0.0107	0.1002	0.0657	0.1063	0.0501	103.4
8	0.4162	0.2837	0.0000	0.0360	0.1201	0.0939	0.0501	105.0
9	0.0000	0.3969	0.1689	0.0000	0.0838	0.3002	0.0501	102.5
10	0.2487	0.2350	0.0588	0.0000	0.1073	0.3001	0.0501	103.9
11	0.1720	0.2198	0.1979	0.0298	0.0302	0.3002	0.0501	99.8
12	0.0010	0.4999	0.1071	0.0742	0.0309	0.2369	0.0501	101.1
13	0.6000	0.0438	0.0107	0.1041	0.0651	0.1261	0.0502	101.2
14	0.3291	0.0000	0.2000	0.0000	0.1199	0.2998	0.0511	104.0
15	0.1029	0.5001	0.0910	0.0069	0.1202	0.1288	0.0502	106.3
16	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501	102.8
17	0.0903	0.4997	0.0000	0.0000	0.0597	0.3002	0.0501	102.7
18	0.5468	0.0000	0.1001	0.1997	0.0389	0.0643	0.0501	99.6
19	0.5998	0.0000	0.0321	0.0000	0.0302	0.2878	0.0501	97.6
20	0.3929	0.0000	0.0000	0.1369	0.1200	0.3001	0.0501	104.2
21	0.0000	0.4290	0.0000	0.1009	0.1200	0.3000	0.0501	106.2
22	0.1009	0.4997	0.2003	0.0000	0.0302	0.1188	0.0501	100.5

23	0.5997	0.0000	0.0000	0.0000	0.1080	0.2422	0.0501	103.0
24	0.1893	0.2294	0.0206	0.1997	0.0892	0.2216	0.0502	103.3
25	0.1671	0.4995	0.0802	0.1728	0.0302	0.0000	0.0501	101.0
26	0.4509	0.0152	0.1178	0.0911	0.1201	0.1547	0.0501	104.0
27	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501	102.7
28	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.0502	106.0
29	0.4392	0.2609	0.0031	0.1967	0.0349	0.0152	0.0501	100.2
30	0.5960	0.1038	0.1369	0.0811	0.0302	0.0018	0.0501	97.6
31	0.0298	0.4996	0.2002	0.1002	0.1200	0.0000	0.0501	105.6
32	0.3797	0.3199	0.0673	0.0000	0.0302	0.1528	0.0501	98.8
33	0.5299	0.0219	0.1901	0.0000	0.0590	0.1491	0.0501	101.1
34	0.3489	0.0000	0.1950	0.1049	0.0302	0.2709	0.0501	98.8
35	0.5997	0.1000	0.1239	0.0000	0.1201	0.0063	0.0501	103.8
36	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501	103.0
37	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501	104.1
38	0.0000	0.3198	0.1001	0.1997	0.0302	0.3002	0.0501	100.6
39	0.2439	0.2588	0.0160	0.1009	0.0302	0.3001	0.0501	100.4
40	0.0000	0.5000	0.0000	0.1998	0.0302	0.2199	0.0501	102.0
41	0.1901	0.2853	0.2001	0.0321	0.1200	0.1223	0.0501	104.8
42	0.4026	0.0000	0.0978	0.0780	0.0711	0.3003	0.0501	101.5
43	0.5539	0.0000	0.2001	0.1001	0.0958	0.0000	0.0501	102.6
44	0.2701	0.0000	0.1002	0.1998	0.0919	0.2879	0.0501	102.9
45	0.2141	0.2987	0.1910	0.1086	0.0483	0.0893	0.0501	101.1
46	0.0000	0.8102	0.0000	0.1002	0.0000	0.0000	0.0896	98.2
47	0.0000	0.4796	0.0000	0.1499	0.0000	0.3002	0.0704	99.8

Table 39.0
Phase III Matrix Test Blends
Component Volume Fractions & Motor Octane Number Results [11]
SORTED FOR ZERO SUPER ALKYLATE

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane	MON
20	0.3929	0.0000	0.0000	0.1369	0.1200	0.3001	0.0501	104.2
14	0.3291	0.0000	0.2000	0.0000	0.1199	0.2998	0.0511	104.0
23	0.5997	0.0000	0.0000	0.0000	0.1080	0.2422	0.0501	103.0
44	0.2701	0.0000	0.1002	0.1998	0.0919	0.2879	0.0501	102.9
43	0.5539	0.0000	0.2001	0.1001	0.0958	0.0000	0.0501	102.6
42	0.4026	0.0000	0.0978	0.0780	0.0711	0.3003	0.0501	101.5
1	0.4224	0.0000	0.0000	0.1995	0.0308	0.2973	0.0515	99.7
18	0.5468	0.0000	0.1001	0.1997	0.0389	0.0643	0.0501	99.6
34	0.3489	0.0000	0.1950	0.1049	0.0302	0.2709	0.0501	98.8
19	0.5998	0.0000	0.0321	0.0000	0.0302	0.2878	0.0501	97.6

Table 40.0 Phase III Matrix Test Blends Component Volume Fractions & Motor Octane Number Results [11] SORTED FOR ZERO SUPER ALKYLATE & META-TOLUIDINE < 4%								
Blend No.	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane	MON
1	0.4224	0.0000	0.0000	0.1995	0.0308	0.2973	0.0515	99.7
18	0.5468	0.0000	0.1001	0.1997	0.0389	0.0643	0.0501	99.6
34	0.3489	0.0000	0.1950	0.1049	0.0302	0.2709	0.0501	98.8
19	0.5998	0.0000	0.0321	0.0000	0.0302	0.2878	0.0501	97.6

Table 41.0 Phase III Matrix Test Blends Component Volume Fractions & Motor Octane Number Results [11] Non-Amine Blends 46 & 47								
Blend No.	**Aviation Alkylate**	**Super Alkylate**	**Toluene**	***tert*-Butyl Benzene**	***meta*-Toluidine**	**ETBE**	***iso*-Pentane**	**MON D 2700**
46	0.0000	0.8102	0.0000	0.1002	0.0000	0.0000	0.0896	98.2
47	0.0000	0.4796	0.0000	0.1499	0.0000	0.3002	0.0704	99.8

6.6.3.2. Blend Component Properties

Phase III blend component physical and chemical properties were determined by the applicable ASTM test method and are summarized in Table 42.0 which is taken from Exhibit II of the Appendix B Dixie Services Laboratory Report. [11]

Table 42.0 Phase III Component Properties [11]							
ASTM Test Method	**Aviation Alkylate**	**Super Alkylate**	**Toluene**	***tert* – Butyl Benzene**	***meta* - Toluidine**	**ETBE**	***iso*-Pentane**
D 4052 Density, 15.56º C	0.6928	0.6994	0.8709	0.8701	0.9925	0.7450	0.6243
D 4052 API Gravity	72.5	70.5	30.8	31.0	10.9	58.2	19.7
D 5191 Vapor Press, DVPE, psi	5.37	1.78	0.79	< 0.10		4.14	< 0.10
D 2700 Motor Octane Number	91.4	99.9	-	-	-	-	-
D 5453 Sulfur Content, mass %	0.0002	<0.0001	<0.0001	<0.0001	-	0.0001	<0.0001
E 1064 Water Content, mass %	-	-	-	-	-	0.012	-
D 2360 Toluene Content, mass %	-	-	99.82	-	-	0.37	-
D 5441* ETBE Content, mass %	-	-	-	-	-	96.35	-
D 5441* Methanol Content, mass %	-	-	-	-	-	0.01	-
D 5441* Ethanol Content, mass %	-	-	-	-	-	0.09	
D 850 Distillation Range, °C 50% recovered, °C	-	-	0.7	0.5	-	-	-

D 86 Distillation, % evaporated °C	-	-	-	-	-	-	-
IBP	38.5	95.5	-	-	-	-	-
5	64.0	98.0	-	-	-	-	-
10	75.5	98.0	-	-	-	-	-
20	87.0	98.5	-	-	-	-	-
30	92.0	99.0	-	-	-	-	-
40	95.5	99.5	-	-	-	-	-
50	100.0	100.0	-	-	203-4(lit.)	73.5	28.0 (lit.)
60	100.5	100.5	-	-	-	73.5	-
70	103.5	101.5	-	-	-	74.0	-
80	106.0	103.0	-	-	-	74.5	-
90	111.5	110.5	-	-	-	76.0	-
95	122.0	164.0	-	-	-	78.5	-
End	144.0	187.0	-	-	-	101.5	-
Recovery	98.5	99.0	-	-	-	99.0	-
Residue	0.9	0.7	-	-	-	0.5	-
Loss	0.6	0.3	-	-	-	0.5	-
Notes: ① ETBE analysis conducted by test method ASTM D 5441 (MTBE gas chromatography method) but calibrated to impurities typical of ETBE.							

6.6.3.3. Blend ASTM D 910 Properties

Select ASTM D 910 properties were determined for the Phase III blends in accordance with the research plan. Each blend was tested for ASTM D 2700 MON rating and ASTM D 4052 density. Eight blends were tested for ASTM D 5191 vapor pressure. Laboratory test results are documented in Exhibit VI of the Appendix B Dixie Services Laboratory Report [(11)], and are also included in Section 2.1 of the FAA Phase III Test Results Report. [(15)] See Section 6.5.3.2 of this report for D 910 properties for the Phase II blends

6.6.3.4. Baseline 100LL Properties

FAA Phase III full scale engine tests included detonation testing of both a Baseline 100LL min spec AVGAS labeled as MF2 and a FBO 100LL AVGAS for comparison with the unleaded blends; see the FAA Phase III Test Results Report [(15)]. Properties of both the min spec MF2 Baseline 100LL and the FBO 100LL are extracted from the FAA report and are repeated in Table 43.0 due to the significance of these parameters.

Table 43.0 Baseline 100LL & FBO 100LL Properties [15] FAA Phase III Full Scale Engine Tests				
ASTM	**Property Description**	**MF2 Min Spec 100LL**	**FBO 100LL**	**ASTM Spec**
D 2700	MON	100.6	103.6	99.5 min
D 5059	Lead content mL Tel/L	0.41	0.48	0.53 max
D 1319	Aromatics	-	0.3 % volume	
D 4529	Net Heat of Combustion 25ºC	-	44.38 MJ/kg	43.5 min
D 909	Supercharge rating	1.35 mL Tel/gal	1.51 mL	
D 909	Performance Number	130.9	133.0	130 min

6.6.4. Engine Test Results

Full scale engine detonation testing of the 47 unleaded experimental blends listed in Table 38.0 was completed in YR2007 at the FAA AFETF located at the FAA William J. Hughes Technical Center in Atlantic City, New Jersey. Results of these tests are documented in FAA Report No. DOT/FAA/AR-08/40 dated September 2008. [15] This report may be accessed at http://actlibrary.tc.faa.gov by searching keyword “avgas”. A description of the IO-540-K test engine and the associated FAA Technical Center test methods, test equipment, and associated procedures are presented in Sections 6.3.3 – 6.3.5 of this report. The objective of the Phase III full scale engine tests was to compare the knock performance of the unleaded fuel blends against a baseline minimum specification 100LL fuel and to explore correlation of blend MON with engine octane requirement and blend composition.

Similar to the FAA Phase II test report, the FAA Phase III Test Results Report[15] contains an exceptionally large amount of data which offers the opportunity for further analysis for effect of blend formulations on engine characteristics such as BSFC, fuel/air ratio, BHP at best power, and EGT in addition to analysis of blend component effectiveness. Comparative analysis of BHP, BSFC, and EGT for the blends tested is addressed within the FAA Test Results Report. This summary research report focuses primarily on engine octane response and correlation with blend MON rating.

Test Methods

The engine test methods followed at the FAA Technical Center consisted of conducting a mixture lean out curve at 100%, 85%, 75%, and 65% power settings [while holding manifold pressure and engine speed constant] for each fuel blend including the baseline 100LL fuel. Each mixture lean out curve was performed by incrementally manually leaning the fuel flow in increments of 1 lb/hr/sec from a pre-determined non-detonation rich mixture setting to the point where either moderate to heavy detonation, maximum allowable EGT, or 50ºF lean of peak EGT was reached. [15] The point at which light detonation was encountered was noted as the fuel flow at detonation onset. Each of the six cylinders was monitored continuously for indications of detonation as indicated by combustion pressure patterns using the instrumented cylinder head technology same as described in Section 6.3.4.1 and in the FAA Test Results Report[15] .

A description of the aircraft piston engine mixture lean out test procedure and its utility is discussed in Section 6.3.5.1 of this report; the mixture lean out curve provides a basis for

consistently and comparatively evaluating engine knock and mixture characteristics for fuels as a function of fuel/air ratio.

Engine Operating Settings for Detonation Testing[15]

- Hottest cylinder head temperature was maintained at 475º ± 3ºF
- All other cylinder head temperatures were maintained within 50ºF of maximum
- Induction inlet air temperature to engine was maintained at 103º ± 3ºF
- Oil inlet temperature to engine was maintained within 10ºF of the 245ºF limit
- Induction air moisture content controlled to 0-2 Grains Moisture/lb dry air

NOTE…… Phase III detonation test methods which test the naturally aspirated engine at maximum conditions of 100% BHP & rated RPM while setting CHT within 10ºF of max allowable, oil temperature within 10ºF of max allowable, low humidity induction air, and induction air temperature equivalent to hot day conditions are consistent with FAA AC33.47-1 which provides guidelines for conducting official detonation tests during the engine FAA certification program.

Mixture Lean Out Curve Presentation

Mixture lean out curves were conducted with complete data sets recorded for each of the unleaded fuel blends same as performed during Phase II; however, graphical representation of each Phase III mixture lean out curve differs from those shown in Figures 26.0 – 33.0 of Section 6.5.4.1 of this report for the Phase II tests. The individual Phase III mixture lean out curves are presented as plots of engine parameters versus time as illustrated by Figure 2 in the FAA Phase III Test Results Report [15]; whereas the FAA Phase II Test Results Report presents the mixture lean out curves in the conventional reciprocating aircraft engine format of BHP, BSFC, and EGT versus fuel flow; the methods and results are the same with only the illustration of results differing.

Average Fuel Flow At Knock Onset

Another difference between the FAA Phase II and Phase III test results is in the area of analysis of knock onset fuel flow. FAA Phase II test results (see Section 6.5.4.1 of this report) compared the **observed fuel flow** at knock onset for each blend at **each power setting** with the fuel flow at knock onset for the Baseline 100LL. Phase III test results as presented in the reference (15) report compares the **average fuel flow** at knock onset as determined by averaging the observed fuel flow at knock onset for each of the four power settings (100%, 85%, 75%, & 65%); observed **average fuel flow** is also used for comparison purposes with the Baseline 100LL.

NOTE……Objective of the Phase III Research was to compare the knock performance of unleaded fuel blends against a baseline min spec 100LL fuel and to explore the relationship between blend composition and knock performance in the full scale engine.

Ranking of Blends

Table 44.0 ranks the Phase III blends on the basis of average mass fuel flow at onset of knock as compared to the Baseline 100LL with blend formulations and respective D 2700 MON rating shown for reference. The ranking is based upon observed average fuel flow at knock onset with blends ranked from the best performing at top of the list to the worst knock performing blends at the bottom of the list. Blends 15 and 21 were knock free at all power settings. Highlighted blends provided knock performance equal to or better than the Baseline 100LL. Table 44.0 indicates those blends characterized by a fuel flow at knock onset less than the Baseline 100LL fuel flow performed equivalent to or better than the 100LL; conversely, those unleaded blends characterized by a fuel flow at knock onset greater than the Baseline 100LL fuel flow performed worse than the Baseline 100LL. As shown by Table 44.0, the fuel blend knock performance tended to follow the D 2700 MON rating of the blend.

Table 45.0 sorts the test results for those blends with zero super alkylate and knock performance equivalent to or better than the Baseline 100LL. Table 46.0 sorts the test results for those blends with zero meta-toluidine which are blends 46 and 47 only.

Significant observations based upon Tables 44.0 through 46.0 are summarized as follows:

- As indicated by the MON rating and fuel flow at knock onset in the far right hand columns, blends with a progressively higher MON rating correlated with an equivalent improvement in engine octane response.
- Similarly those blends with a rating lower than 100 MON provided a progressively worst engine octane response with descending MON values.
- The engine octane response tends to trend well with the ASTM D 2700 MON rating of the blend.
- Generally, Tables 44.0 through 46.0 indicate an unleaded blend with an MON rating approximately 3 MON higher than the Baseline 100LL is required to satisfy the octane requirement of the engine tested. See Section 3.2 of reference (15) for a quantitative assessment of unleaded MON vs leaded MON.

Table 44.0
Phase III Test Results
Ranking by Blend No. Based Upon Engine On-Set of Knock [15]
Knock Performance Ranked From Best At Top to Worst at Bottom

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane	MON	FF_{avg} @ Knock Onset
15	0.1029	0.5001	0.0910	0.0069	0.1202	0.1288	0.0502	106.3	⑥
21	0.0000	0.4290	0.0000	0.1009	0.1200	0.3000	0.0501	106.2	⑥
6	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.5020	106.0	82.0
28	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.0502	106.0	89.0
2	0.2689	0.2702	0.1016	0.1912	0.1180	0.0000	0.0501	104.8	90.1
31	0.0298	0.4996	0.2002	0.1002	0.1200	0.0000	0.0501	105.6	90.6
3	0.0000	0.2299	0.1640	0.1359	0.1205	0.2997	0.0501	105.3	93.3
5	0.0000	0.4998	0.0841	0.1569	0.0832	0.1260	0.0501	104.1	97.5
8	0.4162	0.2837	0.0000	0.0360	0.1201	0.0939	0.0501	105.0	99.2
41	0.1901	0.2853	0.2001	0.0321	0.1200	0.1223	0.0501	104.8	100.9
4	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501	103.9	101.2
35	0.5997	0.1000	0.1239	0.0000	0.1201	0.0063	0.0501	103.8	104.0
10	0.2487	0.2350	0.0588	0.0000	0.1073	0.3001	0.0501	103.9	104.3
37	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501	104.1	105.4
14	0.3291	0.0000	0.2000	0.0000	0.1199	0.2998	0.0511	104.0	105.6
7	0.1672	0.4997	0.0107	0.1002	0.0657	0.1063	0.0501	103.4	106.4
16	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501	102.8	107.4
20	0.3929	0.0000	0.0000	0.1369	0.1200	0.3001	0.0501	104.2	107.7
26	0.4509	0.0152	0.1178	0.0911	0.1201	0.1547	0.0501	104.0	108.3
36	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501	103.0	109.0
100LL								**100.6**	**109.0**
27	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501	102.7	110.0
43	0.5539	0.0000	0.2001	0.1001	0.0958	0.0000	0.0501	102.6	110.3
23	0.5997	0.0000	0.0000	0.0000	0.1080	0.2422	0.0501	103.0	110.8
24	0.1893	0.2294	0.0206	0.1997	0.0892	0.2216	0.0502	103.3	112.4
17	0.0903	0.4997	0.0000	0.0000	0.0597	0.3002	0.0501	102.7	112.7
9	0.0000	0.3969	0.1689	0.0000	0.0838	0.3002	0.0501	102.5	114.5
44	0.2701	0.0000	0.1002	0.1998	0.0919	0.2879	0.0501	102.9	117.1
13	0.6000	0.0438	0.0107	0.1041	0.0651	0.1261	0.0502	101.2	117.9
45	0.2141	0.2987	0.1910	0.1086	0.0483	0.0893	0.0501	101.1	118.6
42	0.4026	0.0000	0.0978	0.0780	0.0711	0.3003	0.0501	101.5	120.3
33	0.5299	0.0219	0.1901	0.0000	0.0590	0.1491	0.0501	101.1	120.8
40	0.0000	0.5000	0.0000	0.1998	0.0302	0.2199	0.0501	102.0	121.3
25	0.1671	0.4995	0.0802	0.1728	0.0302	0.0000	0.0501	101.0	121.4
22	0.1009	0.4997	0.2003	0.0000	0.0302	0.1188	0.0501	100.5	121.6
12	0.0010	0.4999	0.1071	0.0742	0.0309	0.2369	0.0501	101.1	122.0
29	0.4392	0.2609	0.0031	0.1967	0.0349	0.0152	0.0501	100.2	123.2
18	0.5468	0.0000	0.1001	0.1997	0.0389	0.0643	0.0501	99.6	125.1
38	0.0000	0.3198	0.1001	0.1997	0.0302	0.3002	0.0501	100.6	127.0
32	0.3797	0.3199	0.0673	0.0000	0.0302	0.1528	0.0501	98.8	127.1
1	0.4224	0.0000	0.0000	0.1995	0.0308	0.2973	0.0515	99.7	127.8
39	0.2439	0.2588	0.0160	0.1009	0.0302	0.3001	0.0501	100.4	127.9

11	0.1720	0.2198	0.1979	0.0298	0.0302	0.3002	0.0501	99.8	128
34	0.3489	0.0000	0.1950	0.1049	0.0302	0.2709	0.0501	98.8	129.5
30	0.5960	0.1038	0.1369	0.0811	0.0302	0.0018	0.0501	97.6	130.5
19	0.5998	0.0000	0.0321	0.0000	0.0302	0.2878	0.0501	97.6	131.0
46	0.0000	0.8102	0.0000	0.1002	0.0000	0.0000	0.0896	98.2	132.5
47	0.0000	0.4796	0.0000	0.1499	0.0000	0.3002	0.0704	99.8	135.1

Notes:
① MON shown is D 2700 rating as reported by Exhibit 6 of Appendix B. (11)
② Blend Label assigned by laboratory as anonymous identifier for each blend furnished to engine test facility. Compositional data, MON, & PN taken from Exhibit I of Appendix B. (11)
③ Ranking by knock on-set extracted from FAA Test Results Report. (15)
④ Highlighted blends are those providing knock response equivalent to or better than 100LL
⑤ FF = **AVERAGE** fuel flow (lbs/hr) at onset of knock for power settings of 100%, 85%, 75%, 65% as extracted from FAA Phase III Test Results Report. (15)
⑥ Note……..blends 15 and 21 were detonation free at all power settings(15)

Table 45.0
Phase III Test Results
Ranking by Blend No. Based Upon Engine Onset of Knock (15)
Sorted for 0-2.0 % Super Alkylate & Best Knock Performance

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane	MON	FF_{avg} @ Knock Onset
4	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501	103.9	101.2
37	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501	104.1	105.4
14	0.3291	0.0000	0.2000	0.0000	0.1199	0.2998	0.0511	104.0	105.6
20	0.3929	0.0000	0.0000	0.1369	0.1200	0.3001	0.0501	104.2	107.7
26	0.4509	0.0152	0.1178	0.0911	0.1201	0.1547	0.0501	104.0	108.3
100LL								**100.6**	**109**

Table 46.0
Phase III Test Results
Ranking by Blend No. Based Upon Engine Onset of Knock (15)
Sorted for 0% *meta*-Toluidine

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane	MON	FF_{avg} @ Knock Onset
100LL								**100.6**	**109**
46	0.0000	0.8102	0.0000	0.1002	0.0000	0.0000	0.0896	98.2	132.5
47	0.0000	0.4796	0.0000	0.1499	0.0000	0.3002	0.0704	99.8	135.1

Figures 59.0 and 60.0 illustrate the relative ranking of all 47 Phase III blends as a function of the observed average fuel flow at knock onset. See reference (15) for evaluation of other detonation onset indicators. Shown on these curves for comparison is the average fuel flow at knock onset for the Baseline 100LL fuel. The following example is provided to illustrate the comparison.

- Average of the observed fuel flows for the Baseline 100LL at knock onset for the four power settings is 109 lbs/hr
- Blend No. 6 did not encounter detonation until the fuel flow was well lean of the Baseline 100LL knock onset point. Average fuel flow at knock onset for Blend No. 6 was 82 lbs/hr, thus indicating Blend No. 6 provided improved knock margin as compared to the Baseline 100LL
- Blend No. 38 encountered knock at a fuel flow richer than the Baseline 100LL knock onset fuel flow (Figure 60.0). Average fuel flow at knock onset for Blend No. 38 was 127 lbs/hr, thus indicating Blend No. 38 provided a negative detonation margin, with knock occurring at an average fuel flow significantly rich of the 100LL baseline.

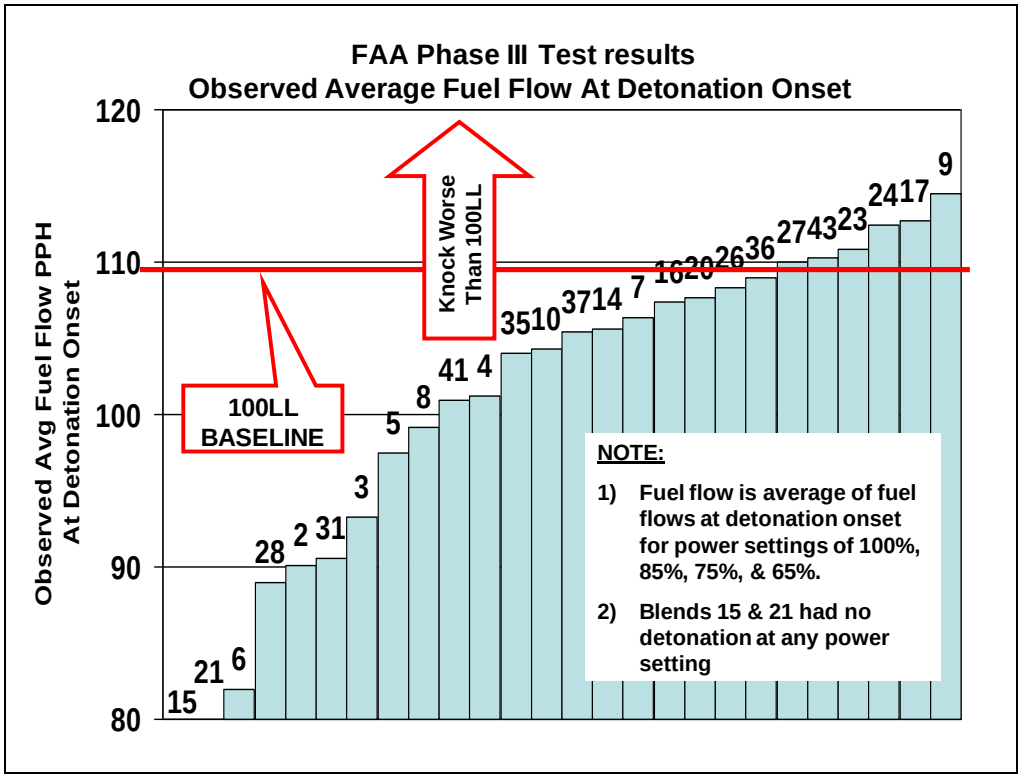

Figure 59.0 – Detonation Ranking of Phase III Blends [15]

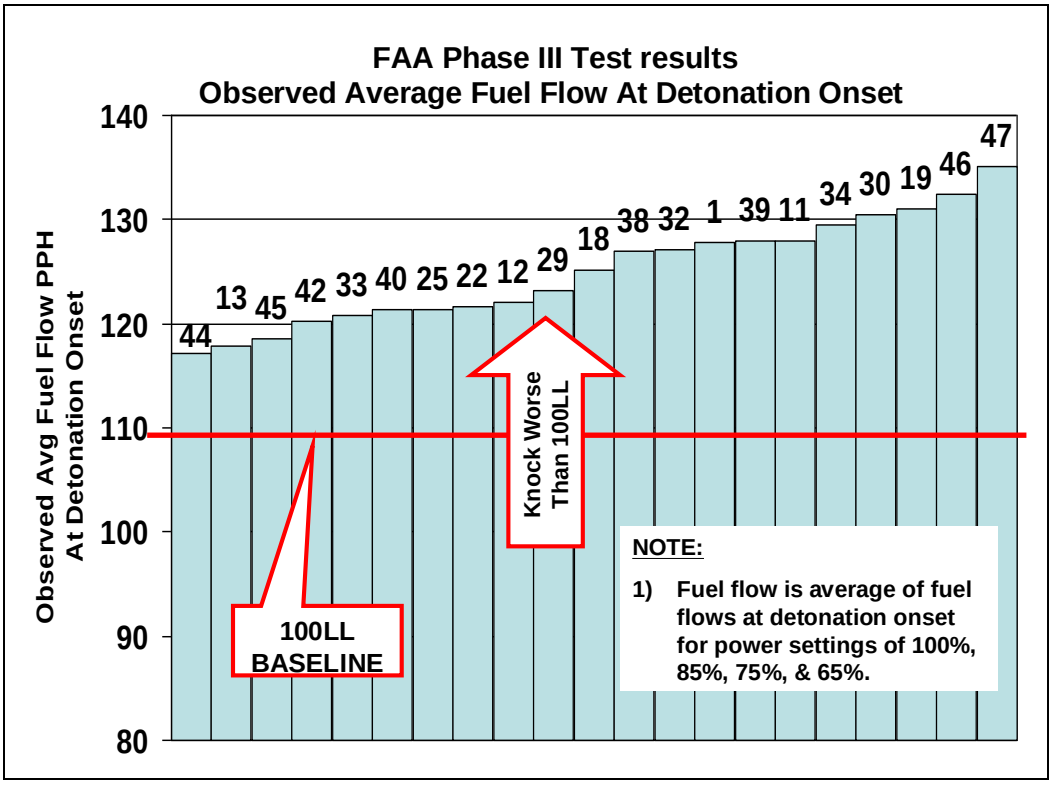

Figure 60.0 – Detonation Ranking of Phase III Blends [15]

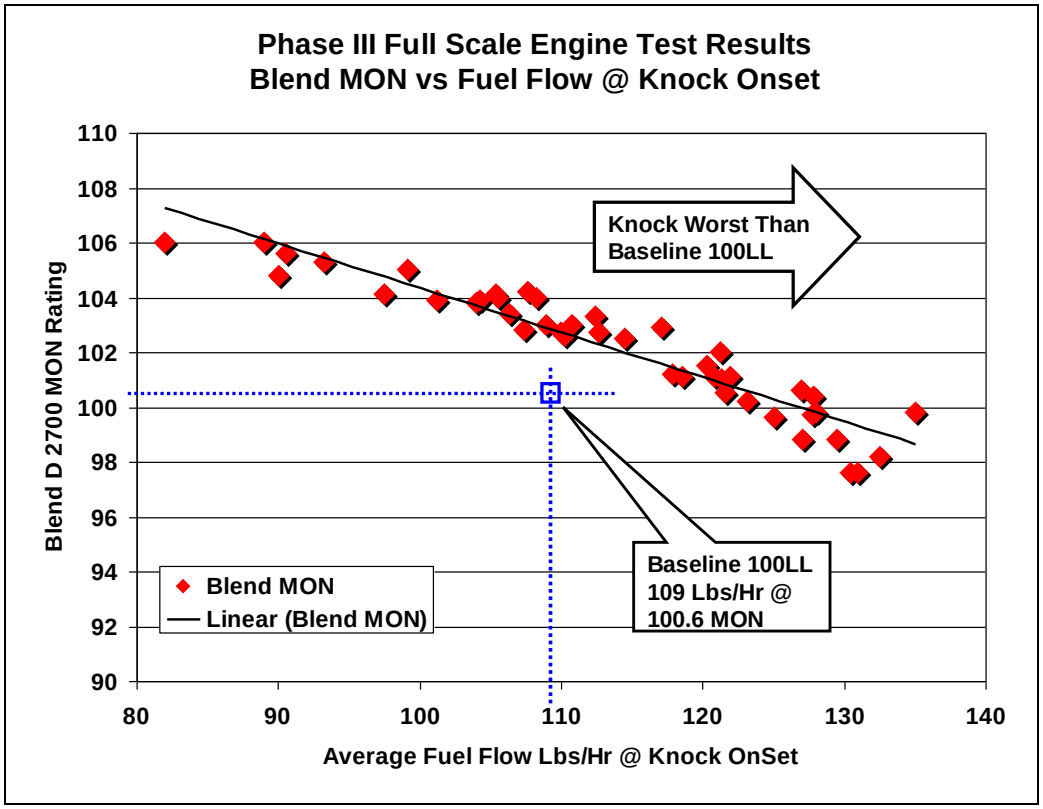

Figure 61.0 – Phase III Blend MON vs Knock Onset Average Fuel Flow [15]

Figure 61.0 explores the correlation between blend D 2700 MON rating and the average fuel flow at knock onset for all 47 unleaded blends. The minimum specification baseline 100LL fuel is shown for comparison. MON ratings for the unleaded blends tend to correlate with measured octane response in the full scale engine. Phase III data scatter is actually less than shown in Figures 54.0 and 56.0 for the Phase II blends. Figure 61.0 indicates an unleaded blend with a MON of 2-3 points higher is required to provide octane response equivalent to the minimum specification baseline 100LL.

6.6.5. Effect of Blend Components

Of significant interest is the effect of blend components on resulting MON and full scale engine knock performance. Section 3.7 of the FAA Test Results Report reference (15) provides results of a first order linear correlation performed on several components. Figure 9 of reference (15) is repeated below as Figure 62.0 which depicts the effect of *meta*-toluidine on blend MON D 2700 rating; the results and conclusions which are quite consistent with the prior research phases show *meta*-toluidine as having a dominant influence on resulting blend MON .[(15)]

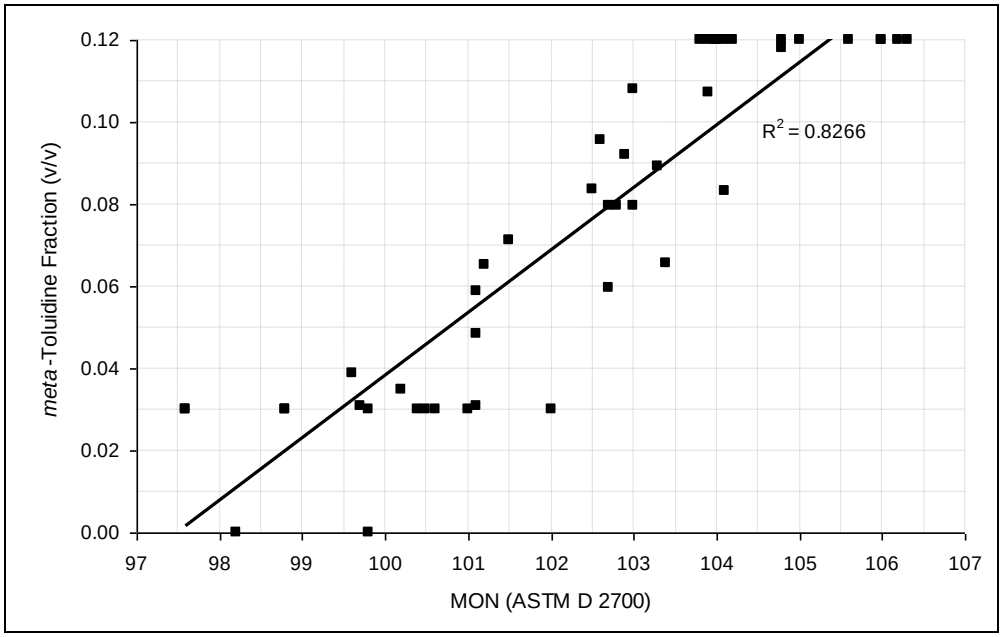

Figure 62.0 – Effect of *meta*-Toluidine on Blend MON [(15)]

Figure 19 of reference (15) plots volume fraction for *meta*-toluidine versus detonation onset fuel flow for the combined Phase II and Phase III blends (total of 77 blends). This plot clearly shows the significance of the effect of *meta*-toluidine on the resulting blend MON rating. Figure 19 of reference (15) is repeated as following Figure 63.0.

Section 3.7 of reference (15) also looked at first order linear correlation for component volume fractions consisting of 1) toluene + *tert* butyl benzene, 2) *tert*-butyl benzene, 3) ETBE, and 4) super alkylate; however, the simple linear analysis did not yield or indicate trends for the latter. The following Figures 64 – 67 explore the effect of *tert*-butyl benzene and ETBE on blend MON and engine knock response (average fuel flow at knock onset), but as indicated by the low R^2 value of each, accuracy of the correlation is well less than desirable and does not confirm the presence of a definitive trend, same as concluded in reference (15). More sophisticated analysis of the data is required to investigate effect of components.

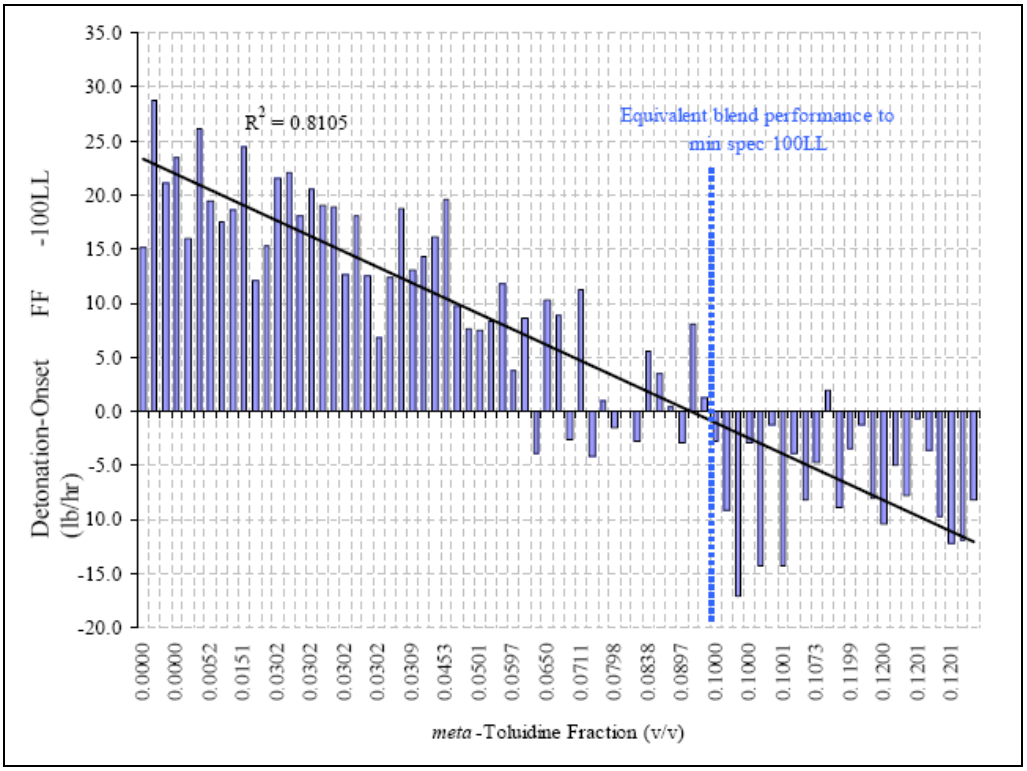

Figure 63.0 – Effect of meta-Toluidine on Blend Detonation Onset Fuel Flow For all 77 Phase II & Phase III Blends[15]

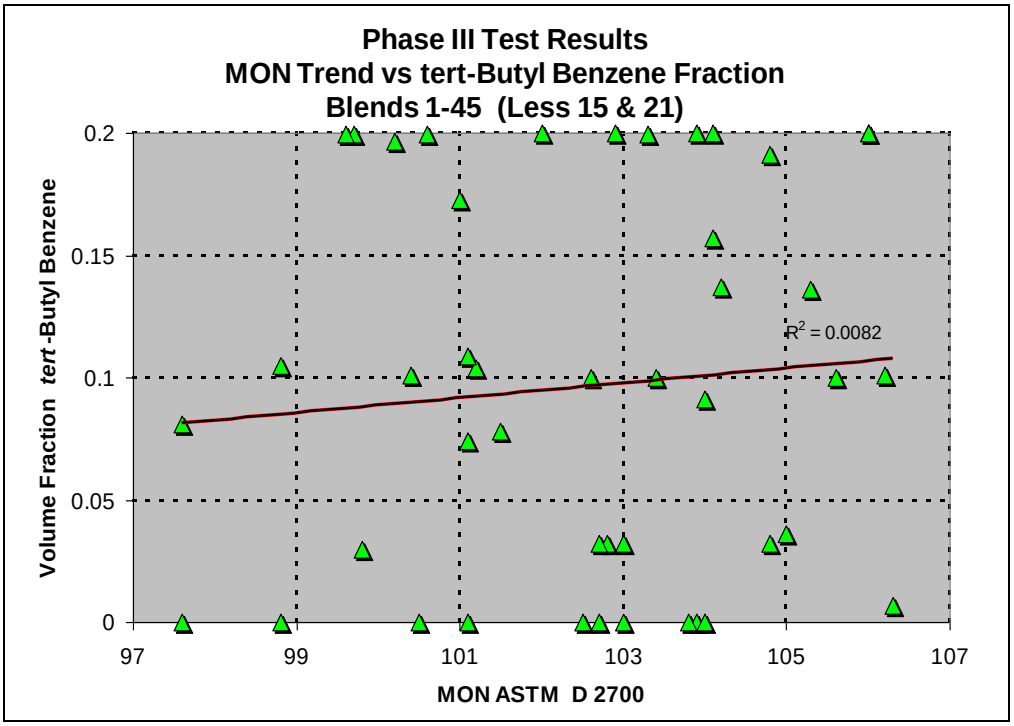

Figure 64.0 – Effect of *tert*-Butyl Benzene on Blend MON

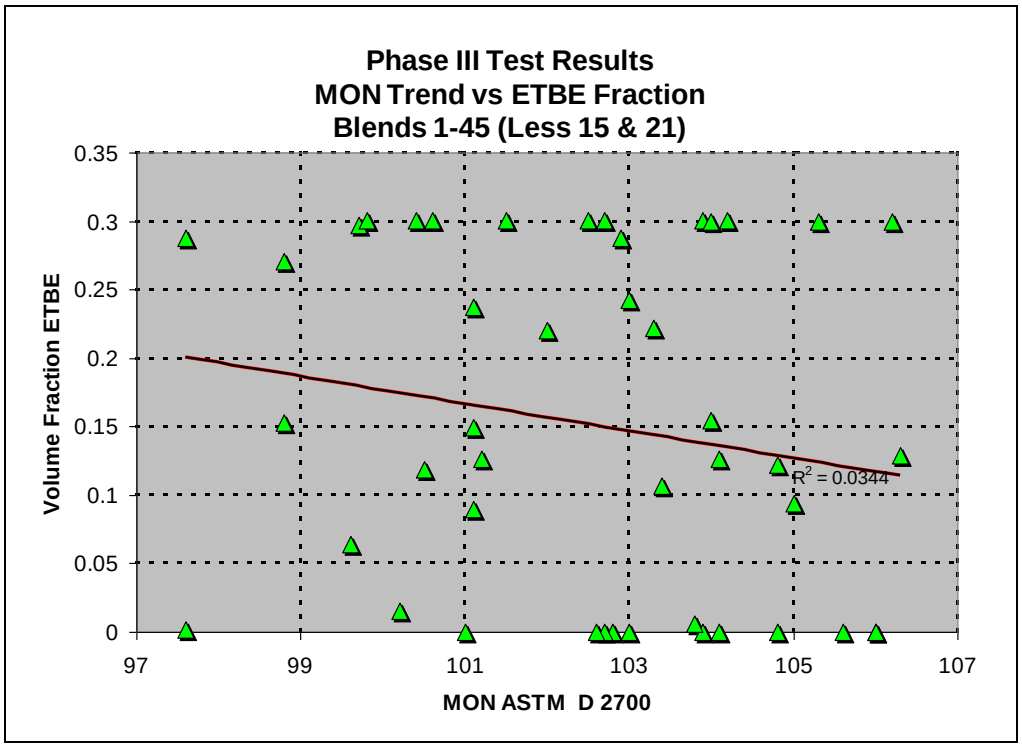

Figure 65.0 – Effect of ETBE on Blend MON

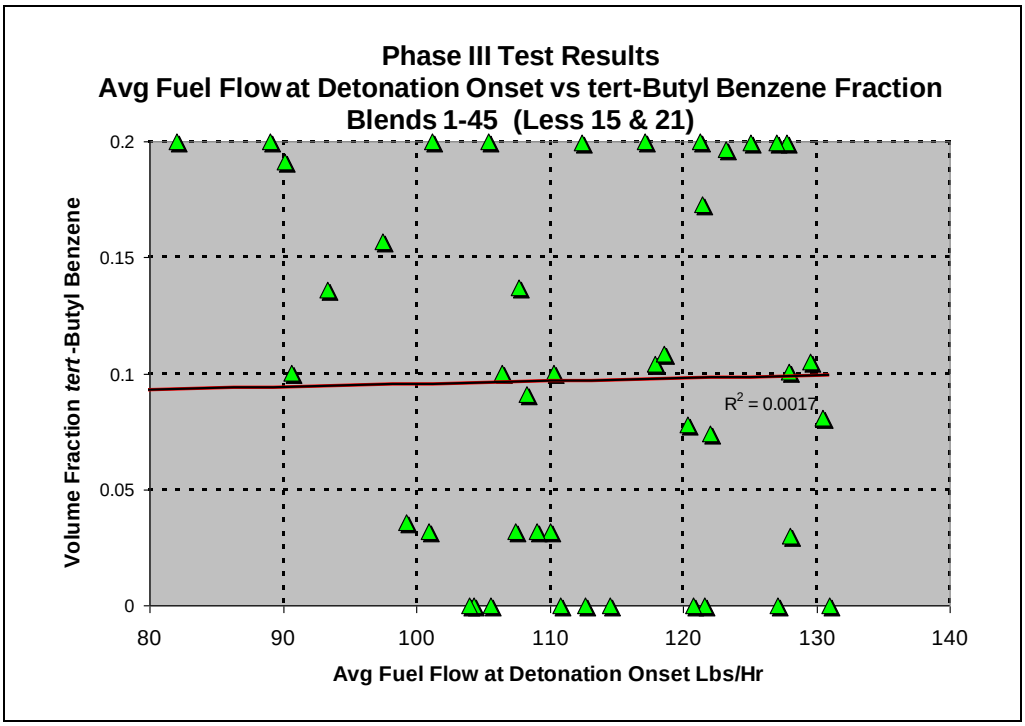

Figure 66.0 – Effect of *tert*-Butyl Benzene on Knock Onset Average Fuel Flow

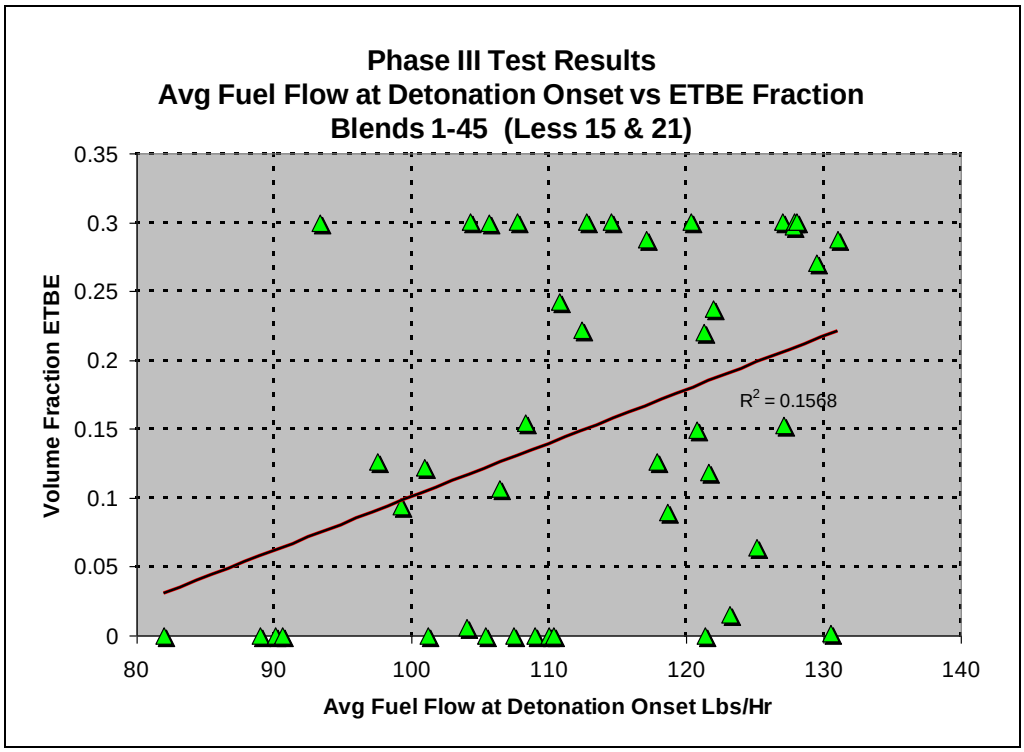

Figure 67.0 – Effect of ETBE on Knock Onset Avg Fuel Flow

6.6.6. Statistical Analysis

The Phase III research project was planned and implemented as a design experiment. The resulting design experiment provided for 45 unleaded blends with the objective of evaluating the interactions of the blend components. Multiple regression analyses of the six fuel compositional variables (aviation alkylate, super alkylate, toluene, *tert*-Butyl Benzene, *meta*-Toluidine, & ETBE) against engine knock response were performed by subcontractor Gary Hatfield of Hats Stats LLC, previously of ConocoPhillips. Mr. Hatfield was the architect of the Phase I design experiment when employed by ConocoPhillips and also conducted the Phase I regression analyses. A copy of Hatfield's Regression Analysis of Phase III test results is included as Appendix G of this report.

Phase III regression analysis responses of interest were fuel MON rating, engine BSFC at knock onset, engine fuel flow at knock onset, and equivalence ratio at knock onset. Responses based upon BSFC, fuel flow, and equivalence ratio (at knock onset) were addressed for each of the four engine power settings (100% @ 2700RPM, 85% @ 2600 RPM, 75%@ 2450 RPM, & 65% @ 2350 RPM). A total of 16 models were successfully developed for the responses of interest and are presented in the Appendix G report.

Takeoff power of 100% BHP at 2700 RPM full throttle represents the most critical power setting for knock for the naturally aspirated engine. Regression coefficients for the responses of fuel MON, fuel flow at 2700 RPM knock onset, BSFC at 2700 RPM knock onset, and equivalence ratio at 2700 RPM knock onset are extracted from the Appendix G report and summarized as follows (adjusted to 4 decimal places) in Table 47.0. See Appendix G report for the other 12 regression models.

Table 47.0
Regression Coefficients [27]
Phase III Regression Analysis

	Model Variable	Regression Coefficients			
		Blend MON	**Fuel Flow @ 2700**	**BSFC @ 2700**	**ER Φ @ 2700**
1	Aviation Alkylate (Avalky)	97.5520	202.5586	0.7868	1.6657
2	Super Alkylate (Sualky)	108.7234	148.6506	0.5433	1.1945
3	Toluene (TOL)	111.6752	155.8250	0.5825	1.1890
4	*tert*-Butyl Benzene (tBB)	104.7373	181.0594	0.7132	1.1289
5	*meta*-Toluidine (mT)	117.4157	①	3.3402	①
6	ETBE (ETBE)	99.6512	197.7336	0.7266	1.5794
7	AvAlky x SuAlky	-8.1114	①	①	①
8	AvAlky x Toluene	①	①	①	①
9	AvAlky x tBB	22.4410	-95.5954	-0.4145	①
10	AvAlky x *m*-Toluidine	80.6986	-328.6269	-5.6109	-1.4255
11	AvAlky x ETBE	9.0764	-84.4398	-0.3198	-0.6387
12	SuAlky x Toluene	-32.3993	84.4804	0.3634	0.8336
13	SuAlky x tBB	①	①	①	0.8066
14	SuAlky x *m*-Toluidine	63.3230	-243.1014	-4.7381	①
15	Toluene x ETBE	①	①	①	①
16	Toluene x tBB	①	①	①	①
17	Toluene x *m*-Toluidine	①	①	-4.3381	-3.3255
18	Toluene x ETBE	①	①	①	①
19	tBB x *m*-Toluidine	-50.5912	①	-3.9113	-3.2177
20	tBB x ETBE	①	①	①	①
21	*m*-Toluidine x ETBE	42.1791	①	-3.8573	-2.1485
22	AvAlky x SuAlky x Toluene	43.1444	①	①	①
23	AvAlky x SuAlky x tBB	①	①	①	①
24	AvAlky x SuAlky x mT	①	①	①	①
25	AvAlky x SuAlky x ETBE	①	①	①	①
26	AvAlky x Toluene x tBB	-172.4486	①	①	①
27	SuAlky x Toluene x tBB	①	①	①	①
28	Toluene x tBB x mT	557.4278	①	①	32.7029
29	Toluene x mT x ETBE	①	①	①	16.3315
30	tBB x mT x ETBE	173.5434	①	①	13.4883
	MSE/Variance	0.015	0.046	0.035	0.052

① NS = found to be not significant for the final regression model

② Composition = component volume fraction (0.XXXX)

③ Fuel Flow , BSFC, & ER Φ are at Knock Onset

④ Negative values indicate antagonistic interaction for the noted variables

NOTE……

1) Equivalence Ratio Φ = (F/A)actual / (F/A)stoichiometric

2) BSFC = Fuel Flow / Engine BHP

Using the above regression coefficients, the equations for predicting the responses for fuel MON rating, 2700 RPM fuel flow at knock onset, 2700 RPM BSFC at knock onset, and equivalence ratio at 2700 RPM knock onset for the variables of interest are extracted from the Appendix G report and presented as follows.[27]

MON Model for Fuel Blend

$$MON_{fuel} = (AVALK\ X\ 97.5520) + (SUALK\ X\ 108.7234) + (TOL\ X\ 111.6752) + (tBB\ X\ 104.7373) + (mT\ X\ 117.4157) + (ETBE\ X\ 99.6512) - (AVALK\ x\ SUALK\ X\ 8.1114) + (AVALK\ x\ tBB\ X\ 22.4410) + (AVALK\ x\ mT\ X\ 80.6986) + (AVALK\ x\ ETBE\ X\ 9.0764) - (SUALK\ x\ TOL\ X\ 32.3993) + (SUALK\ x\ mT\ X\ 63.3230) - (tBB\ x\ mT\ X\ 50.5912) + (mT\ x\ ETBE\ X\ 42.1791) + (AVALK\ x\ SUALK\ x\ TOL\ X\ 43.1444) - (AVALK\ x\ TOL\ x\ tBB\ X\ 172.4486) + (TOL\ x\ tBB\ x\ mT\ X\ 557.4278) + (tBB\ x\ mT\ x\ ETBE\ X\ 173.5434)$$

Fuel Flow Knock Onset 2700 RPM Model

$$FF_{2700} = (AVALK\ X\ 202.5586) + (SUALK\ X\ 148.6506) + (TOL\ X\ 155.8250) + (tBB\ X\ 181.0594) + (ETBE\ X\ 197.7336) - (AVALK\ x\ tBB\ X\ 95.5954) - (AVALK\ x\ mT\ X\ 328.6269) - (AVALK\ x\ ETBE\ X\ 84.4398) + (SUALK\ x\ TOL\ X\ 84.4804) - (SUALK\ x\ mT\ X\ 243.1014)$$

BSFC Knock Onset 2700 RPM Model

$$BSFC_{2700} = (AVALK\ X\ 0.7868) + (SUALK\ X\ 0.5433) + (TOL\ X\ 0.5825) + (tBB\ X\ 0.7132) + (mT\ X\ 3.3402) + (ETBE\ X\ 0.7266) - (AVALK\ x\ tBB\ X\ 0.4145) - (AVALK\ x\ mT\ X\ 5.6109) - (AVALK\ x\ ETBE\ X\ 0.3198) + (SUALK\ x\ TOL\ X\ 0.3634) - (SUALK\ x\ mT\ X\ 4.7381) - (TOL\ x\ mT\ X\ 4.3381) - (tBB\ x\ mT\ X\ 3.9113) - (mT\ x\ ETBE\ X\ 3.8573)$$

Equivalence Ratio at 2700 rpm Model

$$EqR_{2700} = (AVALK \times 1.6657) + (SUALK \times 1.1945) + (TOL \times 1.1890) + (tBB \times 1.1289) + (ETBE \times 1.5794) - (AVALK \times mT \times 1.4255) - (AVALK \times ETBE \times 0.6387) + (SUALK \times TOL \times 0.8336) + (SUALK \times tBB \times 0.8066) - (TOL \times mT \times 3.3255) - (tBB \times mT \times 3.2177) - (mT \times ETBE \times 2.1485) + (TOL \times tBB \times mT \times 32.7029) + (TOL \times mT \times ETBE \times 16.3315) + (tBB \times mT \times ETBE \times 13.4883)$$

Similar to the Phase I statistical analysis, the above equation for fuel MON quality provides a useful engineering model for the prediction of fuel MON quality for the range of blend components investigated. Whereas MON values equivalent to 100 and greater are desirable, the coefficients for primary variables 1-6 in Table 47.0 greater than 100 indicate adding more of the component raises MON. For the binary interaction coefficients 7-21 of Table 47.0, positive coefficients indicate raising either component in the blend increases MON, while negative coefficients lower MON if either component level is raised; the same is true for the three way interaction coefficients.

The models for fuel mixture parameters (fuel flow, BSFC, and equivalence ratio) at knock onset likewise provide an effective method for prediction of engine knock response for the IO-540-K engine and similar engine models when operating with an unleaded fuel containing the fuel components investigated. Smaller values for fuel flow, BSFC, and equivalence ratio, indicate the desired capability to operate at reduced fuel flow without knock.

More sophisticated analysis of the test results data is required to further explore the effect and interaction of blend components.

6.6.7. Minimum Specification Baseline 100LL vs FBO 100LL

FAA Technical Center test and evaluations performed during the Phase III research included comparative analysis and testing of not only the Phase III minimum specification baseline 100LL AVGAS (identified as MF2) but also the Baseline 100LL fuel used for the Phase II testing (identified as MF1) and a typical field purchased FBO 100LL AVGAS (identified as FBO AVGAS). The results of these comparative tests are repeated as follows in consideration of the significance of the TEL content and MON ratings for these three 100LL fuels. Properties for the minimum specification baseline 100LL and the FBO 100LL are included in Section 6.6.3.4 of this report.

The following Table 48.0 is the same as Table 13 of reference (15) and is repeated below to illustrate the differences in MON, PN, and TEL for the three different 100LL fuels described above. Note the higher MON and higher TEL content of the FBO 100LL AVGAS. Figure 1 of reference (15) plots the detonation performance of the above three 100LL AVGAS fuels against BHP as tested on the IO-540-K engine; Figure 1 is repeated below as Figure 68.0 which illustrates the significance of difference in engine knock response between the FBO AVGAS and the Min Spec 100LL. Figure 69.0 is a plot of average fuel flow at knock onset for the Phase III blends with the FBO AVGAS and the Baseline 100LL AVGAS data points shown for comparison.

Table 48.0 Phase III 100LL AVGAS Comparisons MF1 Min Spec 100LL, MF2 Min Spec 100LL, & FBO 100LL[15)]			
Fuel	MON ASTM D 2700	PN ASTM D 909	Lead Content mL TEL/gal
MF1 Min Spec 100LL	100.3	131.5	2.03
MF2 Min Spec 100LL	100.6	130.9	1.55
FBO 100LL	103.6	133.0	1.70

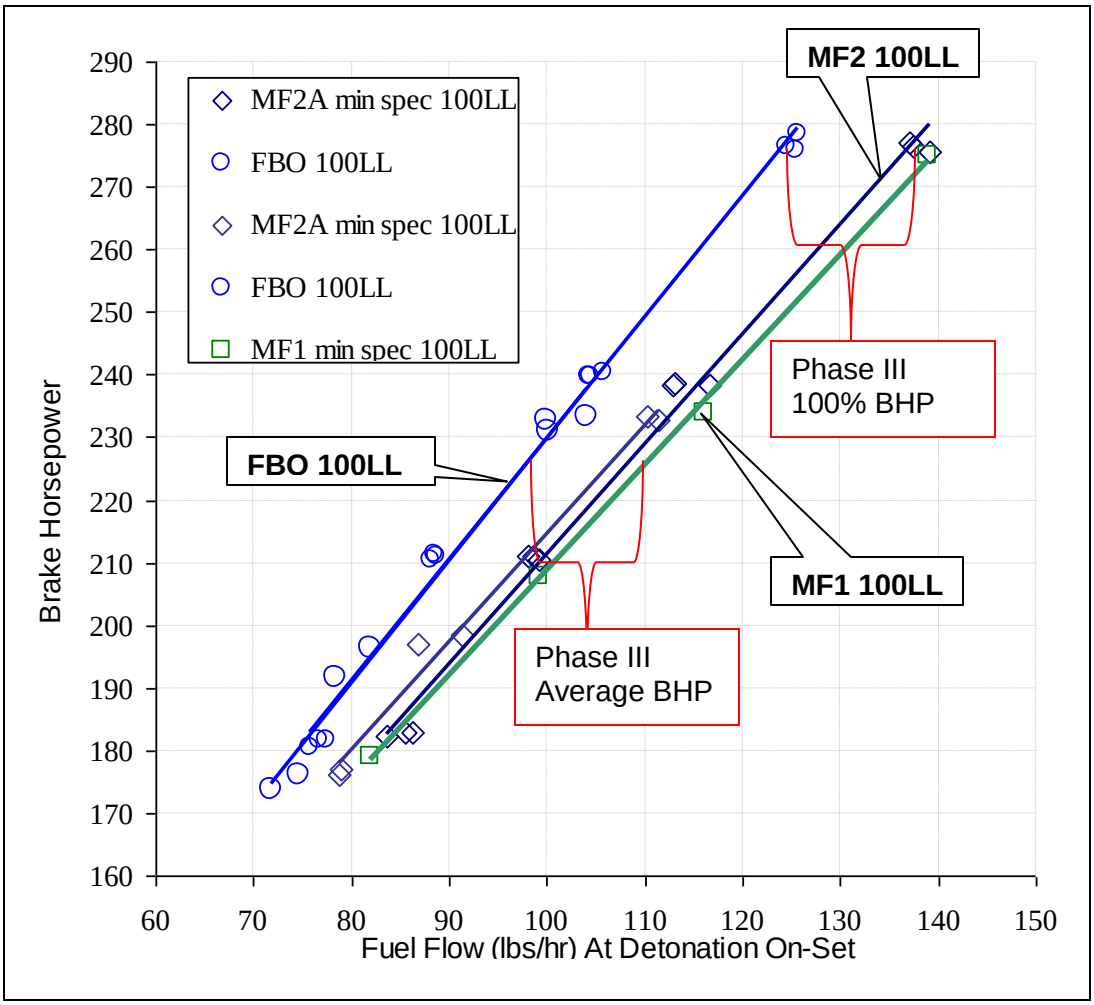

Figure 68.0 – Detonation Performance of Min Spec 100LL & FBO 100LL[(15)]
Brake Horsepower vs Fuel Flow at Detonation Onset

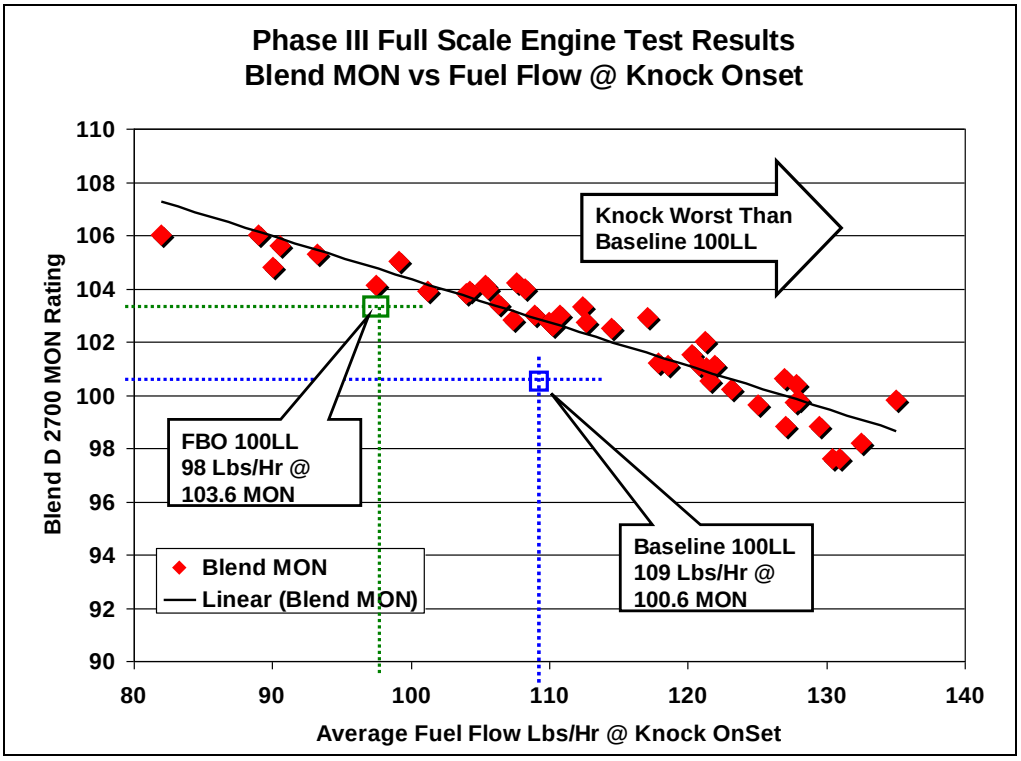

Figure 69.0 – Detonation Performance of Min Spec 100LL & FBO 100LL
D 2700 MON Rating vs Avg Fuel Flow At Knock On-Set

6.6.8. Conclusions

Significant conclusions and observations as related to detonation performance of the Phase III Test Matrix based upon results of full scale engine testing at the FAA Technical Center's Aviation Fuel and Engine Test Facility are summarized as follows. The reader is directed to the respective laboratory and engine test reports references (11) and (15) for an in depth assessment of conclusions and observations. The purpose of this report is to provide a summary of the related testing and to highlight significant conclusions and findings.

Test Results

- Blends with a higher MON rating tended to correlate with a positive detonation response as measured in the engine. Progressively higher MON rated fuels tended to provide greater positive octane margin. Similarly, blends with a lower MON rating tended to correlate with a negative detonation response in the full scale engine. Progressively lower MON rated blends tended to results in a progressively negative detonation response.
- Linear regression analysis as presented in the FAA report[(15)] again reinforced the significance of the aromatic amine as represented by *meta*-toluidine showing that the *meta*-toluidine concentration has a strong correlation to the resulting blend MON rating. "Equivalent detonation performance to the min spec 100LL was found to be accomplished with 6% - 9.5% volume *meta*-toluidine depending on the detonation onset

comparator. None of the blends with less than 6% by volume performed as well as the min spec 100LL. All blends except for two with greater than 6% volume *meta*-toluidine had MON ratings of 102.5 or higher." [15]

- The unleaded blends required an average of 2.0 MON points higher compared to the baseline 100LL octane to achieve equivalent detonation performance in the full scale engine. As summarized in reference (15), "The increase in MON required for the unleaded blends to perform equivalent to minimum specification 100LL was found to range between 1.1 and 3.2 MON depending upon the detonation onset method used; the average required increase in MON was 2." [15]
- Nineteen (19) of the forty seven (47) unleaded blends provided knock performance equivalent to or better than the min spec 100LL when averaged over the power settings. All of the blends that performed better than the minimum specification 100LL were characterized by a higher MON than the min spec 100LL. Fourteen (14) of the forty seven (47) unleaded blends had higher MON than the 100LL but offered lower anti-knock performance in the full size engine. [15]
- "The FBO 100LL with 103.6 MON performed significantly better than the min spec 100LL with 100.6 MON." [15] This serves as a reminder that the ultimate effect on the fleet of a new UL AVGAS will be indicated by the MON difference between MON for the average field 100LL AVGAS and the minimum MON for a new specification AVGAS.
- Whereas Phase III addressed detonation characteristics only, eventually the full spectrum of ASTM D 910 properties will have to be addressed for a candidate UL AVGAS. While addition of *iso*-pentane improved test fuel volatility as planned, limited laboratory analysis as documented in Exhibit VI of the Appendix B Dixie Services Laboratory Report [11] and also included in Section 2.1 of the FAA Phase III Test Results Report [15], showed considerable variance from D 910 specifications for the majority of the test blends.
- The performance of unleaded fuel blends can differ significantly from the performance of a leaded aviation gasoline. Using only MON based upon D 2700 as an indicator of detonation performance of an unleaded fuel may prove inadequate. The full scale engine detonation performance of an unleaded fuel blend can deviate significantly from the performance suggested by its MON rating. For an unleaded fuel to provide full scale engine detonation performance equal to a leaded aviation gasoline, the unleaded fuel will need a higher MON than the leaded aviation gasoline. [15]
- More sophisticated analysis of the test results data is required to investigate effect and interaction of components.
- Equations derived from statistical modeling of Phase III test results provide engineering models useful for prediction of fuel MON quality and engine knock response based upon fuel flow, BSFC, and equivalence ratio when operating with a fuel comprising the range of blend components investigated in an IO-540-K type engine.

6.7. PHASE IV – Full Scale Engine Tests, HI to MID Octane Fuels Leaded & Unleaded

6.7.1. Background

Phases I through III of the CRC Unleaded AVGAS Research initiative focused on laboratory analyses and full scale engine testing of a matrix of unleaded fuel blends using three base fuels (alkylates) in combination with various octane enhancing components with the objective of assessing engine detonation response. Experience gained during these tests indicated, for the test conditions and the specific test engine, an unleaded fuel required a MON rating of 2-3 MON higher than a leaded fuel of the same MON rating in order to provide equivalent anti-knock response in a full scale engine. With the objective of further exploring the detonation response of an engine to leaded and unleaded fuels of equivalent MON, the membership of the CRC Unleaded AVGAS Task Group and the CRC Aviation Engine Octane Rating Group determined that it would be of value to industry to expand the fuels research to conduct comparative full scale engine testing between leaded and unleaded fuels specifically formulated to provide the same MON and PN ratings. It was further determined that the research should include mid-octane leaded and unleaded fuels. Accordingly the following test plan was evolved and implemented under the guidance of the **CRC Aviation Engine Octane Rating Group.**

Results of the Phase IV research are documented in FAA Report No. DOT/FAA/AR-TN07/5 dated March 2007 [(14)], and in several unpublished CRC reports included as Appendices E and F in this report. The following provides a summary of the research results presented in these referenced reports.

6.7.2. Research Plan

Similar to the previous research phases, the Phase IV research plan was defined and implemented as an industry/government collaborative project with planning, logistics, and implementation continuing to follow the methodologies successfully applied during the previous phases. The objective of the Phase IV Research was to quantify the detonation response of engines when operated with leaded and unleaded fuels of the same MON rating. Secondary objectives include correlation of supercharge (PN) and lead effect for mid-octane rated fuels. The resulting research plan provided for full scale engine detonation testing segregated into 1) a group of high-octane leaded and unleaded fuels using an engine rated on 100LL AVGAS and 2) a group of mid-octane leaded and unleaded fuels using an engine rated on 91/96 AVGAS. The latter was of interest in consideration the Lycoming engine fleet includes a large number of older engines rated on 91/96 AVGAS. Unleaded and leaded test fuels described in the following sections were prepared and provided by the participating member companies. The research plan provided for a single engine test facility, the FAA Technical Center's Aviation Fuel and Engine Test Facility, to conduct the specified testing. A single independent laboratory, Dixie Services, provided property analysis of the test fuels. Whereas the objective of Phase IV was testing of specific fuels rather than a matrix of blends and components, design experiment considerations were not applicable to Phase IV.

NOTE…… Objective of the Phase IV research was to quantify the detonation response of engines when operated with leaded and unleaded fuels of the same MON rating. Secondary objectives includes correlation of supercharge (PN) and lead effect for mid-octane rated fuels.

6.7.2.1. Test Fuels & Logistics

A total of nine different fuels were specified to support the Phase IV full scale engine test program and are described as follows. The test fuels were supplied by the CRC Research Group members and were subjected to property analysis by a single independent laboratory with the results documented in the previously unpublished CRC reports in Appendices E and F.

High-Octane Leaded & Unleaded Fuels

The test matrix for the high-octane leaded and unleaded fuel group consisted of 5 different fuels which are summarized below in Figure 70.0. Table 49.0 summarizes the ASTM MON and supercharge rich ratings for each test fuel; the source for each fuel is also noted.

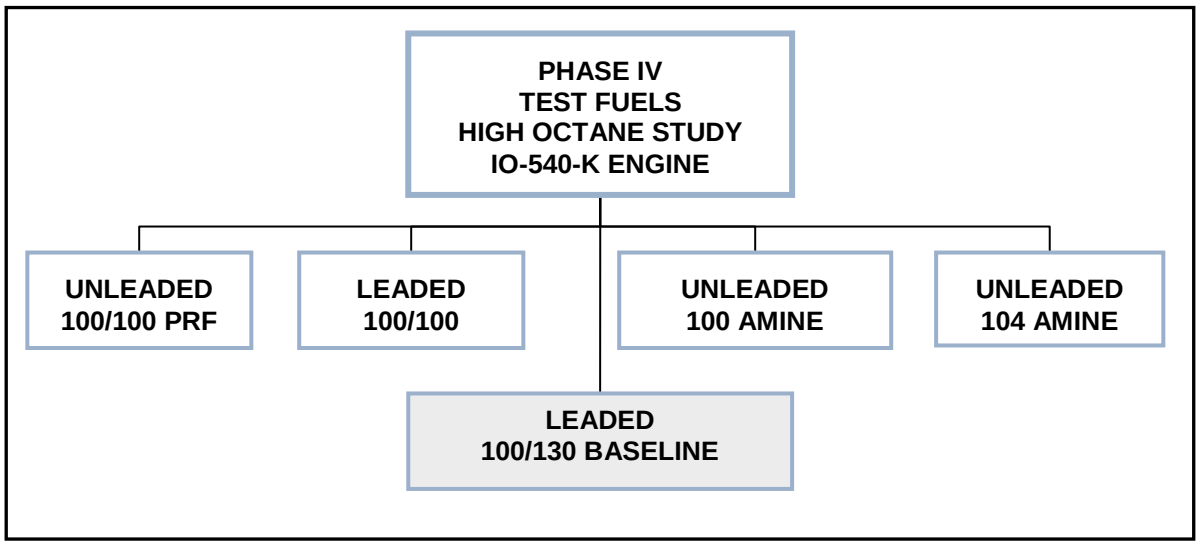

Figure 70.0 – High-Octane Study, Test Fuels - Leaded & Unleaded

Table 49.0
Phase IV High Octane Test Fuels [14]
ASTM MON & Supercharge Ratings

Test Fuel	Isooctane PRF UNLEADED	100/100 AVGAS LEADED	100/130 BASELINE LEADED	100 AMINE UNLEADED	104 AMINE UNLEADED
MON (ASTM D 2700)	100.0	100.0	100.3	100.0	104.0
Supercharge (ASTM D 909)	100	99	132	>161	>161
TEL gPb/L	0.000	0.501	0.568	0.000	0.000
Source	Phillips	Air BP	Phillips	ExxonMobil	ExxonMobil

Mid-Octane Leaded & Unleaded Fuels

The test matrix for the mid-octane leaded and unleaded fuel group also consisted of 5 different fuels which is summarized below in Figure 71.0. Table 50.0 summarizes the ASTM MON and supercharge rich ratings for each test fuel; the source for each fuel is also shown.

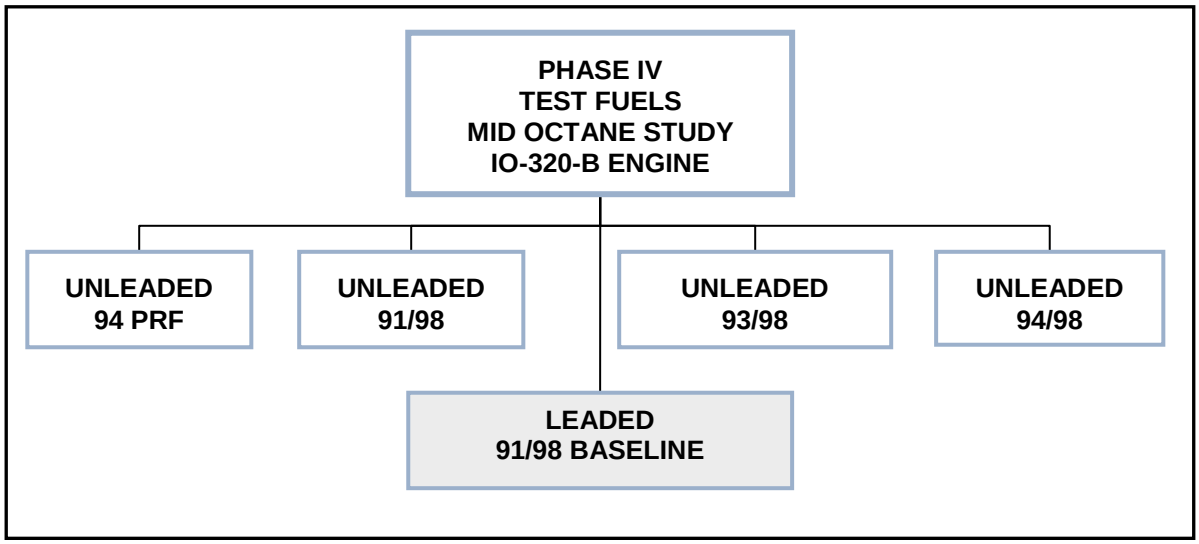

Figure 71.0 – Mid-Octane Study, Test Fuels - Leaded & Unleaded

Table 50.0
Phase IV Mid-Octane Test Fuels [14]
ASTM MON & Supercharge Ratings

Test Fuel	94 PRF UNLEADED	91/98 AVGAS UNLEADED	91/98 BASELINE LEADED	93/98 UNLEADED	94/98 UNLEADED
MON (ASTM D 2700)	94.0	91.9	91.8	93.2	94.1
Supercharge (ASTM D 909)	94	98	98	98	98
TEL gPb/L	0.000	0.000	0.502	0.000	0.000
Source	Phillips	Air BP	Air BP	Air BP	Air BP

6.7.3. Laboratory Analyses

Analysis of Phase IV test fuel properties was performed by Dixie Services. Results of ASTM property analyses for the high-octane test fuels are extracted from the Appendix E previously unpublished CRC Report and are included below as Table 51.0. Properties for the mid-octane group of fuels are extracted from the Appendix F Unpublished CRC Report and are included as Table 52.0.

Table 51.0 – Properties, Phase IV High Octane Test Fuels [22][23]

	Units	Iso-Octane	W02/575	100LL	100 Amine	104 Amine
Description		Unleaded 100/100 PRF *	Leaded 100/100	Leaded 100/130 Base-line	Unleaded 100 Amine	Unleaded 104 Amine
MON		100.0	100.0	100.3	100	104
Supercharge		100.0	99	131.5	>161	>161
Lead	gPb/liter	0.00	0.501	0.568		
D1319 FIA Aromatics	% v/v	0.0	0.3	12.0		
D1319 FIA Olefins	% v/v	0.0	0.3	0.8		
D1319 FIA Saturates	% v/v	100.0	99.4	87.2		
D3338 Specific Energy	MJ/kg	44.345	44.533	43.659		
D381 Existent Gum (Air)	mg/100ml	-	0	-		
IP365 Composite Density	kg/m3	694.0	684.5	720.2		
D86 Initial Boiling Point	Deg C	99.2	36.3	-		
D86 Final Boiling Point	Deg C	99.2	110.5	-		
D86 Loss	% v/v	-	0.6	-		
D86 Recovery	% v/v	-	98.7	-		
D86 Residue	% v/v	-	0.7	-		
D86 10% Evaporated	Deg C	-	68.6	-		
D86 40% Evaporated	Deg C	-	92.4	-		
D86 50% Evaporated	Deg C	-	96.4	-		
D86 90% Evaporated	Deg C	-	99.2	-		
D86 Sum of 10% and 50% Evaporated temps	Deg C	-	165.0	-		
D873 16Hr Accelerated Gum	mg/100ml	-	0	-		
D873 Lead Precipitate	mg/100ml	-	0	-		
IP16 Freeze point	Deg C	<-80	<-80	-		
IP154 Copper Corrosion 2Hrs @100 Deg C	-	-	1b	-		
IP289 Water Reaction Interface Rating	-	-	1b	-		
IP289 Water Reaction Volume change	-	-	2	-		
Vapor Pressure	kPa	11.8	44.5	39.6		
Sulfur (D2622mod)	% w/w	-	0.0010	-		

* API / Defined Properties

Table 52.0 – Properties, Phase IV Mid-Octane Test Fuels [22][23]

Fuel		Leaded 91/98	Unleaded 91/98	Unleaded 93/98	Unleaded 94/98	PRF 94
Analysis	Units	W04/674	W06/057#6	W06/387	W06/386	PRF94
MON ‡	ON	91.9 / 91.8‡‡	91.8	93.2	94.1	94.0*
Supercharge ‡	ON	98	98	98	98	94*
Copper Corr. 2 hrs. at 100 °C		1	1A	1A	1A	
Density at 15 °C	kg/L	0.7156	0.7236	0.7141	0.714	
I.B.P.	°C	35.8	37.0	34.4†	34.3†	
10% v evap. at	°C	68.2	65.5	61.2†	60.6†	
40% v evap. at	°C	94.3	96.5	93.2†	93.9†	
50% v evap. at	°C	97.1	99.0	98.5†	98.7†	
90% v evap. at	°C	101.5	102.0	101.4†	101.2†	
End Point	°C	115	111.0	112.8†	109.9†	
Sum of 10% & 50% Evap	°C	165.3	164.5	159.7†	159.4†	
Recovery	% (v/v)	98.8	99.0	97.6†	97.4†	
Residue	% (v/v)	1.0	0.4	0.9†	0.9†	
Loss	% (v/v)	0.2	0.6	1.5†	1.7†	
Freezing Point	°C	<-60.0	<-70	<-80	<-80	
Potential Gum	Mg/100ml	<1.0	3	6	5	
Precipitate	Mg/100ml	<1.0	0.1	-	-	
Specific Energy (Net)	MJ/kg	43.64	43.58	43.54	43.58**	
Sulfur Content	% (m/m)	<0.01	<0.001	<0.001	<0.001	
Lead	gPb/liter	0.502	0	0	0	
Interface Rating		1B	1B	1	1	
Volume Change	ml	0	0.0	0	0	
Vapor Pressure at 37.8 °C	kPa	42.5	42.9	50.1†	50.7†	

‡ MON and Supercharge measurements all performed by Dixie Testing Services for repeatability.
‡‡ Measured in duplicate.
* Defined by ASTM D 2700, ASTM D 909.
** Calculated from chemical composition and API calorific value data.
† Average of 2 determinations.

6.7.4. Engine Test Results

Full scale engine detonation testing of the leaded and unleaded high-octane and mid-octane fuels listed in Tables 51.0 and 52.0 was completed in YR2006 at the FAA Aviation Fuels and Test Facility located at the FAA William J. Hughes Technical Center in Atlantic City, New Jersey. Results of these tests are documented in FAA Report No. DOT/FAA/AR-TN07/5 dated March 2007. [14] This report may be accessed at http://actlibrary.tc.faa.gov by searching keyword “avgas”. A description of the IO-540-K and IO-320-B test engines and the associated FAA Technical Center test methods, test equipment, and associated procedures are presented in Sections 6.3.3 – 6.3.5 of this report. Further details may be found in the FAA Test Results Report[14] ; details of engine ratings and FAA approved limitations are found in the FAA TCDS[25][26] .

Results of the high-octane and mid-octane tests were also documented in several previously unpublished CRC reports which are included as Appendix E and F respectively of this final report.

The objective of the Phase IV full scale engine tests was to quantify the detonation response of engines when operated with leaded and unleaded fuels of the same MON rating and to explore

the correlation with performance number and effect of lead in mid-octane fuels. Two different model engines were used for these series of test. A Lycoming four cylinder IO-320-B engine rated to operate with a minimum grade 91/96 AVGAS, optionally 100LL, was used for the **mid-octane detonation study**; the IO-320-B model is rated at 160 BHP at 2700 RPM and has a 8.5:1 CR . A Lycoming six cylinder IO-540-K engine rated to operate with a minimum grade 100/100LL AVGAS was used for the **high-octane study**; the IO-540-K model is rated at 300 BHP at 2700 RPM and has an 8.7:1 CR. Cylinder bore for each engine is the same at 5.125" diameter; the IO-540-K has a longer stroke of 4.375 inches as compared to 3.875 inches for the IO-320-B model. Both engines are fuel injected; each engine has a maximum allowable CHT of 500ºF and a maximum allowable oil inlet temperature of 245ºF.

Test Methods

The engine test methods followed at the FAA Technical Center for Phase IV full scale engine testing for both the IO-540-K high-octane tests and the IO-320-B mid-octane tests remained consistent with the methods previously described for the Phase II and III test programs. The detonation testing consisted of conducting a mixture lean out curve at power settings of 100%, 85%, 75%, and 65% [while holding manifold pressure and engine speed constant] for each fuel including the baseline fuels. Each mixture lean out curve was performed by incrementally manually leaning the fuel flow in increments of 1 lb/hr/sec from a pre-determined non-detonation rich mixture setting to the point where either moderate to heavy detonation was encountered, or 25ºF lean of peak EGT was reached. [(14)] Each of the cylinders was monitored continuously for indications of detonation as indicated by combustion pressure patterns using the instrumented cylinder head technology described in Section 6.3.4.1 and in the FAA Test Results Report[(14)]. The point at which light detonation was encountered was noted as the fuel flow at detonation onset. Those engine variables which influence detonation were maintained at the following values for each test.

Engine Operating Settings for Detonation Testing[(14) (22) (23)]

- Hottest cylinder head temperature was maintained at 475º ± 3ºF
- All other cylinder head temperatures were maintained within 50ºF of maximum
- Induction inlet air temperature to engine was maintained at 103º ± 3ºF
- Oil inlet temperature to engine was maintained within 10ºF of the 245ºF limit
- Induction air moisture content controlled to 0-2 Grains Moisture/lb dry air

Note that detonation test methods which test the naturally aspirated engine at maximum conditions of 100% BHP & rated RPM while setting CHT within 10ºF of max allowable, oil temperature within 10ºF of max allowable, low humidity induction air, and induction air temperature equivalent to hot day conditions are consistent with FAA AC33.47-1 which provides guidelines for conducting official detonation tests during the engine FAA certification program. AC33.47-1 requires that the engine lean limit fuel flow is 12% greater than the leanest fuel flow resulting in detonation.

Mixture Lean Out Data

Mixture lean out curves were conducted with complete data sets recorded for each of the fuels tested. Observed data may be viewed in Appendices A and B of the FAA test report, reference (14).

6.7.4.1. High Octane Study Test Results, IO-540-K Engine

FAA Report No. DOT/FAA/AR-TN07/5 [14] provides a detail accounting of the test results for the high octane leaded and unleaded fuels as tested in the model IO-540-K engine. Similarly the unpublished CRC Report included as Appendix E also documents the results of the same tests. Each of the previous reports provides a thorough assessment of the testing conducted including observed data and comparative analysis. The following provides a summary of the test results with an emphasis on the relative effect of the leaded and unleaded fuels of similar MON on engine octane response. The criterion used to evaluate engine detonation response with the fuels tested is "fuel flow at detonation onset", same as used to evaluate the unleaded experimental blends in Phases II and III when tested in a full scale engine.

The results of the high octane fuels study are presented by the following Figure 72.0 which is the same as Figure 1 in the FAA Test Results Report. [14] Figure 72.0 plots the "fuel flow at detonation onset" for each of the 5 fuels listed in Table 49.0 for engine operation at power settings of 100% (2700 RPM WOT), 85% (2600 RPM), 75% (2450 RPM), and 65% (2350 RPM). Each of the diagonal lines represents the knock limit for the fuel shown in the same manner as displayed in Figures 26.0 – 33.0 (Phase II full scale engine tests) and in Figure 68.0 (Phase III full scale engine tests).

A comparison of the 100/130L "detonation line" in Figure 72.0 with the Baseline 100LL "detonation line" in Figures 26.0 – 33.0 and in Figure 68.0 shows correlation between the leaded 100/130L data of Phase IV and the Baseline 100LL data of Phases II and III, thus indicating consistency in test methods and data. It is also of interest that the FBO 100LL "detonation diagonal line" of Figure 68.0 (Phase III tests) lies just to the left of the 104 Amine "detonation diagonal line" of Figure 72.0; the significance being the difference between a typical FBO 100LL and the 100 MON leaded and unleaded fuels of Figure 72.0.

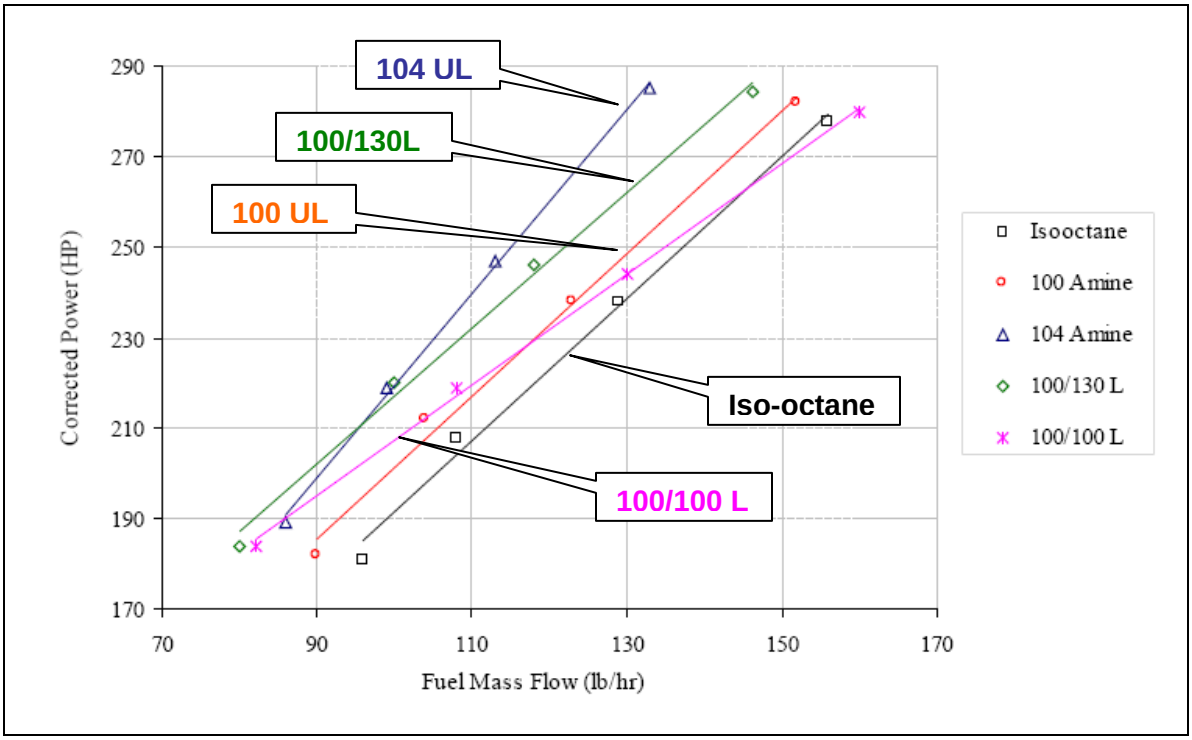

Figure 72.0 – High-Octane Study, "Fuel Flow at Detonation Onset" [14]

Figure 73.0 provides a graphical illustration of the comparative effect of the high-octane fuels tested in Phase IV when compared against the baseline 100/130L leaded AVGAS. Significant observations derived from Figures 72.0 and 73.0 are summarized as follows based upon the test conditions and the specific test engine. The reader is also directed to the reference reports[14][22][23] for additional discussion of conclusions.

- The 1) unleaded high octane fuels [100 AMINE, & Isooctane] and the 2) leaded 100/100L AVGAS resulted in a negative impact on engine detonation as compared to the baseline 100/130L AVGAS. The 100/100L fuel required approximately 9% richer fuel flow to avoid engine detonation as compared to the baseline 100/130 L AVGAS.
- The unleaded Amine fuel with 104 MON and PN > 161 provided better detonation response than any of the other fuels including the baseline leaded 100/130L AVGAS, thus again indicating the significant positive effect on full scale engine detonation response of a fuel with an aromatic amine content.
- The data indicates that an unleaded fuel of approximately 103 MON is required to provide detonation performance equivalent to the baseline leaded100/130L AVGAS of 100.3 MON. The requirement for unleaded fuels to have a greater laboratory MON than leaded fuels to achieve the same engine octane satisfaction is in agreement with the Phase II and Phase III studies reported earlier.
- Based upon comparison of the leaded baseline 100/130L [100.3 MON, 132 PN] with the leaded 100/100L [100 MON, 100 PN], the 100/130L with 132 PN provided better detonation performance than the 100/100L with 100 PN. Reference (22) concluded the data suggests the supercharge rating may become increasingly significant as an indication of a fuel's knock performance as engine power is increased; see Figure 3 of Reference (22).

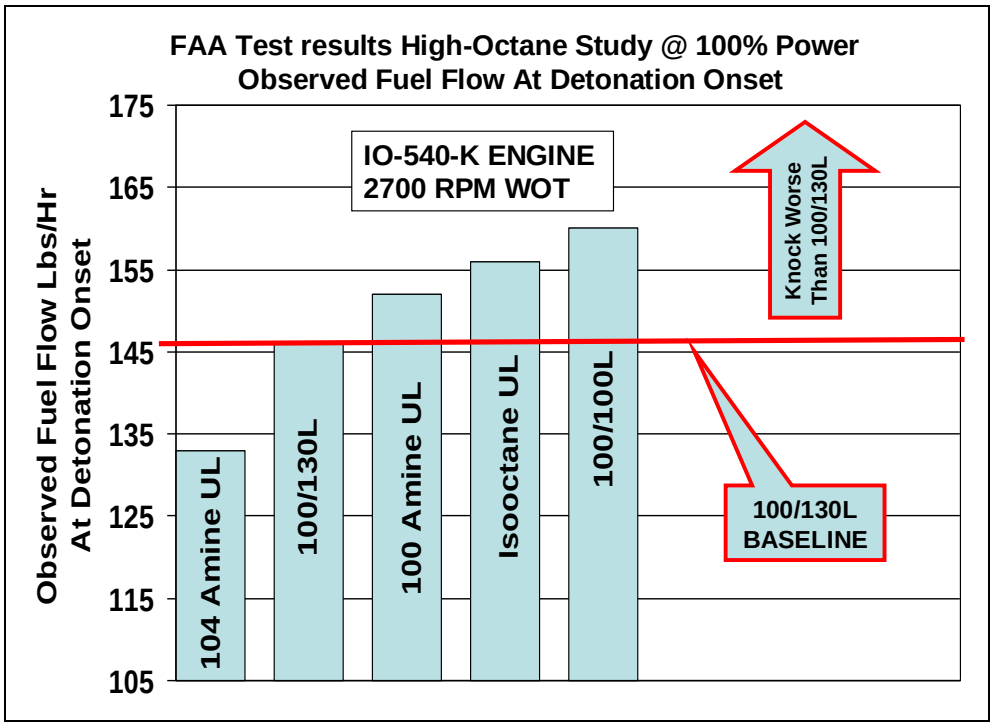

Figure 73.0 – Effect of High-Octane Fuels – "Fuel Flow at Detonation Onset"

6.7.4.2. Mid Octane Study Test Results IO-320-B

FAA Report No. DOT/FAA/AR-TN07/5 [14] provides a detail accounting of the test results for the mid-octane leaded and unleaded fuels as tested in the model IO-320-B engine. The previously unpublished CRC Report included as Appendix F also documents the results of the same tests. Each of the previous reports provides a thorough assessment of the testing conducted including observed data and comparative analysis. The following provides a summary of the test results with an emphasis on the relative effect of the leaded and unleaded fuels of similar MON on engine octane response. The criterion used to evaluate the engine detonation response of the fuels tested is **"fuel flow at detonation onset",** same as used to evaluate the unleaded experimental blends in Phases II and III when tested in a full scale engine. Appendix E report included a preliminary exploration of the mid-octane fuels using the IO-540-K engine; however, it was concluded the mid-octane fuels would be better tested in an engine originally rated for use with 91/96 AVGAS which is the case for the IO-320-B engine.

The results of the mid-octane fuels study are summarized by the following Figures 74.0 – 76.0. Figure 74.0, which is the same as Figure 2 in the FAA Test Results Report [14], is a plot of the **"fuel flow at detonation onset"** for each of the 5 fuels listed in Table 50.0. **Note that engine operation with the 94/98UL fuel was detonation free at all power settings.** The 93/98UL fuel was detonation free except at one point at 2700 RPM WOT.

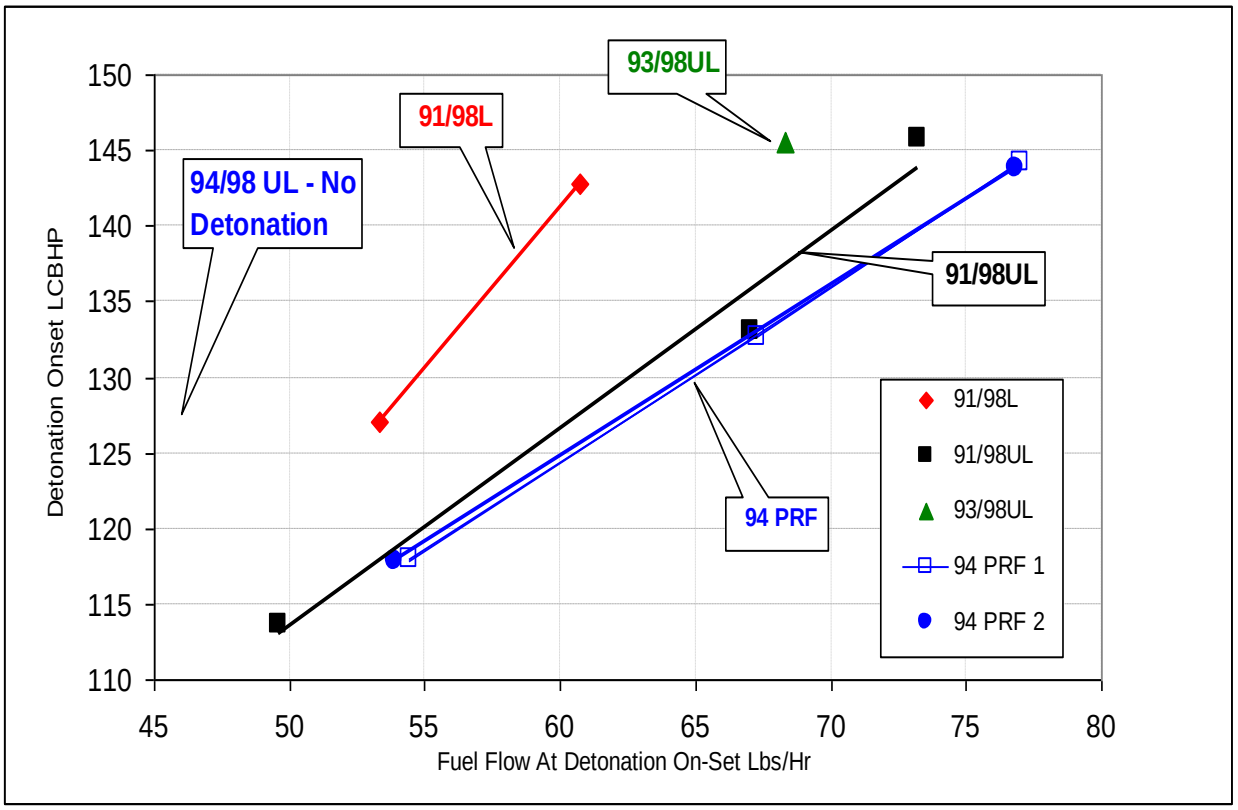

Figure 74.0 – Mid-Octane Study, "Fuel Flow at Detonation Onset" [14]

The data shown in Figure 74.0 were obtained by conducting a series of mixture lean out curves while operating the engine with each test fuel at power settings of 100% (2700 RPM WOT), 85% (2600 RPM), 75% (2450 RPM), and 65% (2350 RPM). Figure 75.0, which is extracted from FAA Phase IV test results data [14], is an aggregate plot of the mixture lean out curves run for the matrix of BHP and mid-octane fuels previously described. Each of the diagonal lines represents the on-set of detonation for the fuel shown in the same manner as displayed in Figures 26.0 – 33.0 (Phase II full scale engine tests) and in Figure 68.0 (Phase III Baseline 100LL vs FBO 100LL). Engine operation to the right of a diagonal is detonation free. The number of data points depicted in Figure 75.0 is indicative of the extent of the engine operating points and data recorded during mixture lean out detonation testing.

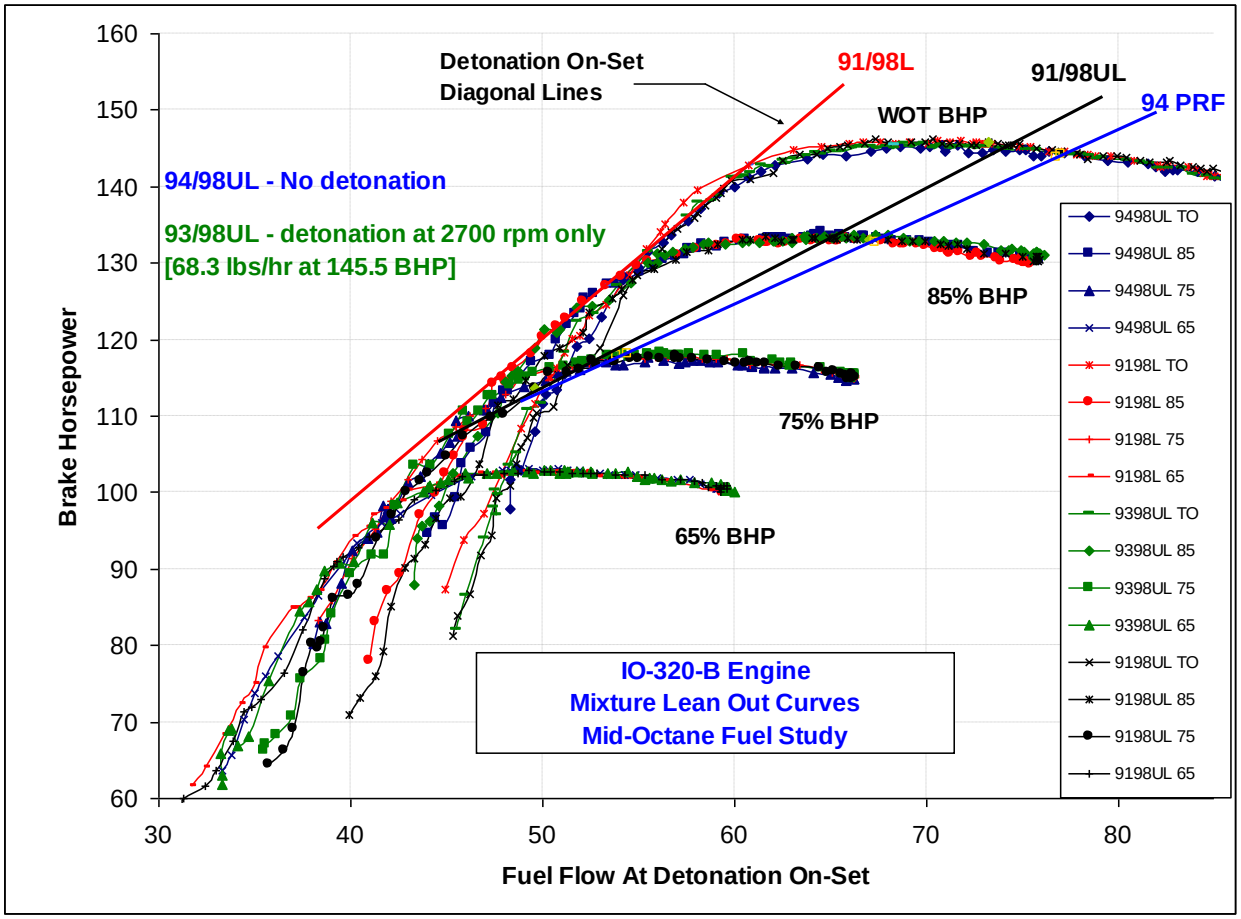

Figure 75.0 – Mid-Octane Fuel Study, Mixture Lean Out Curves [14]

Figure 76.0 provides a graphical illustration of the comparative effect of the mid-octane fuels tested in Phase IV when compared against the baseline 91/98L leaded AVGAS with the engine operating at 2700 RPM, WOT, 100% power. The fuel flows shown at detonation onset are the same as shown in Figure 74.0 for the 100% power settings. Significant observations derived from Figures 74.0 - 76.0 are summarized as follows based upon the test conditions and test engine.

- The unleaded 94/98UL fuel provided detonation free operation throughout the engine envelope explored for the mixture lean out tests.

- The unleaded 93/98UL fuel provided detonation free operation except at one point at 2700 RPM WOT.
- The leaded baseline 91/98L AVGAS provided better engine detonation performance than the unleaded 91/98UL fuel with the difference being most pronounced at 2700 RPM WOT with a 16.8% difference in fuel flow at detonation onset
- The data indicated that an unleaded fuel of approximately 2-3 MON higher is required to provide detonation performance equivalent to the 91/98 leaded fuel

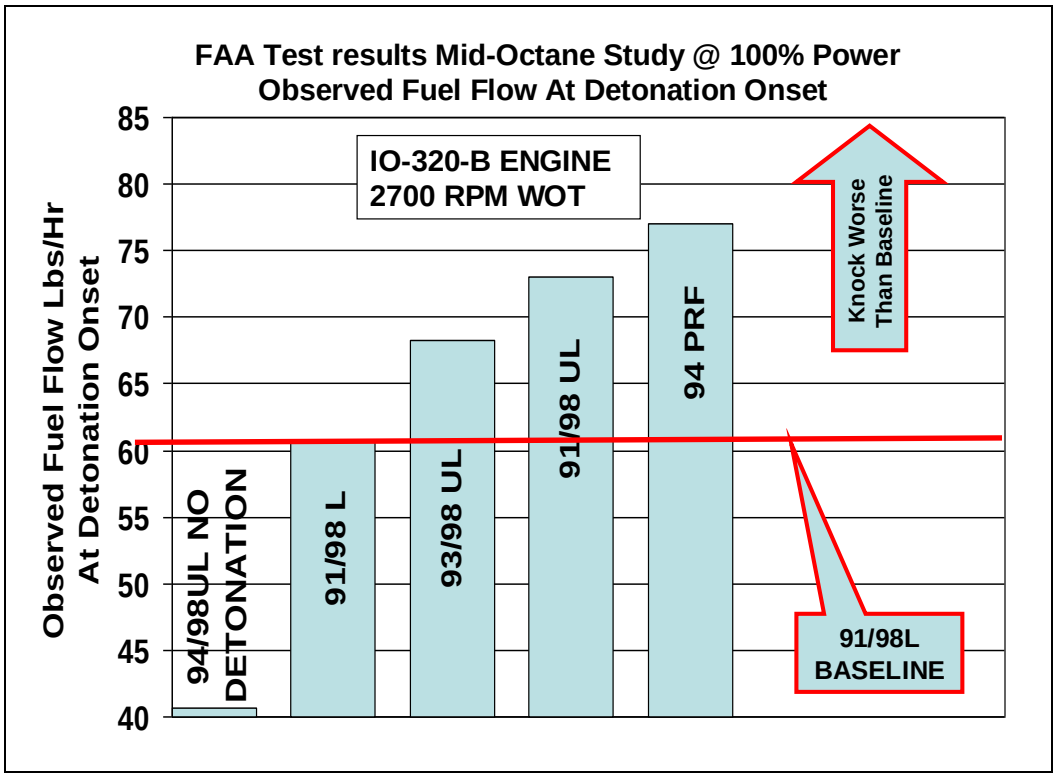

Figure 76.0 – Effect of Mid-Octane Fuels – "Fuel Flow at Detonation On-Set"

6.7.5. Conclusions – Phase IV Test Results

Significant conclusions and findings related to the full scale engine comparative detonation testing of a group of leaded and unleaded mid-octane fuels and a group of leaded and unleaded high-octane fuels are summarized as follows, and with several exceptions are extracted from the referenced reports[14][22][23]. The reader is directed to the FAA Technical Center's test results report, reference (14), and to the previously unpublished CRC UL AVGAS reports in Appendices E and F for a thorough and detailed description of test fuels, test engines, test methods and equipment, and test results. As previously stated, the purpose of this report is to provide a summary of the related testing and to highlight significant conclusions and findings.

Leaded vs Unleaded

- Test results for both the IO-320-B engine and the IO-540-K engine with a group of mid-octane fuels and high-octane fuels showed the leaded fuel in both cases provided better engine octane satisfaction than an unleaded fuel of equivalent MON. This is in agreement with prior test results and is evident in the mixture lean out curves where the leaded fuels of both groups allowed the engine to operate at a leaner fuel/air ratio without detonation as compared to an unleaded fuel of equivalent MON quality.
- For the mid-octane group of fuels investigated in the IO-320-B engine, an unleaded fuel requires 2-3 MON higher rating than the leaded fuel in order to provide the same level of detonation performance in the full scale engine under the test conditions.
- For the group of high-octane fuels investigated in the IO-540-K engine, an unleaded fuel required 4 MON higher than the leaded 100LL fuel in order to provide equivalent detonation performance at engine cruise power under the test conditions.

High-Octane Fuels Study

- Under the test conditions investigated, the leaded high-octane AVGAS provided greater anti-detonation performance in the IO-540-K engine than an unleaded high-octane AVGAS of similar MON and PN.
- The 1) unleaded high octane fuels [100 AMINE, & Isooctane] and the 2) leaded 100/100L AVGAS resulted in a negative impact on engine detonation as compared to the baseline 100/130L AVGAS. The 100/100L fuel required approximately 9% richer fuel flow to avoid engine detonation as compared to the baseline 100/130 L AVGAS.
- The unleaded Amine fuel with 104 MON and PN > 161 provided better detonation response than any of the other fuels including the baseline leaded 100/130L AVGAS, thus again indicating the significant positive effect on full scale engine detonation response of a fuel with sufficient aromatic amine content to meet these criteria.
- The data indicates that an unleaded fuel of approximately 103 MON is required to provide detonation performance equivalent to the baseline leaded100/130L AVGAS of 100.3 MON.
- The baseline leaded 100/130 L AVGAS outperformed the leaded 100/100L AVGAS at high power settings while providing equivalent knock performance at the lower cruise power settings.
- Based upon comparison of the leaded baseline 100/130L [100.3 MON, 132 PN] with the leaded 100/100L [100 MON, 100 PN], the 100/130L with 132 PN provided better detonation performance than the 100/100L with 100 PN. Reference (22) concluded that the data suggests the supercharge rating may become increasingly significant as an indication of a fuel's knock performance as engine power is increased; see Figure 3 of Reference (22).
- The implication of the high-octane fuel study results is that engines such as the IO-540-K which were originally rated on a leaded 100/130 L AVGAS would require an unleaded fuel of at least 3 MON higher in order to ensure detonation free operation with the unleaded fuel assuming no other changes to the engine; otherwise, the engine would experience a loss in detonation margin equivalent to approximately 3 MON.

Mid-Octane Fuels Study

- Under the test conditions investigated, the leaded mid-octane AVGAS provided greater anti-detonation performance than an unleaded mid-octane AVGAS of similar MON and PN, confirming CRC research experience of the significant effect of TEL on combustion in full scale engines. (14)
- The leaded 91/98L AVGAS provided greater anti-detonation performance than the unleaded 91/98UL AVGAS under the test conditions investigated.
- The leaded 91/98L AVGAS did not perform as well as the unleaded 94/98UL AVGAS, but provided somewhat greater anti-detonation performance as compared to the unleaded 93/98 UL fuel.
- The unleaded 94/98 UL fuel was observed to be detonation free in the IO-320-B engine throughout the range of power settings tested. The unleaded 93/98 UL fuel was detonation free except for one point at 2700 RPM WOT.
- The implication of the immediate prior conclusion is that engines such as the IO-320-B which were originally rated on a leaded 91/96 L AVGAS would require an unleaded fuel of 2-3 MON higher to achieve similar engine octane satisfaction under the test conditions chosen for the study.

Supercharge Rich Rating

- Under the test conditions investigated on the IO-540-K engine with the high-octane group of fuels, the FAA Test Results Report (14) concluded "*the lead improves the detonation performance of the fuel above what is suggested by the MON as determined by single cylinder test, and that the supercharge rich rating plays more of a role at the higher power settings than at the cruise power settings*."
- The FAA Test Results Report further concluded *"Supercharge Rich ratings do not appear to have the same significance for unleaded fuels as they do for leaded, hydrocarbon fuels. This is an area that needs further research."*

NOTE……..The preceding Section 6.0 completes the documentation of test results as related to research conducted during Phases I through IV of the CRC Unleaded AVGAS research project. The following Section 6.8 provides insight into critical properties and issues associated with an unleaded AVGAS.

6.8. Critical AVGAS Properties & Operational Issues

Certain properties of aviation gasoline are considered critical as related to flight safety and engine performance. Although the CRC UL AVGAS research project focused primarily on engine octane satisfaction, the following fuel properties and associated operational issues were identified by the CRC UL AVGAS research effort as being significant considerations in the development and implementation of an unleaded aviation gasoline. A summary of these considerations was compiled by the CRC UL AVGAS Group early during its deliberations but was never released as a formal report. The following briefly examines these critical properties and operational aspects, and provides insight into the potential effect on engines and aircraft.

Flight safety (engine and aircraft) can be directly affected by fuel properties including octane rating, volatility, freeze point and water reaction. Operational characteristics including storage stability, energy content, material compatibility, lubricant compatibility, distillation, dye, toxicity, engine wear, transportation, and emissions are equally important considerations relative to performance and service life of the flight hardware.

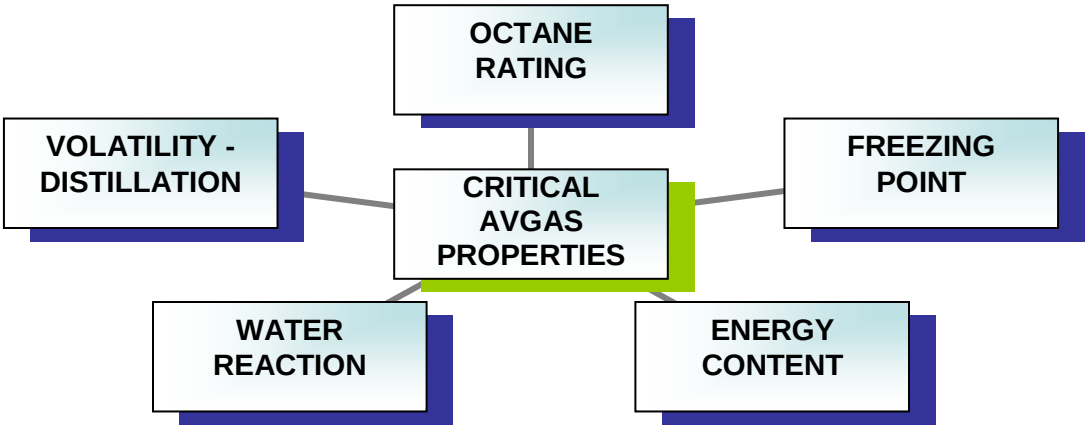

Figure 77.0
Aviation Gasoline Critical Properties

Operational characteristics include those issues which can have a significant effect on engine performance. For example, if an aviation gasoline has significantly less energy content than the original 100LL fuel, aircraft takeoff performance, gross weight, range, and endurance may be affected to the extent take off performance is de-rated with a corresponding reduction in gross weight and a reduction in aircraft range. The use of an oxygenated fuel could result in a significant impact on fuel burn with a resulting loss in aircraft range. Operational issues include those considerations shown in Figure 78.0.

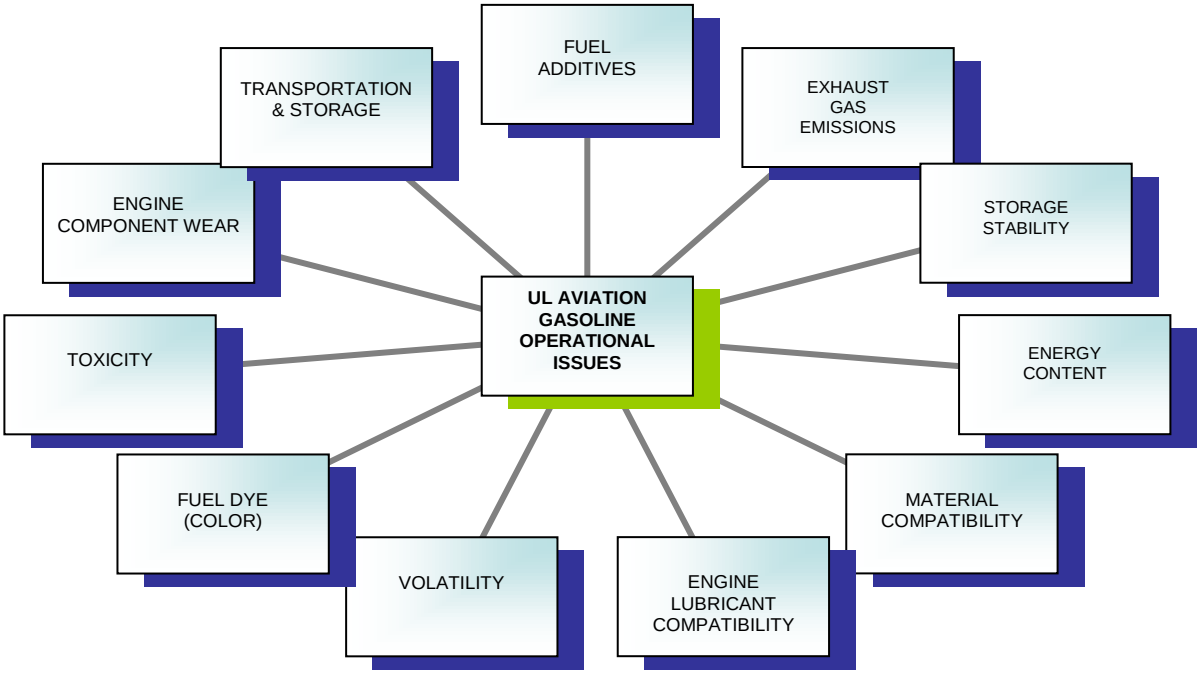

Figure 78.0
Unleaded AVGAS Operational Issues

6.8.1. Octane Requirement

The fuel octane rating needed to insure that an engine will operate knock free is considered to be a first order requirement for an aviation spark ignition piston engine fuel. Traditionally, aircraft engines have been shown to comply with FAA Regulatory requirements using a fuel with a minimum specified octane (the actual octane is typically several or more numbers above the minimum). FAA certification of each new model aircraft engine requires that detonation testing be performed under simulated hot day conditions at rated power and at maximum allowable cruise power with CHT and oil temperature at limit values. In accordance with FAA guidance material, the engine detonation testing demonstrates that the engine has in excess of 12% margin between lean limit fuel flow and knock (reference AC 33.47-1). In-flight detonation testing is normally conducted for turbocharged engines at critical altitude in accordance with AC 33.47-1 with special provisions to simulate worst case hot day altitude conditions. Experience has shown this methodology to provide adequate service life with the engine operating under normal service conditions detonation free for the expected life of the engine.

A formal Industry method to octane rate aircraft engines had not been available until recently[4][5]. It was established early during the CRC research work that there was an urgent need to define the aircraft engine fleet octane requirement in order to facilitate the development of an unleaded aviation gasoline. In order to define an engine's octane requirement, a rating procedure applicable to aviation spark ignition engines was developed by the CRC Octane Rating Group and implemented as an ASTM Standard Practice[4][5]. Modification of general aviation engines to accommodate an unleaded AVGAS should include octane rating testing as part of the validation of interaction between fuel and engine.

6.8.2. Freezing Point

The freezing point specification for aviation gasoline is -58°C per ASTM D 910. This limit was established years ago to indirectly control fuel composition as needed to ensure airworthiness. Data from the Global Upper Air Climatic Atlas indicates the mean atmospheric temperature can approach the existing fuel freeze point at altitudes of 23,000 feet and higher over North America[8]. As supported by a review of flight test data, fuel bulk volume can stabilize at or near ambient temperature. It was concluded the present D 910 freeze point temperature should be maintained without change.

6.8.3. Volatility/Distillation

Sufficient front-end volatility is needed in aviation gasoline to insure proper start-up and good warm-up performance especially in colder climates. Conversely, excessive front-end volatility can cause vapor lock and other related hot and even cold weather fuel handling problems. The hot fuel handling problems are more prevalent in low winged aircraft, but can be experienced in-high winged aircraft as well.

Aviation experience using automotive gasoline as authorized by FAA STC for those carbureted engines rated on 80/87 AVGAS indicates that some higher levels of front-end volatility can be tolerated. However; care must be taken to insure trouble free operation. The goal for a new unleaded aviation fuel should be to mirror the present ASTM D910 specification as much as possible, as the limits also address other issues such as minimizing carburetor icing.

The distillation curve for present aviation gasoline is designed to help insure that there is adequate front-end volatility for starting and warm up, but low enough to prevent vapor lock and/or other hot fuel-handling problems. The high end of the distillation range is controlled to guard against potential engine deposit build up and high gum formation rates during prolonged storage. Ideally, an unleaded avgas specification should replicate as closely as possible the present distillation characteristics. A departure from the present distillation curve will require significant testing to evaluate affect on the engine and aircraft.

6.8.4. Water Reaction

The Water Reaction test is another equally important property for aviation gasoline and will remain a critical consideration for a future unleaded AVGAS as condensed water is an inevitable contaminant in storage and aircraft tanks during operation. The original intent of the water reaction test was to prevent the addition of water-soluble components such as alcohol to aviation gasoline. The test method involves shaking 80 ml of fuel with 20 ml of water under standard conditions and observing if there is any volume change. If any future fuel is formulated using components that make it impossible to pass this test, any changes to the specification requirements must be carefully assessed. Current requirements should not be simply dropped to accommodate the new fuel.

The current Water Reaction Specification in D910 does not include a requirement for phase separation or interface condition. This is not because these properties are not important for AVGAS, but because current AVGAS normally has good water separation properties and additional requirements have not been necessary. However, many of the specifications for AVGAS now include phase separation and interface condition (D 1094, IP 289). Phase separation and interface condition must be considered with any new unleaded AVGAS (particularly one with new and unusual components) to ensure fuel can rapidly and cleanly shed

water for draining from aircraft tanks and to ensure filter-water separators can function correctly during distribution of the fuel. Either the specification should be changed to include these properties, or a new specification developed and the AVGAS evaluated to determine what engine combinations can safely operate with the new fuel. The new specification should control these new or different properties to insure the fuel remains fit for purpose for those aircraft/engine combinations demonstrated to operate safely with the new fuel.

6.8.5. Energy Content

The energy content or heating value (also referred to as heat of combustion) of a fuel is expressed as BTU (British Thermal Units) per pound (or MJ/kg) and directly affects the engine's take off rating and cruising range of the aircraft. A minimum net heat of combustion specification is a requirement for an aviation gasoline and directly influences the design and operation of the engine and aircraft. Fuel composition and hydrocarbon type have a direct effect on the energy content of a fuel. On a mass basis, paraffins have a greater BTU content than aromatics, which are greater than oxygenated compounds such as alcohols or ethers. A reduction in the heating value of the fuel will require reassessment of engine takeoff rating and aircraft performance characteristics. Whereas the aviation engine performance charts are part of the official FAA certification data and are used to construct the aircraft's performance tables which are included in the FAA approved aircraft POH, a significant change in performance due to a reduction in heat of combustion will require re-certification of both engine and aircraft performance.

6.8.6. Additives

An unleaded aviation gasoline formulated as a replacement for the ASTM D910 product will likely contain certain additives in order to achieve an acceptable level of fuel performance. Additives may be required to boost octane to an acceptable level, adjust vapor pressure, and ensure adequate storage life of the new fuel. Sufficient testing of the engine and aircraft will be necessary to substantiate the adequacy of new or unusual additives and their combined compatibility and possible effect on engine and aircraft components. Additional testing may be required to evaluate toxicity of the additive as related to aircraft refueling, exposure of ground personnel to fuel vapors, and effect on engine emissions.

6.8.7. Storage Stability

The storage stability of present quality I00LL AVGAS is generally considered to be one year. By comparison, the storage stability of most automotive gasolines is more on the order of 4 to 6 months, depending upon composition. The primary difference is that the aviation fuels have traditionally been cut to remove gum forming heavy hydrocarbon components. The lack of olefins (reactive molecules) and low aromatics tends to keep AVGAS stable in storage for long periods of time. The importance of storage stability relates to the normal low utilization of aircraft piston engines. It is not untypical to have aircraft engines sit unused for months at a time. In addition, the fuel distribution system in less populated areas is such that the fuel storage tanks could contain fuel that has aged up to or in excess of 12 months since manufacture. Peroxides which develop upon oxidation of the fuel can also contribute to accelerated corrosion of metallic components and embrittle elastomeric components such as o-rings and seals.

Fuels with a decreased storage stability would likely lead to increased gum formation in existing fuel systems. Increased gum could lead to fuel distribution problems in aircraft engines with a resulting significant decrease in engine performance. Therefore, the goal for the new unleaded

product should be to meet the present specification for storage stability as outlined in the ASTM D910 specification.

6.8.8. Material Compatibility

Most aircraft fuel systems contain elastomeric components such as hoses, seals, o-ring, sealant, and tank bladders. Fuel system components and materials in older aircraft were designed to be used with low aromatic non-oxygenated gasoline. Use of a higher aromatic fuel in older aircraft could leech out the plasticizer agent in the elastomer component, resulting in a more brittle part. As the elastomer components become more brittle, the possibility for leaks and or breakage is increased. Fuels with heavy aromatics can potentially carry fuel system deposits (lead, varnish, other, sealants, plasticizers) into the engine combustion chamber.

The goal for a future unleaded fuel specification should be to match the existing aviation gasoline relative to compatibility with fuel system elastomeric components. Changes in fuel aromatic properties and components will require compatibility testing with fuel system non-metallic materials including gaskets, o-rings, hoses, sealing materials, tank/drum linings, and fuel bladders. Depending upon fuel composition, it may also be necessary to address compatibility with metallic components such as electrical probes which provide an indication of fuel tank quantity.

6.8.9. Dye Coloration

Dyes are used to distinguish the different grades of avgas from each other and from other fuels. The international acceptance of the grade colors plays an important role in reducing the risk of mis-fuelling and cross-grade contamination. The grade replacing Avgas I00LL and Avgas 100 will need to be dyed such that it can be clearly distinguished.

The dyes presently used have proved satisfactory for many years and, if possible, should be used for the new grade. This would significantly reduce the amount of work necessary to approve dyes for the new fuel. Any desirable color can be made for avgas using dyes already approved; the primary colors (red, yellow and blue) are in the specification.

Additional work will be necessary if new dyes are required or if the new fuel contains components completely new to AVGAS. The ASTM Standard Practice D 4054 provides a model for the development of similar practice for AVGAS. The new practice could then be used as the basis for approving new dyes and also any other new components. It will need to cover compatibility with other additives, fuels and fuel system components.

6.8.10. Toxicity

The toxicological effects associated with exposure to a new formulation unleaded aviation gasoline must be assessed prior to the certification process in order to screen for fuels which pose an unacceptable hazard to humans coming in contact with the fuel, its vapors or combustion by-products. Whereas the toxicological effects of petroleum light distillate blends used commonly in gasoline are well characterized, this determination need only be made for the specific additives or components used to meet the fuel property requirements for an acceptable high octane, unleaded AVGAS. Middle distillates are typically kerosene, diesel fuels and the like; Avgas is a very light naphtha. Therefore, the assessment that a fuel is acceptable will be the determination that exposure to the fuel additives be below a reference dose defined by the Environmental Protection Agency as an estimate of a daily exposure to the human population

(including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects to humans during a lifetime.

6.8.11. Engine Lubricants

Depending upon fuel type and additives, it may be necessary to re-evaluate adequacy of the engine lubricants with an unleaded AVGAS. The elimination of the lead by-products of combustion should have a beneficial effect relative to the accumulation of lead by-products in sludge buildup, engine oil sump deposits, waste oil, and used oil filters as encountered with the current D910 100LL product. The effect of an oxygenated fuel if any will depend upon level and type of oxygenate. The effect of oxygenated compounds has been minimal in the automotive products. However, once a new fuel is defined, it will be necessary to re-evaluate the lubricant requirements of engines in real world service conditions.

6.8.12. Engine Valve Seat Wear

Service experience has shown that valve seat wear can be one of the more challenging difficulties to overcome when operating with unleaded fuels in conventional aircraft engine designs. Current valve seat alloys, valve head facings, valve stem coatings, and guide materials are designed for compatibility with leaded ASTM D910 aviation gasoline where the TEL content acts as a lubricant, coating the contact areas between the valve, seat, and guide. Small concentrations of lead have been shown to exert a significant influence on minimizing valve seat wear. Field experience has shown that engines originally designed to operate on leaded AVGAS have a better chance of the entire valve train operating satisfactorily with unleaded fuel providing the engine was first broken in on leaded AVGAS, thus indicating the significance of the lubricity properties imparted by a leaded fuel.

The use of unleaded fuel in engines designed for leaded AVGAS can lead to valve seat recession (depending upon component metallurgy). This phenomenon can be remarkable, with cylinder compression deteriorating to unacceptable levels in less than 10 hours of operation.

Design of the engine valve, seat, and guide configuration is a high priority when considering the next generation unleaded high octane aviation gasoline. Material selections and coatings of such parts have continued to evolve in recent years with current production, rebuilt, and new engines offering substantial improvements over the older models. The tribology and heat transfer characteristics at the valve, seat, and guide interfaces are dynamic and are further influenced by engine cooling and valve train dynamics. The valve bridge area on the typical aviation engine which is the aluminum cylinder head structure immediately between the intake and exhaust valve seats tends to run significantly hotter on the aircooled aviation engine as compared to the typical automotive water cooled head structure; this is a significant factor in valve to seat interface and resulting durability. The interference fit valve seat insert in the aluminum aircooled cylinder head operates in a more severe thermal environment as compared to conventional automobile engine designs. The use of special fuel additives may offer some assistance as a substitute for the lubricity effect of TEL

Engine durability testing must be performed to evaluate the effect of a new unleaded AVGAS on valve, seat, and guide wear characteristics in addition to those fuel system components subject to wear and friction which are exposed directly to the aviation fuel.

6.8.13. Engine Deposits

Aircooled piston aircraft engines differ significantly from their automotive counterparts in the size of the cylinder bores, the power output per cylinder, and the typically higher operating metal temperatures. Some fuel additives and oil chemistries, which performed satisfactorily in automotive applications, have been inadequate when utilized in aviation engines. Deposit formation or lack thereof is one of the critical requirements for aircraft cylinders. Deposits may impact the engine in various critical areas.

One of the most obvious components of the cylinder assembly where deposits form is the spark plug. Accumulations can cause disruption of the ignition process by shielding the discharge from the intake charge. The condition can deteriorate to the point where deposits can partially or completely bridge the electrode gap. The corrective action is to remove and clean the spark plugs at periodic intervals. The faster the formation rate of the deposits, the more often the required cleaning interval at a cost of increased maintenance and aircraft downtime.

Combustion deposits can find their way into the piston ring area. Material accumulations in ring grooves and between ring and piston interface surfaces result in a deterioration of sealing performance and increased ring or piston land wear. Either wear condition manifests itself as a reduction in engine service life and performance and possibly increased oil consumption. If wear is too rapid, ring or piston failure might result.

Combustion deposits can form in the seal area between the valve and valve guide. Common deposits found in this area today are lead and oil residues. If deposit build up is too rapid and exceeds the normal wear rate, valve sticking will result. Accumulations in this area can cause deterioration in heat transfer through the guide and result in accelerated valve and guide wear. By all normal engineering standards, the valve/valve guide interface is a severe application and probably would not work from a theoretical analysis. Any undue buildup of foreign material in this area will not be beneficial to cylinder service life.

Deposits in the cylinder area in large bore aircooled engines are critical in their possible contribution to hot spots as a source of pre-ignition. Deposits can interrupt the critical heat transfer path out of the piston or cylinder walls. High performance aircraft engines utilize pistons cooled by oil squirts to aid in heat dissipation. Formation of foreign material under the piston dome will tend to raise the operating temperatures. Once hot spots occur, the pre-ignition event can quickly drive an engine to destruction. Hot spots can also initiate on the combustion chamber walls with equally destructive effects.

Given the above, adequate durability testing and deposit analysis is required for any prospective new unleaded fuel.

6.8.14. Exhaust Gas Emissions

Although aviation reciprocating engines are not currently subject to regulatory control of exhaust gas emissions, introduction of a new unleaded AVGAS (depending upon composition) may very well alter the composition of exhaust gas emissions. Engine testing of a new fuel should include testing to quantify the effect of the new fuel on exhaust gas emissions. Similarly, the introduction of a new unleaded AVGAS offers the opportunity to address energy efficiency as related to fuel burn rates.

6.8.15. Transitional Implementation

Implementation and fielding of a new AVGAS will involve a period of transition where the availability of the new fuel will overlap the availability of the existing 100LL product. Such a transition will require precise coordination and planning among the manufacturers, FAA, and fuel producers on a global scale. Service instructions to the owners and users must be clear and definitive.

7. CONCLUSIONS, UNLEADED AVGAS RESEARCH RESULTS

7.1. Overview

As a preface to a discussion of conclusions, the reader is reminded of the objectives and goals identified by the original Mission Statement [Section 5.2] which served as the guide for the research performed and documented within this report. The purpose of the CRC research was **not** to formulate a commercial blend but rather to conduct research and make the findings available to industry as a means of facilitating industry evaluation of unleaded AVGAS alternatives. The contents of this report fulfill that requirement.

In consideration of the scope and extent of the research performed, significant conclusions and highlights are segregated under the following headings which form the basis for “lessons learned”.

CRC research into unleaded aviation gasoline alternatives focused on meeting engine octane requirements which were determined at the initiation of the research work to be the most demanding criteria for a new unleaded AVGAS. As documented within this report, a large group of unleaded fuel blends involving a matrix of various octane enhancing components were investigated by CRC research. None of the 279 unleaded blends evaluated were found to offer the potential as a transparent replacement for the current ASTM D 910 100LL AVGAS.

Although full scale engine tests indicated certain blends were capable of providing knock free operation in the test engine, these blends represented the use of specialty chemicals which require further evaluation by industry with respect to environmental impact and production viability. Economic and production viability of the blends tested is not the jurisdiction of CRC research and will need to be addressed separately by industry. Furthermore, blend properties were not controlled for agreement with the ASTM D 910 specification as the primary focus was engine octane satisfaction.

Although experimental blends of specialty components may achieve or exceed the 100LL specification of 99.5 MON minimum, such formulations are quite different as compared to the current ASTM D 910 product and potentially compromise other important specifications. The best performing high octane blends were characterized by properties which are non-compliant with the ASTM D 910 specification. Further, as documented by CRC research results, leaded 100LL or 91/98 L AVGAS offer greater octane satisfaction in full size engines when compared to unleaded fuels of similar MON quality. This highlights the necessity to review laboratory quality control specifications when considering the introduction of an unleaded fuel.

It should be noted that even though some unleaded blends provided knock margins equivalent to or worse than a baseline 100LL leaded fuel, it was possible to operate the test engine with these unleaded blends provided the fuel mixture was increased to a setting richer than that required for the100LL fuel. However, the implication is quite negative with respect to energy efficiency and the associated impact on aircraft range and endurance.

7.2. Blend Component Effectiveness

Of the seven blend components evaluated for their effect on octane enhancement, two components *m*-toluidine and super alkylate were shown to have a significant positive effect on fuel octane quality. Blend component effectiveness relative to MON for the formulations and concentration ranges tested is summarized as follows.

- ***m*-Toluidine** - An aromatic amine represented by *meta*-Toluidine was shown to have the most significant positive effect on fuel MON quality when used in concentrations from 6 -12% with either Aviation, Motor, or Super Alkylate.
- **Super Alkylate** – This component was also shown to have a positive effect on resulting fuel blend octane performance but to a lesser degree than the aromatic amine. It should be noted that super alkylate was selected as a candidate component at the beginning of the CRC research in consideration that plants previously committed to production of MTBE might be converted to make super alkylate; this production capability did not ultimately materialize.
- **MMT** - Higher concentrations had a positive effect on fuel MON quality when used with aviation and motor alkylates, but the reverse was true when used with super alkylate.
- **ETBE** - Higher concentrations exhibited modest improvements in fuel MON performance when blended with aviation and motor alkylates, but resulted in little to no improvement when blended with super alkylate.
- **Toluene** - Higher concentrations had little impact on fuel MON quality when blended with Aviation and Motor Alkylates, and yielded a negative MON response when blended with Super Alkylate.
- **Ethanol –** Ethanol was shown to have no impact on fuel MON performance when blended with either Aviation, Motor, or Super Alkylate.
- ***tert*-Butyl Benzene –** This component was used only with Phase III blends. Preliminary analysis was insufficient to confirm effect on fuel MON performance. More sophisticated analysis of Phase III data is needed to explore the effect of tert-Butyl Benzene which has been shown to be an effective octane improver in other fuel formulations.

7.3. Best Performing Unleaded Blends

Blends which provided performance equivalent to or better than the baseline 100LL fuel are summarized as follows based upon either a D 2700 MON rating or detonation response in a full scale engine.

- Best performing Phase I blend overall, based upon ASTM D 2700 MON test
  - Blend No. 65 [Volume fractions: 0.500 super alkylate, 0.250 toluene, 0.100 meta-Toluidine, 0.151 ETBE, 0.000 ethanol, 0.015 MMT] had D 2700 Mon rating of **104.98**
    - Phase I Blend No. 65 is similar in composition to Phase II blend AV7 (**104.6** MON) which was shown by full scale engine test to provide detonation performance better than 100LL. AV7 was the top performing blend in Phase II full scale engine tests.

- Best performing Phase I blends, based upon ASTM D 2700 MON test, where alkylate content was 80% or higher
  - **Aviation Alkylate** - Blend No. 62, [Volume fractions: 0.842 aviation alkylate, 0.002 super alkylate, 0.000 toluene, 0.100 meta-Toluidine, 0.045 ETBE, 0.011 ethanol, 0.027 MMT] had D 2700 Mon rating of **102.3**
  - **Motor Alkylate** - Blend No. 137, [Volume fractions: 0.842 motor alkylate, 0.002 super alkylate, 0.000 toluene, 0.100 meta-Toluidine, 0.045 ETBE, 0.011 ethanol, 0.027 MMT] had D 2700 Mon rating of **101.9**
  - **Super Alkylate** - Blend No. 191, [Volume fractions: 0.855 super alkylate, 0.000 toluene, 0.100 meta-Toluidine, 0.000 ETBE, 0.045 ethanol, 0.039 MMT] had D 2700 Mon rating of **104.9**
- Best performing blends Phase II, based upon full scale engine knock response
  - Blends AV7, AV6, AV4, and AV3 [**105.6** MON to **102.9** MON respectively] were the best performing blends for the aviation alkylate blends without MMT and were shown to provide knock margins better than the Baseline 100LL. Note that the AV blends tended to contain a relatively high percentage of super alkylate (35% to 50% v/v). FAA test results showed Blend AV8 provided a positive octane response; whereas the opposite was observed in the Cessna test.
  - Blend AV7, [Volume fractions: 0.000 aviation alkylate, 0.4997 super alkylate, 0.100 meta-Toluidine] had D 2700 MON of **104.6** and was shown to provide greater knock margin than the 100LL baseline, thus indicating the significance of components super alkylate and meta-Toluidine. See Figures 34, 46, & 50.
  - Blend AV4, [Volume fractions: 0.4002 aviation alkylate, 0.4997 super alkylate, 0.100 meta-Toluidine] had D 2700 MON of **104.4** and was also shown to provide greater knock margin than the 100LL baseline. See Figures 34, 46, & 50.
  - Blend MO8, [Volume fractions: 0.0000 motor alkylate, 0.4997 super alkylate, 0.100 meta-Toluidine] had D 2700 MON of **104.6** and was shown to provide greater knock margin than the 100LL baseline, again indicating the significance of components super alkylate and meta-Toluidine. See Figures 36, 48, & 52.
- Best performing blends, Phase III, based upon full scale engine knock response
  - Blend Nos 15 and 21 provided knock free operation throughout the range of power settings tested.
  - Blend No. 15 [Volume fractions: 0.1029 aviation alkylate, 0.5001 super alkylate, 0.1202 meta-Toluidine, 0.1288 ETBE] had D 2700 Mon rating of **106.3**
  - Blend No. 21 [Volume fractions: 0.0000 aviation alkylate, 0.290 super alkylate, 0.1200 meta-Toluidine, 0.3000 ETBE] had D 2700 Mon rating of **106.2**
  - Note that blend no's 14 and 20 provided knock response slightly better than the Baseline 100LL. Blend No. 14 [Volume fractions: 0.3291 aviation alkylate, 0% super alkylate, 0.1199 meta-Toluidine, 0.2998 ETBE] had D 2700 MON rating of **104.0.** Blend No. 20 [Volume fractions: 0.3929 aviation alkylate, 0% super alkylate, 0.1200 meta-Toluidine, 0.3001 ETBE] had D 2700 MON rating of **104.2**.

7.4. Blend Performance Without Specialty Components

Table 53.0 summarizes blend performance for those unleaded blends which did not contain the specialty chemicals super alkyate, *meta*-toluidine, and MMT. Phase I blends 16 and 44 met this criterion (without use of specialty chemicals) and were characterized by relatively low D 2700 MON ratings of 94.10 to 94.0. Although these blends were not tested in a full scale engine, the low MON ratings are indicative of a poor octane response in a full scale engine. Using equations of Section 6.4.3.4, the predicted MON for Blends 16 and 44 would be 94.9.

Each of the Phase II blends contained a level of super alkylate and *meta*-toluidine. The two blends shown in Table 53.0 are listed since volume fractions of *meta*-toluidine less than 6% have been shown to have less impact on blend MON. Blends AM3 and MO6 were two of the worst performing blends in Phase II full scale engine tests as compared to the Baseline 100LL.

The four Phase III blends listed in Table 53.0 met the above criteria for not containing specialty chemicals but blends 19 and 34 were two of the worst performing Phase III blends relative to knock response in the full scale engine.

Table 53.0
Blend Performance, Phases I – III
Blends With **0%** Super Alkylate, **0%** meta-Toluidine, **0%** MMT
Component Volume Fractions & D 2700 Motor Octane Number Results

Blend No.	MON	Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	*tert*-Butyl Benzene	MMT g/gal
Phase I Research – Based Upon D 2700 MON Test										
16	95.10	0.6500	0	0	0	0.3000	0	0.0500	0	0
44	94.90	0.4500	0	0	0.2500	0.3000	0	0	0	0
91	94.94	0	0.6500	0	0	0.3000	0	0.0500	0	0
119	94.44	0	0.4500	0	0.2500	0.3000	0	0	0	0
Phase II Research – Based Upon Engine Knock Response										
AM3	97.3	.8695	0	0	0	0.0705	0.0250	0.0350	0	0.1
M06	97.1	0	0.9400	0	0.0147	0	0.0453	0	0	0
Phase III Research – Based Upon Engine Knock Response										
1	99.7	0.4224	0	0	0	0.2973	0	0	0.1995	0
18	99.6	0.5468	0	0	0.1001	0.0643	0	0	0.1997	0
19	97.6	0.5998	0	0	0.0321	0.2878	0	0	0	0
34	98.8	0.3489	0	0	0.1950	0.2709	0	0	0.1049	0

7.5. Unleaded Blend Properties

Whereas the objective of the research described within this report was engine octane satisfaction, properties such as vapor pressure, freeze point, heat content, and distillation were not controlled for the experimental unleaded blends described in this report. As indicated by the ASTM D 910 laboratory analysis of Phase II blend properties (Tables 26.0 and 27.0), many of the blends exhibited vapor pressure, heat of combustion, distillation, and freezing point properties which were non-compliant with the ASTM D 910 specification. Further adjustment of such blends would be required to meet ASTM D 910 specifications.

7.6. MON Correlation With Engine Knock Response

Unleaded blends with a higher MON rating tended to correlate well with a positive anti-knock response as measured in the full scale engine. Progressively higher MON rated fuels tended to provide greater positive knock margin. Similarly, unleaded blends with a lower MON rating tended to correlate with the relative negative or poor knock response as measured in the engine. Blends with progressively lower MON ratings tended to provide an increasingly negative knock margin. See summary of Phase II test results in Figures 54.0 and 56.0. See summary of Phase III test results in Figures 61.0 and 69.0.

However, test results indicate that leaded and unleaded fuel blends of equivalent MON can perform quite differently relative to detonation in a full scale engine as indicated in the following discussion of leaded versus unleaded blends.

7.7. Leaded Versus Unleaded Fuels of Similar MON

Test results in both the IO-320-B engine and the IO-540-K engine with groups of mid-octane fuels and high-octane fuels showed the leaded fuel in each engine provided better engine octane satisfaction than an unleaded fuel of equivalent MON. This was in agreement with prior test results and is quite evident in the mixture lean out curves where the leaded fuels of both groups allowed the engine to operate at a leaner fuel/air ratio without detonation as compared to an unleaded fuel of equivalent MON quality.

For the mid-octane group of fuels investigated in the IO-320-B engine, an unleaded fuel was found to require 2-3 MON higher rating than the leaded fuel in order to provide the same level of detonation performance in the full scale engine under the test conditions.

For the group of high-octane fuels investigated in the IO-540-K engine, an unleaded fuel was found to require 4 MON higher than the leaded 100LL fuel in order to provide equivalent detonation performance at engine cruise power under the test conditions.

7.8. Empirical Model for MON Prediction

A significant work product derived from the Phase I research and Phase III research was a series of mathematical models which were shown to provide a reasonably accurate empirical tool for prediction of MON performance for the range of blend components tested. The models were used to predict blend MON performance for the Phase II blends where close correlation was shown with measured MON values. The Phase III models also provide an empirical tool for prediction of engine knock response for the IO-540-K engine when using fuels containing the components investigated. Future research should give consideration to use of design experiment and statistical methods as a means of enabling prediction of fuel MON quality. Such methods offer the means to refine or trim component concentrations for maximum octane effect in advance of full scale engine testing while simultaneously meeting other ASTM D 910 AVGAS specifications. Application of statistical methods as a means of predicting octane is already done in refineries for conventional blend stocks.

7.9. Engine Knock Margins

Results of the full scale engine tests serve as a reminder of the importance of addressing the impact of a next generation unleaded fuel on engine design margins. The safety of Aviation products is strongly influenced by the design margins established for that product. FAA regulations require that aviation products are certified to standards which ensure the required

levels of flight safety. For example, the majority of the reciprocating engine models which power the current general aviation fleet were certified to FAA standards which required that the lean limit fuel flow be 12% greater than the leanest fuel flow resulting in detonation [Ref FAA AC 33.47]. CRC research results indicate that with an unleaded fuel of same MON as the leaded 100LL fuel, engine detonation margin would be reduced the equivalent of 3-4 MON as compared to operation with a leaded fuel of same MON quality, assuming no changes to the engine. Additionally there are tolerances associated with a production fuel, and there will likely be a difference between a minimum and nominal production fuel; for example, as indicated by the Phase III results, Figures 68.0 and 69.0, the difference between a minimum specification 100LL and a typical field FBO 100LL AVGAS can approach 3 MON.

The implication is that an engine originally rated on 100LL could experience a loss in detonation margin equivalent to 6-7 MON when operated with a 100 MON UL fuel as compared to operation with a nominal spec 100 LL fuel.

7.10. Technology Challenge

From a broader perspective, the industry's pursuit of an acceptable unleaded aviation gasoline is facing a technology limitation. An acceptable octane enhancing component capable of providing the necessary octane effect in an unleaded aviation gasoline within the constraints of ASTM D 910 AVGAS specifications and giving equivalent anti-detonation margin to 100LL in full size engines has not yet been identified.

8. RECOMMENDATIONS

CRC research results are indicative of the significant challenge facing a high octane unleaded AVGAS formulation and further serve as a reminder that aviation fuels represent specialized products refined over many years to optimize flight safety and performance. Representatives of Industry and Government, supported by specialized facilities, have collaborated under the sponsorship of CRC to investigate this issue. As documented within this report, CRC sponsored research offers an effective means of integrating technical specialists from Industry and Government to work collaboratively on significant industry issues. Although the research conducted to date has yielded a great amount of data and knowledge, the conclusions clearly indicate the need and opportunity for further investigations. Recommendations are therefore provided as follows.

1. Explore options for continuation of research into unleaded AVGAS alternatives and associated technology including blend components, properties, and methodologies. Include consideration of investigations into optimizing mid-octane unleaded alternatives. The goal should remain a viable solution which assures performance and flight safety for both the existing and future general aviation fleets. Expand, modify or evolve a suitable mission statement to serve as a guide for future research.
2. Give consideration to a research plan providing for investigation of an unleaded blend matrix without specialty chemicals, but expand the matrix to accommodate mid-octane MON blends based upon aviation and motor alkylates. Include consideration of viability of synthetic and organic components which might offer promise as an octane enhancer.
3. Future research plans should include investigation of critical ASTM D 910 properties for those unleaded blends which show promise.
4. Future research should continue to apply design experiment and statistical methods as a means of facilitating and maximizing test results where applicable.

5. In consideration of the growing national emphasis on energy conservation, the industry's continued pursuit of an unleaded AVGAS alternative must also give consideration to the impact of the next generation fuel on fleet fuel economy.
6. Similarly, fuel toxicity and the effect of combustion on exhaust emissions should also be evaluated.

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10. ACKNOWLEDGEMENTS

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- END OF TEXT –

APPENDIX A
DIXIE SERVICES REPORT
NOVEMBER 2004
1) MON MATRIX SCREENING RESULTS
202 UL BLENDS, &
2) LABORATORY ANALYSES 30 UL BLENDS

UNLEADED AVIATION GASOLINE DEVELOPMENT PROGRAM

CRC MATRIX FUEL FORMULATIONS

Summary

This report summarizes the results of two programs undertaken by the CRC Unleaded Aviation Gasoline Development Group to acquire data on the detonation characteristics of a series of unleaded aviation gasoline formulations. The initial program involved Motor octane number (MON) tests of 202 one-liter gasoline blends in an experiment designed to elucidate the relationship between MON and certain classes of compounds that were projected to be useful in future fuel formulations. In the second phase, thirty unleaded aviation gasoline formulations having Motor octane numbers from 95 to 105 were prepared in 70-gallon batches for testing on full scale engines by the FAA Technical Center and Cessna Aircraft.

This report covers the sources and properties of the components used to blend these experimental fuels, the compositions of the fuels tested in both programs, the Motor octane number test results and related regression analysis of the initial 202 fuel blends and the results of laboratory tests of the 30 larger blends for ASTM D 910 Grade 100LL specification properties. The results of the full scale engine tests by the FAA and Cessna are documented separately.

Background

The Unleaded Aviation Gasoline Development Group was organized under the sponsorship of the Coordinating Research Council (CRC) in the 1990's to conduct research and testing that would facilitate development of a high octane unleaded aviation gasoline (avgas) that could be an environmentally compatible replacement for the current ASTM D 910 Grade 100LL fuel, which contains tetraethyllead (TEL). This group consists of voluntary representatives from various elements of the aviation industry, including fuel producers, airframe and engine manufacturers, the Federal Aviation Administration, industry-related organizations (AOPA, EAA, GAMA) and other interested parties.

The stated goal of the CRC Unleaded Avgas Development Group is not to formulate a commercial fuel product to replace 100LL aviation gasoline, but rather to accumulate and make publicly available technical information that will facilitate development of a TEL-free fuel that will meet the operating, safety and environmental requirements of both the current and future general aviation fleet.

Phase I - The MON Matrix Mixtures

A meeting of the Unleaded Avgas Task Group (a working sub-unit of members of the CRC Development Group having particular interest and expertise in aviation fuel compositions, properties and performance) was held at the FAA William J. Hughes Technical Center in November 2000, at which it was decided to undertake a program to explore the relationship

between certain classes of materials that might be useful to produce future high octane unleaded avgas formulations and the detonation characteristics of such formulations.

Starting from the premise that future fuels would contain a hydrocarbon base component, the task group identified three such components for the study: aviation alkylate, motor alkylate and super alkylate.

> Aviation alkylate is a petroleum refinery-produced stream that is a major component of current aviation gasolines. It consists of a mixture, primarily of branched hydrocarbons, with a high concentration of isooctane. (Isooctane, 2,2,4-trimethylpentane, possesses excellent antiknocking properties, so much so that the pure compound has become the basis for the ASTM octane rating scale for both aviation and motor gasolines, having a defined value of 100 octane).
>
> Motor alkylate is a similar refinery-produced stream that is an important component of automobile gasolines. Motor alkylate differs from aviation alkylate in that it contains a wider range of compounds, including more low- and high-boiling components, which results in slightly lower octane values than aviation alkylate.
>
> Super alkylate is a term used to describe an emerging refinery stream that is projected for future production to meet the need for high octane blending components in automobile gasoline. It can be produced by dimerization of isobutylene with subsequent hydrogenation of the reaction mixture, resulting in a stream containing over 90 % isooctane and a higher octane value than aviation alkylate.

It was decided that the aviation and motor alkylate base components should be evaluated independently in combination with one or more compounds known to improve detonation characteristics. Since super alkylate could be used as either a base component or an octane-enhancing additive, it was decided to include it as an additive in the aviation and motor alkylate formulations and to also use it as a the hydrocarbon base component in a third series of formulations.

The task group identified five classes of compounds that were known to enhance the detonation properties of gasolines for inclusion in the program, namely aromatic hydrocarbons, ethers, alcohols, aromatic amines and organometallic manganese compounds.

> Toluene was selected as the aromatic hydrocarbon based on its wide use in current aviation gasoline formulations.
>
> Ethyl-*tertiary*-butyl ether (ETBE), which can be produced from ethanol and isobutylene in refinery-located or independent production facilities, was selected as the ether based on its known value as an octane-enhancing component in automobile gasolines. ETBE had also been successfully evaluated as a major component in an aviation gasoline formulation developed and tested by Cessna Aircraft.

meta-Toluidine (3-aminotoluene, 3-methylaniline) was selected as the aromatic amine based on its octane-improving performance in a preliminary study conducted by the task group several years earlier in which nine blends of aviation alkylate, *meta*-toluidine and methyl-*tertiary*-butyl ether were tested for motor octane number.

Ethanol (ethyl alcohol) was the obvious choice for the alcohol component because of its history of use in automobile gasolines.

Methylcyclopentadienyl manganese tricarbonyl (MMT) was selected as the metal-based octane improver for evaluation.

The task group also assigned a range of compositions for the various components, which resulted in the following table of compositions to be evaluated:

	Base Component		
Additive	Aviation Alkylate	Motor Alkylate	Super Alkylate
Super Alkylate, vol-%	0 - 50	0 - 50	-
Toluene, vol-%	0 - 25	0 - 25	0 - 25
ETBE, vol-%	0 - 30	0 - 30	0 - 30
m-Toluidine, vol-%	0 - 10	0 - 10	0 - 10
Ethanol, vol-%	0 - 5	0 - 5	0 - 5
Manganese, g Mn/gal	0 - 0.1	0 - 0.1	0 - 0.1

Finally, the task group decided that only the detonation characteristics of the formulations as measured by Motor octane number (MON) would be evaluated in this initial set of experiments. While it was recognized that other properties such as volatility characteristics are critical to developing a finished aviation gasoline formulation, the objective of this study was limited to exploring the relationships and influences of the various component classes relative to MON alone.

A designed experiment was developed to evaluate the selected range of compositions (to which the term "MON Matrix" was applied). The experimental design was based on mixture and cubic design structures and resulted in 75 fuel blends for the seven-component matrices based on aviation and motor alkylate and 52 blends for the six-component super alkylate matrix. Replicate blends were included in each matrix to assess experimental error. The detailed compositions of the 202 mixtures are tabulated with the test results below.

The component materials to be used in preparing the test mixtures were supplied by task group member companies, as listed in Exhibit I. The components were shipped to a single independent laboratory that was commissioned to prepare the blends from the components and test them for Motor octane number by ASTM D 2700. The individual blending components were also tested for selected chemical and physical properties, which are detailed in Exhibit I.

The last of the requisite components was received by the laboratory on March 1, 2001, and preparation of the aviation alkylate test mixtures commenced on March 16. One liter of each

mixture was prepared by volumetric additions dispensed directly into brown glass bottles from burets of 100 to 500 mL capacity. For blends requiring manganese, the manganese compound was added immediately before engine testing using a "dilute basis" MMT mixture that is designed for use in octane testing laboratories. All the mixtures of the aviation alkylate matrix were prepared and tested first, followed by the motor alkylate mixtures and concluding with the super alkylate set. The order of preparation and testing of the individual mixtures in each matrix was randomized. All the MON tests were conducted by a single engine operator who was not privy to the composition of the test mixtures. The experimental program was completed on April 16, 2001 when the last of the 202 mixtures was tested for MON. The individual mixture compositions and MON test results, which were distributed to the task group in May 2001 for review and analysis, are tabulated in Exhibit II.

Multiple regression analyses of composition variables against MON were conducted on the three matrices, and a set of equations was developed that predict MON from the test mixture composition (expressed as volume fraction for all components except manganese, which is expressed as g/gal). A separate equation was developed for each of the alkylate matrices; the regression coefficients are tabulated below:

	Regression Coefficients		
Variable	Aviation Alkylate	Motor Alkylate	Super Alkylate
Aviation Alkylate (AvAlky)	92.000	na	na
Motor Alkylate (MoAlky)	na	91.367	na
Super Alkylate (SuAlky)	99.499	99.702	100.480
Toluene	92.697	92.340	94.428
ETBE	101.131	101.393	100.646
m-Toluidine	-195.428	-166.555	151.466
Ethanol	95.240	95.701	94.269
AvAlky * Manganese	21.138	na	na
MoAlky * Manganese	na	21.810	na
SuAlky * Manganese	13.653	14.244	7.437
m-Toluidine * Manganese	-184.508	-187.174	-123.838
AvAlky * *m*-Toluidine	434.984	na	na
MoAlky * *m*-Toluidine	na	402.424	na
SuAlky * *m*-Toluidine	393.428	359.464	ns
Toluene * *m*-Toluidine	441.070	407.982	36.398
ETBE * *m*-Toluidine	357.430	328.772	-21.965
Ethanol * *m*-Toluidine	353.220	302.538	ns

na = not applicable in this matrix; ns = found to be not significant for this matrix

The goodness of fit statistics for the regression equations were as follows:

	Base Component		
Statistic	Aviation Alkylate	Motor Alkylate	Super Alkylate
R^2	0.99999	0.99999	0.99999
Adjusted R^2	0.99999	0.99999	0.99999
Standard deviation of residuals	0.3567	0.2996	0.2922
Standard deviation of replicates	0.2518	0.2117	0.1533

Phase II - Fuels for Full Scale Engine Tests

The task group met in November 2001 to consider plans for further development. It was decided to explore the relationship between composition, MON and full scale aircraft engine performance by testing thirty fuel formulations on full scale engine test stands. The compositions of the fuels to be tested would be derived from the relationships between composition and octane number that emerged from the MON matrix mixtures, with the following conditions:

test fuels having Motor octane numbers ranging from 97 to 105;

test fifteen formulations derived from the MON matrix as a function of composition relationships that emerged from the aviation alkylate set, only seven of which would contain manganese;

test fifteen formulations derived from the MON matrix as a function of composition relationships that emerged from the motor alkylate set, only seven of which would contain manganese.

If fuel compositions that were tested in the previous MON matrix series met these conditions, they were specified for full scale testing. In other cases, the regression equations from the MON matrix set were applied to define fuel compositions that were projected to meet the octane number criteria. Exhibit III contains the thirty formulations that were specified for the program.

As with the previous study, the component materials to be used for blending the fuels were supplied by task group member companies to an independent laboratory, which was commissioned to blend them into batches of appropriate size to allow for engine testing by both the FAA Technical Center and Cessna Aircraft, and also to test each blend for the properties specified in ASTM D 910 for 100LL aviation gasoline. The individual blending components were tested for selected chemical and physical properties, which are reported along with the sources for the components in Exhibit IV.

Because multi-drum quantities of super alkylate were not available commercially for this program, it was necessary to prepare a simulated super alkylate by blending purchased components. A prospective future producer of super alkylate indicated that a mixture of 92.6

mass % *iso*-octane and 7.4 mass % *iso*-dodecane was appropriate, based on pilot scale production. Accordingly, reference fuel grade *iso*-octane was purchased from ChevronPhillips Chemical Company and *iso*-dodecane was purchased from The Fanning Corporation (Fancol ID-CG, 98 % C_{12} *iso*-paraffins, primarily pentamethylheptane, 2 % other isoparaffins) for blending. The super alkylate was prepared in fourteen individual drum batches (304 pounds net) as needed for the program by combining the quantities indicated in Exhibit V. The density of each drum batch was measured for quality control, and these data are included in Exhibit V.

It was decided that a batch size of 265 liters (70 gallons) would be needed to provide sufficient fuel for testing by FAA (47 gallons), Cessna (20 gallons) and D 910 specification (3 gallons). Because of the quantities involved, it was decided to prepare the blends by mass additions rather than volume. Accordingly, the volume fraction formulations were converted to the equivalent mass fractions using the densities of the components at 15.56 °C (60 °F).

Before beginning the blend program, the blends each of the four categories of fuel in the formula table (Exhibit III) were randomly assigned the following labels:

AV1 - AV8	Aviation alkylate blends without manganese
MO1 - MO8	Motor alkylate blends without manganese
AM1 - AM7	Aviation alkylate blends containing manganese
MM1 - MM7	Motor alkylate blends with manganese

The fuels without metal additive were prepared first (AV1 - AV8, then MO1 - MO8), after which the manganese-containing blends were prepared (AM1 - AM7, followed by MM1 - MM7).

The blends were prepared in an 85-gallon container on a platform scale readable to 0.25 pound, with the following order of addition of components: aviation or motor alkylate, super alkylate, toluene, ETBE, *meta*-toluidine, ethanol. When called for, the manganese component was added volumetrically by pipet using the conversion formula provided by the supplier (Hitec 3062 = 151g Mn/L = 0.151g /mL). Each batch was stirred for thirty minutes after addition of the last component, following which an aliquot was withdrawn for density measurement. The batch was then divided into three parcels: 3 gallons were withdrawn volumetrically into a five-gallon can for D 910 specification testing; 20 gallons were transferred by mass (calculated from the batch density) into a thirty-gallon drum for Cessna testing, and the balance of the batch was transferred into a 55-gallon drum for FAA testing. After all the fuels of a given category (AV, MO, AM, MM) were blended, they were shipped to the testing locations identified only by the label designations noted above: the fuel formulations were not provided to the either of the engine testing locations or the D 910 specification testing laboratory.

The actual mass fraction compositions of the thirty fuels as calculated from the blend weight measurements are tabulated in Exhibit VI. The corresponding volume fraction data, calculated from the component densities at 15.56 °C, appear in Exhibit VII.

The results of the full scale engine tests of the thirty blends are covered by reports issued separately by the FAA Technical Center and Cessna Aircraft.

The fuels were also tested for all the properties specified for ASTM D 910 Grade 100LL aviation gasoline except for sulfur content (which was known to be less than 0.001% for each of the individual components) tetraethyl lead (which was known to be not present in any of the blends), color (because the blends were undyed) and electrical conductivity (because of the known presence of higher polar substances in many of the blends). The ASTM test methods employed were as follows (comments on application of the methods to the blends are also noted where appropriate):

D 2700	Motor Octane Number
D 909	Supercharge Rating - The knock-limited power curves for most of the blends did not follow the pattern of the reference fuel framework of the leaded reference fuels, typically being displaced to higher fuel-air ratios. In a number of cases, the blends did not exhibit a peak IMEP in the range of fuel-air ratios available on the D 909 engine. Numerical ratings were calculated for those cases where the knock-limited power curve of the blend power curve passed over a peak IMEP value of one of the reference fuels; when the knock-limited power curve of a blend exceeded the peak IMEP of the isooctane + 6 mL TEL reference fuel, the rating was reported as greater than 6 mL (>6.00) and the corresponding performance number (>161.0).
D 4052	Density by Digital Density Meter
D 5191	Vapor Pressure, Mini Method (Grabner)
D 2386	Freezing Point - Several of the blends did not exhibit the formation of distinct solid crystals, such as those customarily observed with aviation turbine fuels. Instead, these blends showed evidence of liquid/liquid non-homogeneity as the temperature was decreased, e.g., cloudiness, turbidity, separation into two layers. This type of behavior is noted by "nh" in the results table (Exhibit VIII).
D 4809	Net Heat of Combustion by Bomb Calorimeter - This method was employed because the estimation methods (D 3338 and D 4529) are not applicable to these blends. The hydrogen content value needed to calculate the net heat value was determined by ASTM D 1018.
D 130	Copper Corrosion
D 873	Oxidation Stability (Potential Residue Method)
D 1094	Water Reaction
D 86	Distillation (manual procedure)

In addition to the D 910 tests, the blends containing manganese additive were also analyzed for manganese content by ASTM D 3831, "Standard Test Method for Manganese in Gasoline by Atomic Absorption Spectroscopy."

The results of the specification tests are tabulated by blend category (AV, MO, AM, MM) in Exhibit VIII. Specification limits for Grade 100LL are included for comparison: test results outside the specification limits are outlined with shaded backgrounds. Because these blends were originally formulated to explore the relationship between detonation characteristics and classes of blending components without regard to other properties, it is not unexpected that most of the fuels fail to meet other Grade 100LL requirements, notably volatility (vapor

pressure, distillation), heat of combustion and freezing point. Exploration and refinement of these property requirements remains the subject for future research.

The Motor octane number test results for the thirty full scale engine fuels are tabulated in Exhibit IX, along with the octane number that was predicted for the blend using the regression equations from the MON Matrix. Nine of the full scale blends were exact duplicates of blends tested for MON in the Matrix. The MON results for these nine blends from the Matrix are also included in the table. The tabulated MON data are presented graphically on Page 2 of Exhibit IX.

EXHIBIT I

Properties and Suppliers of Components for MON Matrix Blends

		Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	Ethanol	*meta*-Toluidine
D 4052	Relative density, 15.56/15/56	0.6949	0.6928	0.7001	0.8718	0.7468	0.7940	0.9934
	API gravity, °	72.1	72.8	70.6	30.8	58.0	46.7	10.9
D 5191	Vapor pressure, DVPE, psi	4.84	8.59	1.78	0.88	4.54	2.16	<0.10
D 2699	Research octane number	93.4	93.6	100.5	116.7	111.1	107.2	
D 2700	Motor octane number	91.5	91.3	99.6	108.3	97.8	93.0	
E 1064	Water content, mass %					0.0485	0.0903	
D 2360	Toluene content, mass %				99.94			
D 5441*	ETBE content, mass %					97.03		
D 5501	Ethanol content, mass %						99.69	
D 850	Distillation range, °C				0.6			
D 86	Distillation, % evaporated, °C							
	IBP	43.5	32.0	97.0		68.5		
	5	66.0	50.5	97.5		70.0		
	10	77.5	62.5	98.0		70.5		
	20	87.0	81.0	98.0		71.0		
	30	92.0	91.0	98.5		71.0		
	40	96.0	95.5	99.0		71.5		
	50	98.5	99.0	99.5		71.5		
	60	100.5	101.0	100.0		72.0		
	70	102.5	104.5	100.5		72.5		
	80	105.5	109.0	102.0		72.5		
	90	111.5	121.5	107.5		73.0		
	95	121.0	157.0	124.0		74.5		
	End	148.0	187.5	192.5		85.5		
	Recovery	98.0	97.9	99.1		99.1		
	Residue	1.4	1.2	0.8		0.8		
	Loss	0.6	0.9	0.1		0.1		

* ETBE analysis conducted by test method ASTM D 5441 (MTBE gas chromatography method), but calibrated for impurities typical of ETBE.

Suppliers: (MMT for manganese blends supplied by Ethyl)	Conoco-Phillips	Chevron-Texaco	Lyondell Chemical	Ultramar Diamond Shamrock	Conoco-Philips	Cessna Aircraft	Chevron-Texaco

EXHIBIT II

Compositions and Motor Octane Numbers of MON Matrix Blends

Aviation Alkylate Blends
(volume fraction)

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	MMT (g/gal)	MON
1	0.296	0.156	0.118	0.300	0.079	0.050	0.085	102.08
2	0.306	0.366	0.069	0.212	0.000	0.047	0.100	98.18
3	0.514	0.008	0.134	0.300	0.034	0.011	0.041	98.64
4	0.494	0.118	0.250	0.032	0.064	0.043	0.021	100.94
5	0.061	0.500	0.201	0.174	0.013	0.050	0.000	98.96
6	0.121	0.500	0.250	0.050	0.065	0.014	0.100	102.50
7	0.250	0.500	0.250	0.000	0.000	0.000	0.000	95.87
8	0.333	0.288	0.138	0.168	0.050	0.025	0.050	101.01
9	0.871	0.000	0.053	0.000	0.041	0.036	0.000	97.96
10	0.725	0.106	0.065	0.037	0.067	0.000	0.100	101.17
11	0.444	0.100	0.134	0.227	0.092	0.004	0.000	102.84
12	0.073	0.328	0.250	0.300	0.000	0.050	0.033	97.26
13	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.74
14	0.711	0.001	0.134	0.004	0.100	0.050	0.000	102.40
15	0.210	0.251	0.250	0.139	0.100	0.050	0.100	102.81
16	0.650	0.000	0.000	0.300	0.000	0.050	0.000	95.10
17	0.700	0.000	0.250	0.000	0.000	0.050	0.100	93.69
18	0.215	0.500	0.107	0.141	0.035	0.002	0.048	100.94
19	0.336	0.378	0.200	0.005	0.033	0.048	0.100	100.00
20	0.693	0.000	0.183	0.010	0.086	0.027	0.100	101.69
21	0.278	0.326	0.197	0.078	0.100	0.022	0.000	103.58
22	0.346	0.387	0.174	0.009	0.080	0.003	0.021	102.54
23	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.89
24	0.100	0.500	0.250	0.000	0.100	0.050	0.000	104.16
25	0.000	0.500	0.189	0.300	0.000	0.011	0.100	99.64
26	0.000	0.288	0.138	0.168	0.050	0.025	0.050	100.57
27	0.244	0.389	0.250	0.085	0.000	0.032	0.040	96.74
28	0.453	0.500	0.000	0.047	0.000	0.000	0.100	97.61
29	0.347	0.079	0.241	0.271	0.025	0.038	0.100	98.32
30	0.461	0.079	0.195	0.231	0.000	0.034	0.000	94.71
31	0.292	0.500	0.000	0.099	0.078	0.032	0.000	103.02
32	0.574	0.375	0.000	0.000	0.040	0.012	0.045	100.37
33	0.650	0.000	0.250	0.000	0.100	0.000	0.033	102.39
34	0.107	0.321	0.202	0.300	0.069	0.000	0.100	102.32
35	0.466	0.219	0.010	0.300	0.005	0.000	0.082	97.93
36	0.253	0.497	0.000	0.230	0.000	0.020	0.027	98.50
37	0.364	0.260	0.197	0.177	0.003	0.000	0.065	96.98
38	0.871	0.000	0.053	0.000	0.041	0.036	0.000	97.67
39	0.000	0.133	0.000	0.078	0.010	0.035	0.078	96.55
40	0.652	0.021	0.127	0.121	0.029	0.050	0.052	97.50

EXHIBIT II

Compositions and Motor Octane Numbers of MON Matrix Blends

Aviation Alkylate Blends
(volume fraction)

Blend No.	Aviation Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	MMT (g/gal)	MON
41	0.314	0.000	0.250	0.300	0.086	0.050	0.000	101.92
42	0.193	0.136	0.250	0.300	0.100	0.022	0.054	102.66
43	0.748	0.015	0.000	0.200	0.037	0.000	0.000	98.34
44	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.90
45	0.164	0.388	0.084	0.300	0.028	0.036	0.000	100.54
46	0.583	0.144	0.248	0.000	0.015	0.011	0.085	96.42
47	0.333	0.288	0.138	0.168	0.050	0.025	0.050	101.06
48	0.753	0.000	0.056	0.178	0.000	0.013	0.100	95.74
49	1.000	0.000	0.000	0.000	0.000	0.000	0.051	92.16
50	0.078	0.472	0.000	0.300	0.100	0.050	0.000	104.96
51	0.000	0.257	0.043	0.000	0.100	0.036	0.065	102.80
52	0.729	0.000	0.197	0.051	0.022	0.002	0.000	95.34
53	0.333	0.288	0.138	0.168	0.050	0.025	0.050	101.26
54	0.092	0.500	0.027	0.300	0.081	0.000	0.000	103.48
55	0.400	0.500	0.000	0.000	0.100	0.000	0.092	103.58
56	0.111	0.457	0.078	0.238	0.100	0.016	0.100	103.93
57	0.000	0.435	0.212	0.239	0.076	0.039	0.041	102.68
58	0.101	0.500	0.000	0.300	0.049	0.050	0.100	101.80
59	0.471	0.139	0.000	0.298	0.071	0.021	0.040	101.68
60	0.127	0.338	0.250	0.241	0.034	0.011	0.000	100.64
61	0.600	0.000	0.000	0.300	0.100	0.000	0.100	102.68
62	0.842	0.002	0.000	0.045	0.100	0.011	0.027	102.32
63	0.000	0.500	0.122	0.000	0.007	0.023	0.056	97.34
64	0.616	0.176	0.158	0.000	0.000	0.050	0.001	93.32
65	0.000	0.500	0.250	0.151	0.100	0.000	0.015	104.98
66	0.860	0.000	0.000	0.000	0.090	0.050	0.100	101.30
67	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.40
68	0.413	0.328	0.000	0.166	0.093	0.000	0.069	103.16
69	0.418	0.275	0.000	0.208	0.049	0.050	0.002	101.08
70	0.505	0.000	0.245	0.169	0.073	0.008	0.078	101.18
71	0.629	0.250	0.053	0.062	0.000	0.006	0.000	94.48
72	0.450	0.500	0.000	0.000	0.000	0.050	0.000	95.71
73	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.70
74	0.618	0.000	0.042	0.203	0.097	0.039	0.054	101.96
75	0.107	0.321	0.202	0.300	0.069	0.000	0.100	101.89

EXHIBIT II

Compositions and Motor Octane Numbers of MON Matrix Blends

Motor Alkylate Blends
(volume fraction)

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	MMT (g/gal)	MON
76	0.296	0.156	0.118	0.300	0.079	0.050	0.085	101.66
77	0.306	0.366	0.069	0.212	0.000	0.047	0.100	98.00
78	0.514	0.008	0.134	0.300	0.034	0.011	0.041	98.06
79	0.494	0.118	0.250	0.032	0.064	0.043	0.021	100.61
80	0.061	0.500	0.201	0.174	0.013	0.050	0.000	99.22
81	0.121	0.500	0.250	0.050	0.065	0.014	0.100	101.92
82	0.250	0.500	0.250	0.000	0.000	0.000	0.000	95.66
83	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.96
84	0.871	0.000	0.053	0.000	0.041	0.036	0.000	96.88
85	0.725	0.106	0.065	0.037	0.067	0.000	0.100	100.48
86	0.444	0.100	0.134	0.227	0.092	0.004	0.000	102.41
87	0.073	0.328	0.250	0.300	0.000	0.050	0.033	97.66
88	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.46
89	0.711	0.001	0.134	0.004	0.100	0.050	0.000	101.74
90	0.210	0.251	0.250	0.139	0.100	0.050	0.100	102.44
91	0.650	0.000	0.000	0.300	0.000	0.050	0.000	94.94
92	0.700	0.000	0.250	0.000	0.000	0.050	0.100	93.41
93	0.215	0.500	0.107	0.141	0.035	0.002	0.048	100.87
94	0.336	0.378	0.200	0.005	0.033	0.048	0.100	99.35
95	0.693	0.000	0.183	0.010	0.086	0.027	0.100	100.88
96	0.278	0.326	0.197	0.078	0.100	0.022	0.000	103.40
97	0.346	0.387	0.174	0.009	0.080	0.003	0.021	102.34
98	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.64
99	0.100	0.500	0.250	0.000	0.100	0.050	0.000	104.04
100	0.000	0.500	0.189	0.300	0.000	0.011	0.100	100.00
101	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.64
102	0.244	0.389	0.250	0.085	0.000	0.032	0.040	96.28
103	0.453	0.500	0.000	0.047	0.000	0.000	0.100	97.55
104	0.347	0.079	0.241	0.271	0.025	0.038	0.100	98.21
105	0.461	0.079	0.195	0.231	0.000	0.034	0.000	94.47
106	0.292	0.500	0.000	0.099	0.078	0.032	0.000	102.78
107	0.574	0.375	0.000	0.000	0.040	0.012	0.045	100.14
108	0.650	0.000	0.250	0.000	0.100	0.000	0.033	101.86
109	0.107	0.321	0.202	0.300	0.069	0.000	0.100	102.08
110	0.466	0.219	0.010	0.300	0.005	0.000	0.082	97.82
111	0.253	0.497	0.000	0.230	0.000	0.020	0.027	98.41
112	0.364	0.260	0.197	0.177	0.003	0.000	0.065	96.42
113	0.871	0.000	0.053	0.000	0.041	0.036	0.000	96.50
114	0.743	0.133	0.000	0.078	0.010	0.035	0.078	96.00
115	0.652	0.021	0.127	0.121	0.029	0.050	0.052	96.90

EXHIBIT II

Compositions and Motor Octane Numbers of MON Matrix Blends

Motor Alkylate Blends
(volume fraction)

Blend No.	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	MMT (g/gal)	MON
116	0.314	0.000	0.250	0.300	0.086	0.050	0.000	101.84
117	0.193	0.136	0.250	0.300	0.100	0.022	0.054	102.61
118	0.748	0.015	0.000	0.200	0.037	0.000	0.000	98.13
119	0.450	0.000	0.250	0.300	0.000	0.000	0.000	94.44
120	0.164	0.388	0.084	0.300	0.028	0.036	0.000	100.09
121	0.583	0.144	0.248	0.000	0.015	0.011	0.085	96.00
122	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.86
123	0.753	0.000	0.056	0.178	0.000	0.013	0.100	95.09
124	1.000	0.000	0.000	0.000	0.000	0.000	0.051	92.16
125	0.078	0.472	0.000	0.300	0.100	0.050	0.000	104.46
126	0.564	0.257	0.043	0.000	0.100	0.036	0.065	102.07
127	0.729	0.000	0.197	0.051	0.022	0.002	0.000	95.05
128	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.90
129	0.092	0.500	0.027	0.300	0.081	0.000	0.000	103.94
130	0.400	0.500	0.000	0.000	0.100	0.000	0.092	103.29
131	0.111	0.457	0.078	0.238	0.100	0.016	0.100	104.35
132	0.000	0.435	0.212	0.239	0.076	0.039	0.041	102.88
133	0.101	0.500	0.000	0.300	0.049	0.050	0.100	101.76
134	0.471	0.139	0.000	0.298	0.071	0.021	0.040	101.54
135	0.127	0.338	0.250	0.241	0.034	0.011	0.000	100.51
136	0.600	0.000	0.000	0.300	0.100	0.000	0.100	102.18
137	0.842	0.002	0.000	0.045	0.100	0.011	0.027	101.92
0	0.348	0.500	0.122	0.000	0.007	0.023	0.056	97.33
139	0.616	0.176	0.158	0.000	0.000	0.050	0.001	93.03
140	0.000	0.500	0.250	0.151	0.100	0.000	0.015	104.58
141	0.860	0.000	0.000	0.000	0.090	0.050	0.100	101.02
142	0.247	0.458	0.093	0.071	0.081	0.050	0.056	102.68
143	0.413	0.328	0.000	0.166	0.093	0.000	0.069	103.01
144	0.418	0.275	0.000	0.208	0.049	0.050	0.002	100.62
145	0.505	0.000	0.245	0.169	0.073	0.008	0.078	100.80
146	0.629	0.250	0.053	0.062	0.000	0.006	0.000	93.86
147	0.450	0.500	0.000	0.000	0.000	0.050	0.000	95.64
148	0.333	0.288	0.138	0.168	0.050	0.025	0.050	100.83
149	0.618	0.000	0.042	0.203	0.097	0.039	0.054	101.95
150	0.107	0.321	0.202	0.300	0.069	0.000	0.100	102.06

EXHIBIT II

Compositions and Motor Octane Numbers of MON Matrix Blends

Super Alkylate Blends
(volume fraction)

Blend Number	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	MMT (g/gal)	MON
151	0.350	0.250	0.300	0.100	0.000	0.000	104.38
152	0.607	0.083	0.288	0.000	0.023	0.075	100.44
153	0.700	0.000	0.300	0.000	0.000	0.000	100.34
154	0.773	0.128	0.000	0.100	0.000	0.000	105.69
155	0.482	0.208	0.187	0.085	0.038	0.000	103.32
156	0.828	0.055	0.025	0.079	0.013	0.100	103.50
157	0.600	0.250	0.000	0.100	0.050	0.100	103.95
158	0.650	0.125	0.150	0.050	0.025	0.050	102.11
159	0.810	0.156	0.000	0.017	0.017	0.052	100.82
160	0.718	0.172	0.081	0.020	0.008	0.000	101.06
161	0.965	0.000	0.000	0.035	0.000	0.017	102.09
162	0.659	0.059	0.228	0.055	0.000	0.044	102.22
163	0.438	0.146	0.300	0.100	0.017	0.049	103.50
164	0.774	0.000	0.196	0.018	0.012	0.100	101.30
165	0.937	0.000	0.032	0.000	0.032	0.031	100.64
166	0.650	0.238	0.056	0.057	0.000	0.054	102.12
167	0.493	0.186	0.300	0.021	0.000	0.099	100.78
168	0.600	0.000	0.300	0.100	0.000	0.100	104.72
169	0.630	0.250	0.068	0.018	0.034	0.100	100.34
170	0.710	0.185	0.000	0.067	0.039	0.055	102.68
171	0.463	0.127	0.299	0.060	0.050	0.095	101.82
172	0.804	0.053	0.052	0.056	0.036	0.000	103.08
173	0.650	0.125	0.150	0.050	0.025	0.050	101.99
174	0.550	0.000	0.300	0.100	0.050	0.000	104.70
175	0.561	0.115	0.242	0.073	0.009	0.000	103.25
176	0.531	0.250	0.210	0.000	0.009	0.033	99.24
177	0.650	0.125	0.150	0.050	0.025	0.050	102.04
178	0.700	0.250	0.000	0.000	0.050	0.000	98.10
179	0.640	0.174	0.142	0.000	0.045	0.079	100.04
180	0.531	0.250	0.210	0.000	0.009	0.033	98.70
181	0.764	0.000	0.126	0.100	0.010	0.025	105.06
182	0.426	0.216	0.300	0.024	0.035	0.000	100.26
183	0.848	0.071	0.081	0.000	0.000	0.068	100.63
184	0.650	0.000	0.300	0.000	0.050	0.100	101.01
185	0.766	0.000	0.116	0.068	0.050	0.074	103.42
186	0.540	0.194	0.166	0.100	0.000	0.100	104.21
187	0.303	0.250	0.300	0.100	0.047	0.060	103.50
188	0.671	0.054	0.212	0.017	0.046	0.007	100.87
189	0.828	0.055	0.025	0.079	0.013	0.100	103.46
190	0.603	0.042	0.217	0.100	0.038	0.100	104.39

EXHIBIT II

Compositions and Motor Octane Numbers of MON Matrix Blends

Super Alkylate Blends
(volume fraction)

Blend Number	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	MMT (g/gal)	MON
191	0.855	0.000	0.000	0.100	0.045	0.039	104.91
192	0.659	0.116	0.075	0.100	0.050	0.040	104.46
193	0.400	0.250	0.300	0.000	0.050	0.100	98.72
194	0.750	0.250	0.000	0.000	0.000	0.100	99.41
195	0.438	0.146	0.300	0.100	0.017	0.049	104.02
196	0.471	0.250	0.188	0.041	0.050	0.047	100.76
197	0.867	0.063	0.000	0.020	0.050	0.100	101.06
198	0.650	0.125	0.150	0.050	0.025	0.050	102.04
199	0.393	0.250	0.270	0.070	0.017	0.100	101.92
200	0.583	0.250	0.047	0.100	0.020	0.033	104.58
201	0.619	0.000	0.300	0.050	0.031	0.047	102.10
202	0.550	0.000	0.300	0.100	0.050	0.000	104.92

EXHIBIT III

Fuel Compositions Specified for Full Scale Engine Blends
(volume fraction)

Blend No.*	Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	Manganese (g/gal)
65X	0.000		0.500	0.250	0.150	0.100	0.000	0.000
50X	0.000		0.350	0.250	0.300	0.100	0.000	0.000
24X	0.400		0.500	0.000	0.000	0.100	0.000	0.000
54x	0.000		0.500	0.250	0.190	0.060	0.000	0.000
31	0.292		0.500	0.000	0.099	0.078	0.032	0.000
60X	0.000		0.470	0.250	0.250	0.030	0.000	0.000
25x	0.040		0.400	0.250	0.300	0.010	0.000	0.000
12X	0.073		0.327	0.250	0.300	0.000	0.050	0.000
140X		0.000	0.500	0.250	0.151	0.100	0.000	0.000
125		0.078	0.472	0.000	0.300	0.100	0.050	0.000
132X		0.000	0.435	0.212	0.239	0.065	0.050	0.000
117X		0.193	0.136	0.250	0.300	0.100	0.022	0.000
135X		0.000	0.425	0.250	0.300	0.025	0.000	0.000
80		0.061	0.500	0.201	0.174	0.013	0.050	0.000
111X		0.250	0.450	0.000	0.300	0.000	0.000	0.000
113X		0.940	0.000	0.015	0.000	0.045	0.000	0.000
61X	0.600		0.000	0.000	0.300	0.100	0.000	0.050
66	0.860		0.000	0.000	0.000	0.090	0.050	0.100
23	0.333		0.288	0.138	0.168	0.050	0.025	0.050
3X	0.800		0.000	0.125	0.000	0.055	0.020	0.050
36X	0.250		0.500	0.000	0.200	0.000	0.050	0.100
63X	0.355		0.500	0.140	0.000	0.005	0.000	0.050
39X	0.870		0.000	0.000	0.070	0.025	0.035	0.100
131		0.111	0.457	0.078	0.238	0.100	0.016	0.100
130		0.400	0.500	0.000	0.000	0.100	0.000	0.092
141		0.860	0.000	0.000	0.000	0.090	0.050	0.100
148		0.333	0.288	0.138	0.168	0.050	0.025	0.050
94X		0.700	0.000	0.240	0.000	0.060	0.000	0.100
138X		0.226	0.500	0.250	0.000	0.000	0.023	0.100
115X		0.500	0.100	0.100	0.235	0.015	0.050	0.052

* X behind blend number means the original MON Matrix recipe of this blend was changed to get better diversity in components, or a blend with or without MMT, or a MON nearer the target.

EXHIBIT IV

Properties and Suppliers of Components for Full Scale Engine Blends

		Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	Ethanol	*meta*-Toluidine
D 4052	Relative density, 15.56/15/56	0.6917	0.6912	0.6996	0.8710	0.7465	0.7939	0.9925
	API gravity, °	72.9	73.0	70.5	30.8	57.9	46.6	10.9
D 5191	Vapor pressure, DVPE, psi	5.70	7.76	1.81	0.90	4.41	2.20	< 0.1
D 2700	Motor octane number	91.1	89.7	99.7	108.3	98.2	88.6	
D 2622	Sulfur content, mass %	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	
E 1064	Water content, mass %					0.0486	0.332	
D 2360	Toluene content, mass %				99.88			
D 5441*	ETBE content, mass %					96.64		
D 5501	Ethanol content, mass %						99.61	
D 850	Distillation range, °C				0.5			
D 86	Distillation, % evaporated, °C							
	IBP	40.0	43.0	97.0		68.0		
	5	61.0	51.0	98.0		70.0		
	10	75.0	60.0	98.0		71.0		
	20	84.5	75.0	98.5		72.0		
	30	91.5	87.0	99.0		73.0		
	40	95.5	95.0	99.5		73.0		
	50	98.0	99.0	100.0	110.6	73.5	78.0 (lit.)	203-4 (lit.)
	60	100.5	103.0	100.5		73.5		
	70	103.0	107.0	102.0		74.0		
	80	106.0	113.5	103.5		74.5		
	90	113.0	128.0	111.5		76.0		
	95	125.0	157.5	161.5		78.5		
	End	151.5	193.5	187.0		101.5		
	Recovery	97.9	98.0	99.0		99.0		
	Residue	0.9	1.0	0.2		0.5		
	Loss	1.2	1.0	0.8		0.5		

* ETBE analysis conducted by test method ASTM D 5441 (MTBE gas chromatography method), but calibrated for impurities typical of ETBE.

Suppliers: (Hytech 3062 for manganese blends supplied by Ethyl)	Conoco-Phillips	Chevron-Texaco	see separate table	Ultramar Diamond Shamrock	Cessna Aircraft	High Plains Ethanol York, NE	Exxon-Mobil

EXHIBIT V

Composition and Densities of Super Alkylate used for Full Scale Engine Blends

Super Alkylate Batch Recipe

92.6 mass % iso-C8 =	93.12%	vol %
7.4 mass % iso-C12 =	6.88%	vol %

For each drum of SuAlky, 304 pounds net:

iso-C8, lb.	281.50	92.60%
iso-C12, lb.	22.50	7.40%

Batch No.	Density (15.56 °C)
1	0.69958
2	0.69962
3	0.69963
4	0.69960
5	0.69960
6	0.69956
7	0.69962
8	0.69962
9	0.69962
10	0.69958
11	0.69958
12	0.69956
13	0.69956
14	0.69962
Average	0.69960

EXHIBIT VI

Actual Mass Fraction of Full Scale Engine Blends

Blend Label	Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	Manganese (g/gal)	Blend No.
AV1	0.0664		0.3009	0.2863	0.2942	0.0000	0.0523		12X
AV2	0.0366		0.3685	0.2868	0.2946	0.0135	0.0000		25x
AV3	0.0000		0.4549	0.2834	0.1843	0.0774	0.0000		54x
AV4	0.3815		0.4817	0.0000	0.0000	0.1368	0.0000		24X
AV5	0.0000		0.4307	0.2855	0.2445	0.0393	0.0000		60X
AV6	0.0000		0.3115	0.2772	0.2849	0.1264	0.0000		50X
AV7	0.0000		0.4489	0.2797	0.1440	0.1275	0.0000		65X
AV8	0.2772		0.4803	0.0000	0.1010	0.1069	0.0346		31
MO1		0.2429	0.4426	0.0000	0.3145	0.0000	0.0000		111X
MO2		0.0564	0.4664	0.2338	0.1733	0.0171	0.0530		80
MO3		0.1693	0.1208	0.2771	0.2847	0.1263	0.0218		117X
MO4		0.0000	0.3894	0.2852	0.2930	0.0325	0.0000		135X
MO5		0.0722	0.4418	0.0000	0.2997	0.1330	0.0533		125
MO6		0.9183	0.0000	0.0181	0.0000	0.0635	0.0000		113X
MO7		0.0000	0.3941	0.2389	0.2317	0.0837	0.0516		132X
MO8		0.0000	0.4489	0.2791	0.1445	0.1275	0.0000		140X
AM1	0.3084		0.2700	0.1608	0.1677	0.0666	0.0264	0.0500	23
AM2	0.8221		0.0000	0.0000	0.0000	0.1229	0.0550	0.1000	66
AM3	0.8511		0.0000	0.0000	0.0745	0.0351	0.0393	0.1000	39X
AM4	0.5623		0.0000	0.0000	0.3032	0.1345	0.0000	0.0500	61X
AM5	0.7553		0.0000	0.1484	0.0000	0.0748	0.0216	0.0500	3X
AM6	0.3398		0.4837	0.1693	0.0000	0.0071	0.0000	0.0500	63X
AM7	0.2429		0.4913	0.0000	0.2099	0.0000	0.0559	0.1000	36X
MM1		0.3811	0.4820	0.0000	0.0000	0.1369	0.0000	0.0920	130
MM2		0.6430	0.0000	0.2780	0.0000	0.0790	0.0000	0.1000	94X
MM3		0.1016	0.4245	0.0897	0.2355	0.1317	0.0170	0.1000	131
MM4		0.3086	0.2701	0.1609	0.1678	0.0667	0.0259	0.0500	148
MM5		0.2103	0.4706	0.2944	0.0000	0.0000	0.0248	0.1000	138X
MM6		0.4717	0.0952	0.1191	0.2393	0.0204	0.0543	0.0520	115X
MM7		0.8220	0.0000	0.0000	0.0000	0.1230	0.0550	0.1000	141

EXHIBIT VII

Actual Volume Fraction of Full Scale Engine Blends

Blend Label	Aviation Alkylate	Motor Alkylate	Super Alkylate	Toluene	ETBE	*meta*-Toluidine	Ethanol	Manganese (g/gal)	Blend No.
AV1	0.0730		0.3272	0.2500	0.2997	0.0000	0.0501		12X
AV2	0.0402		0.3998	0.2500	0.2997	0.0103	0.0000		25x
AV3	0.0000		0.5000	0.2502	0.1898	0.0600	0.0000		54x
AV4	0.4002		0.4997	0.0000	0.0000	0.1000	0.0000		24X
AV5	0.0000		0.4698	0.2501	0.2499	0.0302	0.0000		60X
AV6	0.0000		0.3500	0.2501	0.2999	0.1001	0.0000		50X
AV7	0.0000		0.4997	0.2501	0.1502	0.1000	0.0000		65X
AV8	0.2916		0.4997	0.0000	0.0985	0.0784	0.0318		31
MO1		0.2501	0.4501	0.0000	0.2998	0.0000	0.0000		111X
MO2		0.0613	0.5001	0.2014	0.1742	0.0129	0.0501		80
MO3		0.1926	0.1358	0.2501	0.2999	0.1001	0.0216		117X
MO4		0.0000	0.4251	0.2501	0.2998	0.0250	0.0000		135X
MO5		0.0780	0.4718	0.0000	0.2999	0.1001	0.0501		125
MO6		0.9400	0.0000	0.0147	0.0000	0.0453	0.0000		113X
MO7		0.0000	0.4342	0.2114	0.2393	0.0650	0.0501		132X
MO8		0.0000	0.4997	0.2496	0.1507	0.1000	0.0000		140X
AM1	0.3324		0.2876	0.1376	0.1675	0.0500	0.0248	0.0500	23
AM2	0.8602		0.0000	0.0000	0.0000	0.0897	0.0501	0.1000	66
AM3	0.8695		0.0000	0.0000	0.0705	0.0250	0.0350	0.1000	39X
AM4	0.6001		0.0000	0.0000	0.2998	0.1000	0.0000	0.0500	61X
AM5	0.8000		0.0000	0.1248	0.0000	0.0552	0.0199	0.0500	3X
AM6	0.3549		0.4995	0.1404	0.0000	0.0052	0.0000	0.0500	63X
AM7	0.2500		0.4998	0.0000	0.2001	0.0000	0.0501	0.1000	36X
MM1		0.4001	0.4999	0.0000	0.0000	0.1001	0.0000	0.0920	130
MM2		0.6999	0.0000	0.2401	0.0000	0.0599	0.0000	0.1000	94X
MM3		0.1108	0.4575	0.0776	0.2379	0.1000	0.0162	0.1000	131
MM4		0.3327	0.2877	0.1377	0.1675	0.0501	0.0243	0.0500	148
MM5		0.2260	0.4998	0.2511	0.0000	0.0000	0.0232	0.1000	138X
MM6		0.5000	0.0997	0.1002	0.2349	0.0151	0.0501	0.0520	115X
MM7		0.8602	0.0000	0.0000	0.0000	0.0896	0.0501	0.1000	141

EXHIBIT VIII
ASTM D 910 Specification Properties

	AV1	AV2	AV3	AV4	AV5	AV6	AV7	AV8	100LL
Motor Octane Number	97.0	99.8	103.4	104.4	101.2	105.2	105.6	103.4	99.5 min
Supercharge Rating, mL TEL	1.83	2.94	>6.00	>6.00	4.00	>6.00	>6.00	>6.00	
Performance No.	136.6	146.1	>161.0	>161.0	152.5	>161.0	>161.0	>161.0	130 min
Density, 15 ° kg/m3	762.1	760.2	770.3	726.2	764.0	789.5	780.7	729.5	
Vapor pressure, 38 ° kPa	24.8	18.7	14.6	22.1	16.6	15.4	13.3	27.0	38.0-49.0
Freezing Point, ºC	<-70	-41 nh*	<-70	+19 nh*	-47	<-70	<-70	-33 nh*	-58 max
Net heat of combustion, MJ/kg	40.184	40.783	41.080	43.162	40.960	39.962	40.982	42.032	43.5 min
Copper corrosion	1b	1a	1a	1b	1a	1a	1a	1a	1 max
Potential residue, 5 h, 100 °C									
Precipitate, mg/100 mL	0.6	0.3	0.4	0.3	<0.1	<0.1	<0.1	<0.1	3 max
Potential gum, mg/100 mL	4	3	6	5	4	6	7	5	6 max
Water reaction, Interface rating	1b	1b	1b	1b	1b	1b	1b	1b	
Separation rating	2	2	2	2	2	2	2	2	
Volume change, mL	3	0	0	0	0	0	0	2	± 2 max
Distillation, % evaporated, °C IBP	67.5	79.5	86.5	53.5	82.5	81.5	87.5	62.5	
5	72.5	85.0	91.5	64.5	87.5	87.5	92.5	70.0	
10	75.0	88.5	92.5	73.0	90.0	89.5	94.5	76.0	75 max
15	77.5	88.5	93.5	76.5	91	90.5	95.5	81.5	
20	80.0	90.0	94.5	79.5	91.5	91.5	96.5	87.0	
30	87.0	91.5	95.5	84.0	93.5	92.5	97.5	93.5	
40	91.0	93.0	97.5	87.5	94.5	94.5	99.5	96.5	75 min
50	93.5	94.5	100.0	91.0	96.5	97.5	101.5	98.5	105 max
60	96.0	97.0	101.5	85.5	98.5	100.5	104.5	100.5	
70	98.5	99.5	104.5	101.0	101	104.5	107.5	104.5	
80	101.5	103.0	109.5	109.0	104.5	112.5	114.5	109.5	
85	103.5	105.5	115.0	119.0	107.5	121.0	124.0	116.0	
90	106.0	109.5	127.0	163.0	113.5	161.0	169.0	155.0	135 max
95	111.0	122.0	187.0	192.0	150.0	195.0	195.5	195.0	
End	156.5	178.0	197.5	199.5	189.5	198.0	198.0	197.5	170 max
Sum of 10%+50%	168.5	183.0	192.5	164.0	186.5	187.0	195.5	174.5	135 min
Recovery	98.6	98.9	99.1	97.9	98.5	99.0	99.1	99.0	97 min
Residue	1.3	1.0	0.8	0.7	0.8	0.8	0.8	0.8	1.5 max
Loss	0.1	0.1	0.1	1.4	0.7	0.2	0.1	0.2	

EXHIBIT VIII
ASTM D 910 Specification Properties

	MO1	MO2	MO3	MO4	MO5	MO6	MO7	MO8	100LL
Motor Octane Number	98.1	99.2	103.6	101.0	104.6	96.7	102.3	105.0	99.5 min
Supercharge Rating, mL TEL	0.43	0.85	4.00	1.37	4.86	0.78	3.44	>6.0	
Performance No.	114.1	123.1	152.5	131.2	156.6	121.8	149.4	>161	130 min
Density, 15 ° kg/m3	711.2	750.9	790.9	765.1	750.3	711.2	773.3	780.6	
Vapor pressure, 38 ° kPa	30.7	24.9	26.4	17.4	25.5	48.9	21.2	14.5	38.0-49.0
Freezing Point, ºC	<-70	<-70	<-70	<-70	<-70	+4 nh*	<-70	<-70	-58 max
Net heat of combustion, MJ/kg	41.835	40.909	39.376	40.607	39.706	43.849	39.864	40.899	43.5 min
Copper corrosion	1a	1b	1a	1a	1a	1b	1a	1a	1 max
Potential residue, 5 h, 100 °C									
Precipitate, mg/100 mL	0.2	0.3	0.1	<0.1	1.2	0.3	0.3	<0.1	3 max
Potential gum, mg/100 mL	2	<1	9	2	6	9	5	8	6 max
Water reaction, Interface rating	1b	2	2	1b	1b	1b	2	1b	
Separation rating	2	2	2	2	2	1	2	1	
Volume change, mL	3	0	1	0	3	0	3	0	± max
Distillation, % evaporated, °C IBP	59.0	67.5	58.0	81.0	66.0	38.0	70.0	86.5	
5	73.5	72.0	70.5	88.0	70.5	55.5	76.5	92.0	
10	79.0	75.0	77.5	89.5	73.0	65.5	78.0	93.5	75 max
15	81.0	79.0	81.5	90.0	75.0	73.5	80.0	94.5	
20	83.0	84.0	84.5	91.0	77.5	80.0	83.0	95.5	
30	86.0	91.0	89.0	92.0	82.0	90.5	89.0	97.5	
40	89.0	94.5	93.0	93.5	88.5	97.5	93.0	99.5	75 min
50	90.5	96.5	97.0	95.0	91.5	102.0	96.0	100.5	105 max
60	93.0	98.5	100.5	97.5	96.0	106.0	99.0	103.5	
70	96.5	100.0	104.5	100.0	100.0	110.5	102.5	112.0	
80	100.5	103.0	113.5	104.0	106.5	120.5	108.5	115.5	
85	103.5	105.0	123.0	107.0	116.0	129.5	113.0	125.5	
90	109.0	110.0	163.5	112.5	175.0	152.5	126.5	174.5	135 max
95	132.5	135.5	193.5	127.5	195.5	182.5	188.5	196.0	
End	181.0	184.5	204.0	191.5	198.0	199.5	198.0	198.0	170 max
Sum of 10%+50%	169.5	171.5	174.5	184.5	164.5	167.5	174.0	194.0	135 min
Recovery	98.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	97 min
Residue	1.3	0.3	0.4	0.9	0.7	0.4	0.6	0.8	1.5 max
Loss	0.7	0.7	0.6	0.1	0.3	0.6	0.4	0.2	

EXHIBIT VIII
ASTM D 910 Specification Properties

	AM1	AM2	AM3	AM4	AM5	AM6	AM7	100LL
Motor Octane Number	101.0	101.6	96.4	102.9	99.6	96.6	99.6	99.5 min
Supercharge Rating, mL TEL	3.00	5.80	1.13	4.62	2.18	0.81	1.25	
Performance No.	146.6	160.3	127.8	155.6	140.1	122.4	129.6	130 min
Density, 15 ° kg/m3	747.0	725.8	707.4	741.5	733.6	723.1	712.0	
Vapor pressure, 38 ° kPa	28.6	41.7	44.2	33.7	38.4	21.3	31.7	38.0-49.0
Freezing Point, ºC*	<-70	-9 nh*	-64 nh*	<-70	-37.5 nh*	<-70	<-70	-58 max
Net heat of combustion, MJ/kg	41.392	42.509	42.916	40.699	42.790	43.440	41.552	43.5 min
Copper corrosion	1a	1a	1a	1a	1a	1a	1b	1 max
Manganese, as Mn, g/gal	0.054	0.108	0.108	0.054	0.052	0.056	0.109	
Potential residue, 5 h, 100 °C								
Precipitate, mg/100 mL	<0.1	<0.1	<0.1	0.1	0.7	0.8	0.2	3 max
Potential gum, mg/100 mL	10	4	2	10	3	<1	3	6 max
Water reaction, Interface rating	1b	2	1b	1b	1b	1b	1b	
Separation rating	2	2	2	2	2	1	2	
Volume change, mL	2	4	2	1	2	1	4	± max
Distillation, % evaporated, °C IBP	58.0	48.0	48.0	50.0	45.0	70.0	64.5	
5	71.5	58.5	59.0	68.0	60.5	89.0	68.0	
10	78.0	64.0	64.0	74.0	71.0	93.0	71.0	75 max
15	82.5	68.5	68.0	78.0	79.0	95.0	74.5	
20	86.5	74.0	74.0	80.0	86.5	96.5	79.0	
30	92.0	87.0	87.0	84.5	94.0	98.0	87.0	
40	95.0	97.0	93.0	87.5	98.5	99.0	91	75 min
50	97.0	100.5	97.0	91.0	101.0	100.0	93.0	105 max
60	100.0	103.5	100.0	95.0	103.5	101.0	95.5	
70	103.0	108.0	103.0	100.0	106.5	102.0	97.5	
80	107.0	115.0	112.5	108.5	111.0	104.0	101.5	
85	112.0	123.0	116.0	117.5	115.0	106.0	103.5	
90	124.0	148.5	117.5	166.5	123.0	110.0	107.5	135 max
95	177.5	195.0	135.0	195.0	176.0	130.0	130.5	
End	197.5	198.0	190.5	198.5	196.5	174.5	181.5	170 max
Sum of 10%+50%	175.0	164.5	161.0	165.0	172.0	193.0	164.0	135 min
Recovery	99.0	99.0	99.0	99.0	99.0	99.0	99.0	97 min
Residue	0.8	0.8	0.9	0.8	0.9	0.9	0.4	1.5 max
Loss	0.2	0.2	0.1	0.2	0.1	0.1	0.6	

EXHIBIT VIII
ASTM D 910 Specification Properties

	MM1	MM2	MM3	MM4	MM5	MM6	MM7	100LL
Motor Octane Number	103.8	99.4	104.0	100.7	96.8	96.2	100.9	99.5 min
Supercharge Rating, mL TEL	>6.0	3.73	>6.0	2.67	1.47	0.78	4.91	
Performance No.	>161	151.1	>161	144.2	132.5	121.8	156.8	130 min
Density, 15 ° kg/m3	713.7	757.6	757.0	747.1	742.8	734.3	727.0	
Vapor pressure, 38 ° kPa	28.9	37.8	23.3	33.4	28.7	43.3	52.9	38.0-49.0
Freezing Point, ºC	8.5 nh*	-57 nh*	<-70	<-70	<-70	<-70	-9 nh*	-58 max
Net heat of combustion, MJ/kg	42.779	42.630	40.704	41.338	42.846	40.894	42.303	43.5 min
Copper corrosion	1a	1a	1a	1a	1a	1a	1b	1 max
Manganese, as Mn, g/gal	0.107	0.107	0.107	0.053	0.094	0.057	0.110	
Potential residue, 5 h, 100 °C								
Precipitate, mg/100 mL	0.3	0.9	0.2	1.6	1.2	0.6	0.7	3 max
Potential gum, mg/100 mL	10	6	18	9	5	6	1	6 max
Water reaction, Interface rating	1b	1b	1b	1b	1b	2	2	
Separation rating	2	2	2	2	2	2	2	
Volume change, mL	1	1	2	1	1	4	4	± max
Distillation, % evaporated, °C IBP	47.0	42.0	65.0	54.0	62.0	47.0	38.0	
5	75.0	64.0	76.5	67.0	70.0	58.5	49.5	
10	86.0	77.0	81.0	74.0	83.0	64.0	56.0	75 max
15	91.0	86.0	84.5	79.5	91.5	67.0	61.0	
20	94.0	91.5	87.0	84.0	96.0	70.5	66.0	
30	97.5	98.5	90.5	90.5	98.5	78.5	79.5	
40	100.0	102.0	93.5	94.5	100.0	86.0	94.0	75 min
50	100.5	105.5	96.0	97.0	101.0	91.0	102.5	105 max
60	104.0	108.0	99.0	100.0	102.0	95.0	103.5	
70	108.0	113.0	103.0	104.0	103.0	99.0	114.0	
80	114.0	119.5	111.0	110.0	105.0	104.5	127.0	
85	123.0	127.5	125.5	116.0	106.5	109.0	144.5	
90	153.0	151.5	180.5	131.0	110.0	118.5	177.5	135 max
95	183.5	190.5	196.0	182.5	132.0	153.5	194.5	
End	199.5	201.0	199.0	196.0	179.5	186.5	198.5	170 max
Sum of 10%+50%	186.5	182.5	177.0	171.0	184.0	155.0	158.5	135 min
Recovery	99.0	99.0	99.0	99.0	98.0	98.5	98.5	97 min
Residue	0.5	0.6	0.7	0.9	1.0	0.7	0.6	1.5 max
Loss	0.5	0.4	0.3	0.1	1.0	0.8	0.9	

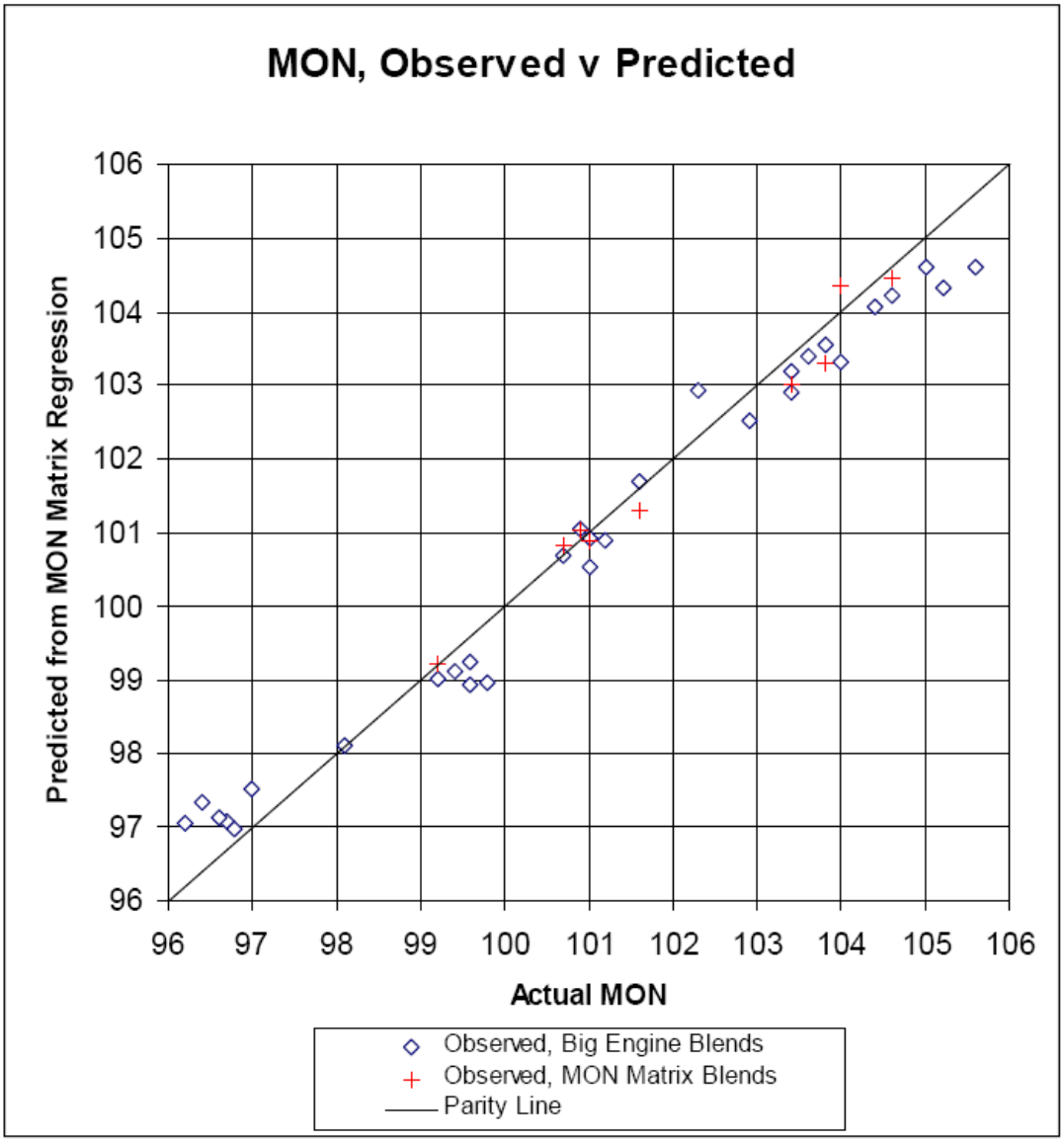
EXHIBIT IX

Comparison of Motor Octane Numbers, Observed v Predicted

Blend Label	Observed for MON Matrix Blend	Predicted from MON Matrix Regression	Observed for Big Engine Blend
AV1		97.5	97.0
AV2		99.0	99.8
AV3		102.9	103.4
AV4		104.1	104.4
AV5		100.9	101.2
AV6		104.3	105.2
AV7		104.6	105.6
AV8	103.0	103.2	103.4
MO1		98.1	98.1
MO2	99.2	99.0	99.2
MO3		103.4	103.6
MO4		100.6	101.0
MO5	104.5	104.2	104.6
MO6		97.1	96.7
MO7		102.9	102.3
MO8		104.6	105.0
AM1	100.9	100.9	101.0
AM2	101.3	101.7	101.6
AM3		97.3	96.4
AM4		102.5	102.9
AM5		99.2	99.6
AM6		97.1	96.6
AM7		99.0	99.6
MM1	103.3	103.6	103.8
MM2		99.1	99.4
MM3	104.4	103.3	104.0
MM4	100.8	100.7	100.7
MM5		97.0	96.8
MM6		97.0	96.2
MM7	101.0	101.1	100.9

EXHIBIT IX

Comparison of Motor Octane Numbers, Observed v Predicted



APPENDIX B
LAB ANALYSIS 47 UL BLENDS
FOR FULL SCALE ENGINE TESTING
DIXIE SERVICES REPORT
JULY 26, 2007

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UNLEADED AVIATION GASOLINE DEVELOPMENT PROGRAM - PHASE III

COMPOSITION AND MON RATINGS OF EXPERIMENTAL FUELS FOR FULL-SCALE ENGINE TESTS AT FAA TECHNICAL CENTER

I. Background

The Unleaded Aviation Gasoline Development Group was organized under the sponsorship of the Coordinating Research Council (CRC) in the 1990's to conduct research and testing that would facilitate development of a high octane unleaded aviation gasoline (avgas) that could be an environmentally compatible replacement for the current ASTM D 910 Grade 100LL fuel, which contains tetraethyllead (TEL). This group consists of voluntary representatives from various elements of the aviation industry, including fuel producers, airframe and engine manufacturers, the Federal Aviation Administration, industry-related organizations (AOPA, EAA, GAMA) and other interested parties.

The stated goal of the CRC Unleaded Aviation Gasoline Development Group is not to formulate a commercial fuel product to replace 100LL aviation gasoline, but rather to accumulate and make publicly available technical information that will facilitate development of a TEL-free fuel that will meet the operating, safety and environmental requirements of both the current and future general aviation fleet.

The program described in this report was based on the results of two earlier programs conducted by the Unleaded Aviation Gasoline Development Group and FAA Technical Center, namely

Phase I - Blending and Motor Octane Number (MON) Testing of 202 Fuel Formulations (completed in 2002)
Phase II - Composition and Properties of 30 Fuels for Full Scale Engine Tests (completed in 2004)

Details and results of these earlier programs were published in the following three documents:

"Technical Report - CRC Matrix Fuel Formulations," dated January 12, 2004, prepared by Dixie Services Inc. pursuant to Award No DTFACT03P1089

"Cessna Evaluation of CRC Fuel Matrix Blends," dated January 2003, prepared by Cesar Gonzalez and Richard Jesik

"Full-Scale Engine Knock Tests of 30 Unleaded, High-Octane Blends", Report No. DOT/FAA/AR-04/25, dated September 2004, issued by FAA William J. Hughes Technical Center.

II. Phase III Program Outline

Based on the results of the earlier programs, in 2005 the Unleaded AvGas Task Group, a subcommittee of the CRC Unleaded Aviation Gasoline Development Group, concluded that an additional test program was needed to better define the relationship between composition and detonation characteristics in a full scale engine, with particular emphasis on fuel blends that could be expected to have motor octane numbers (MON) close to or above 100. It was decided to conduct a designed experiment (similar to that employed for the Phase I MON Matrix program) using the following components and compositional constraints:

Blend Component	Constraint, volume %
Aviation alkylate	0 - 60
Super alkylate	0 - 50
Toluene	0 - 20
tert-Butylbenzene	0 - 20
meta-Toluidine	3 - 12
Ethyl-*tert*-butyl ether (ETBE)	0 - 30
iso-Pentane, constant for all blends at	5
Total aromatic content	30 max
Total alkylate (aviation+super+*iso*-pentane)	75 max

The experimental design to evaluate these constraints was again provided by ConocoPhillips Research Center statisticians. The recommended program required a total of 45 fuel blends to evaluate the interactions of the specified components. Because all of the fuels in the designed experiment would contain 3 - 12 volume % *meta*-toluidine, it was decided to also prepare and test two fuels containing no amine component. Two specific non-amine formulations were recommended, and these were included as Blends 46 and 47 in the program.

The detailed compositions for the entire 47-fuel set are tabulated in the attached Exhibit I, "Fuel Compositions Specified for Phase III Full Scale Engine Tests."

III. Blend Component Properties

The component materials to be used for blending the fuels were supplied by task group member companies and the FAA Technical Center to an independent laboratory, which was commissioned to blend them into 45-gallon batches and also to test each blend for motor octane number (MON). The individual blending components were tested for selected chemical and physical properties, which are reported along with the sources for the components in Exhibit II, "Properties of Blending Components."

Because multi-drum quantities of super alkylate were not available commercially for this program, it was necessary to prepare a simulated super alkylate by blending purchased components. Prior to the Phase II program, a prospective future producer of super alkylate indicated that a mixture of 92.6 mass % *iso*-octane and 7.4 mass % *iso*-dodecane was appropriate, based on pilot scale production, and this recipe was used to prepare the Phase II fuels. It was decided to follow the same practice for this Phase III program. Accordingly, pure grade *iso*-octane (99%) was purchased from ChevronPhillips Chemical Company and *iso*-

dodecane was purchased from The Fanning Corporation (Fancol ID-CG, 98 % C_{12} *iso*-paraffins, primarily pentamethylheptane, 2 % other isoparaffins) for blending. The super alkylate was prepared in ten individual drum batches (313 pounds net) as needed for the program by combining the quantities indicated in Exhibit III, "Composition and Densities of Super Alkylate Batches." The density of each drum batch was measured for quality control, and these data are included in Exhibit III.

IV. Preparation of Blends

The blends were prepared in 45-gallon batches. Because of the quantities involved, it was decided to prepare the blends by mass additions rather than volume. Accordingly, the volume fraction formulations were converted to the equivalent mass fractions using the densities of the components at 15.56 °C (60 °F). Each blend was prepared in a clean and dry 55-gallon drum using a platform scale readable to 0.25 pound. The following order of addition of components was followed: aviation alkylate, super alkylate, toluene, *tert*-butyl benzene, *meta*-toluidine, ethyl-*tert*-butyl ether (ETBE), *iso*-pentane. Each batch was mixed with a high speed stirrer for ten minutes after addition of the last component. The batch was then divided into two parcels: three gallons were withdrawn into one-gallon cans for density and motor octane number testing and for retain storage by the blending laboratory in the event additional testing is required; the balance of the batch was then sealed in the blending drum for shipment to the FAA Technical Center for full scale engine testing. Both parcels were identified to the testing laboratories only by the blend numbers noted in Exhibit I: the fuel formulations were not provided to either testing location.

The actual mass fraction compositions of the forty-seven fuels as calculated from the blend weight measurements are tabulated in Exhibit IV, "Actual Composition (Mass Fraction) of Phase III Fuel Blends." The corresponding volume fraction data, calculated from the component densities at 15.56 °C, appear in Exhibit V "Actual Composition (Volume Fraction) of Phase III Fuel Blends."

V. Laboratory Testing of Blends

MON, Density, Vapor Pressure, Elemental Data

The Phase III Program Outline called for each blend to be tested for motor octane number (ASTM D 2700). Each blend was also tested for density as a part of the fuel blending task (ASTM D 4052). In addition, because the effect on vapor pressure of including *iso*-pentane as a blend component was of interest, eight blends were also tested for this property (ASTM D 5191). The blends tested for vapor pressure included the two non-amine blends (Blends 46 and 47) and, from the experimental design set, three that were predicted (on the basis of the vapor pressures of their components) to have the lowest vapor pressures and three that were expected to have the highest vapor pressures. The results of the tests for motor octane number, density and vapor pressure are reported in Exhibit VI, "Test Results and Elemental Compositions."

Information on the elemental composition of the blends was requested by the FAA Technical Center for use in the full-scale engine testing program. These data were calculated

from the concentrations and molecular compositions of the blend components, all of which were known precisely, except for the composition of the aviation alkylate. For purposes of these calculations, the aviation alkylate was assumed to have the average molecular composition corresponding to $C_{8.5}H_{18.5}$ (molecular weight = 117.74). The elemental composition of each blend was then calculated from the actual mass fraction blending data (Exhibit IV) using the individual component elemental data from the following table:

Elemental Composition of Blend Components
(mass fraction)

Element	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane
Carbon	0.84162	0.84170	0.91248	0.89486	0.78462	0.70530	0.83236
Hydrogen	0.15838	0.15830	0.08752	0.10514	0.08466	0.13811	0.16764
Nitrogen					0.13072		
Oxygen						0.15659	

The calculated elemental compositions of the forty-seven blends are recorded with the MON and physical property data in Exhibit VI.

Full Scale Engine Tests

The results of the full-scale engine tests of the forty-seven blends will be reported separately by the FAA Technical Center.

Report prepared by:
Mical C. Renz
Dixie Services Incorporated
July 26, 2007

EXHIBIT I

Fuel Compositions Specified for Phase III Full Scale Engine Tests
(volume fraction)

Blend	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane
1	0.422	0.000	0.000	0.200	0.030	0.298	0.050
2	0.269	0.270	0.102	0.191	0.118	0.000	0.050
3	0.000	0.230	0.164	0.136	0.120	0.300	0.050
4	0.600	0.017	0.013	0.200	0.120	0.000	0.050
5	0.000	0.500	0.084	0.157	0.083	0.126	0.050
6	0.130	0.500	0.000	0.200	0.120	0.000	0.050
7	0.167	0.500	0.011	0.100	0.066	0.106	0.050
8	0.416	0.284	0.000	0.036	0.120	0.094	0.050
9	0.000	0.397	0.169	0.000	0.084	0.300	0.050
10	0.249	0.235	0.059	0.000	0.107	0.300	0.050
11	0.172	0.220	0.198	0.030	0.030	0.300	0.050
12	0.001	0.500	0.107	0.074	0.031	0.237	0.050
13	0.600	0.044	0.011	0.104	0.065	0.126	0.050
14	0.330	0.000	0.200	0.000	0.120	0.300	0.050
15	0.103	0.500	0.091	0.007	0.120	0.129	0.050
16	0.295	0.395	0.148	0.032	0.080	0.000	0.050
17	0.090	0.500	0.000	0.000	0.060	0.300	0.050
18	0.547	0.000	0.100	0.200	0.039	0.064	0.050
19	0.600	0.000	0.032	0.000	0.030	0.288	0.050
20	0.393	0.000	0.000	0.137	0.120	0.300	0.050
21	0.000	0.429	0.000	0.101	0.120	0.300	0.050
22	0.101	0.500	0.200	0.000	0.030	0.119	0.050
23	0.600	0.000	0.000	0.000	0.108	0.242	0.050
24	0.189	0.229	0.021	0.200	0.089	0.222	0.050
25	0.167	0.500	0.080	0.173	0.030	0.000	0.050
26	0.451	0.015	0.118	0.091	0.120	0.155	0.050
27	0.295	0.395	0.148	0.032	0.080	0.000	0.050
28	0.130	0.500	0.000	0.200	0.120	0.000	0.050
29	0.439	0.261	0.003	0.197	0.035	0.015	0.050
30	0.596	0.104	0.137	0.081	0.030	0.002	0.050
31	0.030	0.500	0.200	0.100	0.120	0.000	0.050
32	0.380	0.320	0.067	0.000	0.030	0.153	0.050
33	0.530	0.022	0.190	0.000	0.059	0.149	0.050
34	0.349	0.000	0.195	0.105	0.030	0.271	0.050
35	0.600	0.100	0.124	0.000	0.120	0.006	0.050
36	0.295	0.395	0.148	0.032	0.080	0.000	0.050
37	0.600	0.017	0.013	0.200	0.120	0.000	0.050
38	0.000	0.320	0.100	0.200	0.030	0.300	0.050
39	0.244	0.259	0.016	0.101	0.030	0.300	0.050
40	0.000	0.500	0.000	0.200	0.030	0.220	0.050
41	0.190	0.286	0.200	0.032	0.120	0.122	0.050
42	0.403	0.000	0.098	0.078	0.071	0.300	0.050
43	0.554	0.000	0.200	0.100	0.096	0.000	0.050
44	0.270	0.000	0.100	0.200	0.092	0.288	0.050
45	0.214	0.299	0.191	0.109	0.048	0.089	0.050
46	0.000	0.810	0.000	0.100	0.000	0.000	0.090
47	0.000	0.480	0.000	0.150	0.000	0.300	0.070

EXHIBIT II

Properties of Blending Components

		Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane
D 4052	Density, 15.56 °C	0.6928	0.6994	0.8709	0.8701	0.9925	0.7450	0.6243
D 4052	API gravity, °	72.5	70.5	30.8	31.0	10.9	58.2	19.7
D 5191	Vapor pressure, DVPE, psi	5.37	1.78	0.79	<0.1		4.14	< 0.1
D 2700	Motor octane number	91.4	99.9					
D 5453	Sulfur content, mass %	0.0002	< 0.0001	< 0.0001	< 0.0001		0.0002	< 0.0001
E 1064	Water content, mass %						0.012	
D 2360	Toluene content, mass %			99.82			0.37	
D 5441*	ETBE content, mass %						96.35	
	Methanol content, mass %						0.01	
	Ethanol content, mass %						0.09	
D 850	Distillation range, °C			0.7	0.5			
	50% recovered, °C			110.6	169.0			
D 86	Distillation, % evaporated, °C							
	IBP	38.5	95.5					
	5	64.0	98.0					
	10	75.5	98.0					
	20	87.0	98.5					
	30	92.0	99.0					
	40	95.5	99.5					
	50	98.0	100.0			203-4 (lit.)		28.0 (lit.)
	60	100.5	100.5					
	70	103.5	101.5					
	80	106.0	103.0					
	90	111.5	110.5					
	95	122.0	164.0					
	End	144.0	187.0					
	Recovery	98.5	99.0					
	Residue	0.9	0.7					
	Loss	0.6	0.3					

* ETBE analysis conducted by test method ASTM D 5441 (MTBE gas chromatography method), but calibrated for impurities typical of ETBE.

Suppliers:	Conoco-Phillips	FAA Tech Center/Dixie	FAA Tech Center	BP Oil	Exxon-Mobil	FAA Tech Center	FAA Tech Center

EXHIBIT III

Composition and Densities of Super Alkylate Batches

Super Alkylate Batch Recipe

92.6 mass % *iso*-octane =	93.11 vol %
7.4 mass % *iso*-dodecane =	6.89 vol %

For each drum of super alkylate, 313 pounds net:

iso-octane	289.75 lbs.	(92.57 mass %)
iso-dodecane	23.25 lbs.	(7.43 mass %)

Batch No.	Density (15.56 °C)
1	0.6994
2	0.6994
3	0.6994
4	0.6994
5	0.6994
6	0.6994
7	0.6994
8	0.6994
9	0.6994
10	0.6994

Suppliers: *iso*-octane - FAA Technical Center
iso-dodecane - Dixie Services

EXHIBIT IV

Actual Composition (Mass Fraction) of Phase III Fuel Blends

Blend	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane
1	0.3904	0.0000	0.0000	0.2316	0.0408	0.2955	0.0417
2	0.2393	0.2427	0.1137	0.2137	0.1504	0.0000	0.0402
3	0.0000	0.2020	0.1795	0.1486	0.1503	0.2805	0.0392
4	0.5445	0.0157	0.0148	0.2277	0.1562	0.0000	0.0410
5	0.0000	0.4557	0.0955	0.1780	0.1076	0.1224	0.0408
6	0.1177	0.4577	0.0000	0.2276	0.1561	0.0000	0.0410
7	0.1570	0.4738	0.0126	0.1182	0.0884	0.1074	0.0424
8	0.3904	0.2687	0.0000	0.0424	0.1614	0.0947	0.0424
9	0.0000	0.3639	0.1928	0.0000	0.1091	0.2932	0.0410
10	0.2300	0.2194	0.0684	0.0000	0.1421	0.2984	0.0417
11	0.1576	0.2033	0.2280	0.0343	0.0396	0.2958	0.0414
12	0.0009	0.4683	0.1249	0.0865	0.0410	0.2364	0.0419
13	0.5647	0.0416	0.0127	0.1231	0.0878	0.1276	0.0425
14	0.2937	0.0000	0.2243	0.0000	0.1533	0.2877	0.0411
15	0.0947	0.4646	0.1053	0.0080	0.1584	0.1274	0.0416
16	0.2731	0.3692	0.1726	0.0374	0.1059	0.0000	0.0418
17	0.0862	0.4812	0.0000	0.0000	0.0816	0.3080	0.0431
18	0.5000	0.0000	0.1151	0.2293	0.0510	0.0633	0.0413
19	0.5778	0.0000	0.0389	0.0000	0.0417	0.2981	0.0435
20	0.3557	0.0000	0.0000	0.1557	0.1557	0.2922	0.0409
21	0.0000	0.3939	0.0000	0.1153	0.1563	0.2934	0.0410
22	0.0940	0.4700	0.2346	0.0000	0.0403	0.1191	0.0421
23	0.5657	0.0000	0.0000	0.0000	0.1460	0.2457	0.0426
24	0.1707	0.2088	0.0234	0.2262	0.1153	0.2149	0.0407
25	0.1551	0.4679	0.0936	0.2014	0.0401	0.0000	0.0419
26	0.4054	0.0138	0.1331	0.1029	0.1547	0.1495	0.0406
27	0.2731	0.3692	0.1726	0.0374	0.1059	0.0000	0.0418
28	0.1177	0.4577	0.0000	0.2276	0.1561	0.0000	0.0410
29	0.4125	0.2473	0.0036	0.2319	0.0469	0.0153	0.0424
30	0.5596	0.0984	0.1616	0.0957	0.0406	0.0018	0.0424
31	0.0264	0.4468	0.2230	0.1115	0.1523	0.0000	0.0400
32	0.3651	0.3105	0.0813	0.0000	0.0416	0.1580	0.0434
33	0.4902	0.0204	0.2211	0.0000	0.0782	0.1483	0.0417
34	0.3157	0.0000	0.2217	0.1191	0.0391	0.2635	0.0409
35	0.5552	0.0934	0.1441	0.0000	0.1593	0.0062	0.0418
36	0.2731	0.3692	0.1726	0.0374	0.1059	0.0000	0.0418
37	0.5445	0.0157	0.0148	0.2277	0.1562	0.0000	0.0410
38	0.0000	0.2907	0.1133	0.2258	0.0389	0.2907	0.0407
39	0.2294	0.2457	0.0190	0.1192	0.0407	0.3035	0.0425
40	0.0000	0.4671	0.0000	0.2322	0.0400	0.2189	0.0418
41	0.1700	0.2575	0.2249	0.0361	0.1536	0.1176	0.0403
42	0.3682	0.0000	0.1125	0.0896	0.0931	0.2953	0.0413
43	0.4974	0.0000	0.2259	0.1129	0.1233	0.0000	0.0405
44	0.2383	0.0000	0.1111	0.2214	0.1162	0.2731	0.0399
45	0.1943	0.2735	0.2178	0.1237	0.0627	0.0871	0.0409
46	0.0000	0.7983	0.0000	0.1229	0.0000	0.0000	0.0788
47	0.0000	0.4574	0.0000	0.1779	0.0000	0.3049	0.0599

EXHIBIT V

Actual Composition (Volume Fraction) of Phase III Fuel Blends

Blend	Aviation Alkylate	Super Alkylate	Toluene	*tert*-Butyl Benzene	*meta*-Toluidine	ETBE	*iso*-Pentane
1	0.4224	0.0000	0.0000	0.1995	0.0308	0.2973	0.0501
2	0.2689	0.2702	0.1016	0.1912	0.1180	0.0000	0.0501
3	0.0000	0.2299	0.1640	0.1359	0.1205	0.2997	0.0500
4	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501
5	0.0000	0.4998	0.0841	0.1569	0.0832	0.1260	0.0501
6	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.0502
7	0.1672	0.4997	0.0107	0.1002	0.0657	0.1063	0.0501
8	0.4162	0.2837	0.0000	0.0360	0.1201	0.0939	0.0501
9	0.0000	0.3969	0.1689	0.0000	0.0838	0.3002	0.0501
10	0.2487	0.2350	0.0588	0.0000	0.1073	0.3001	0.0501
11	0.1720	0.2198	0.1979	0.0298	0.0302	0.3002	0.0501
12	0.0010	0.4999	0.1071	0.0742	0.0309	0.2369	0.0501
13	0.6000	0.0438	0.0107	0.1041	0.0651	0.1261	0.0502
14	0.3291	0.0000	0.2000	0.0000	0.1199	0.2998	0.0511
15	0.1029	0.5001	0.0910	0.0069	0.1202	0.1288	0.0502
16	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501
17	0.0903	0.4997	0.0000	0.0000	0.0597	0.3002	0.0501
18	0.5468	0.0000	0.1001	0.1997	0.0389	0.0643	0.0501
19	0.5998	0.0000	0.0321	0.0000	0.0302	0.2878	0.0501
20	0.3929	0.0000	0.0000	0.1369	0.1200	0.3001	0.0501
21	0.0000	0.4290	0.0000	0.1009	0.1200	0.3000	0.0501
22	0.1009	0.4997	0.2003	0.0000	0.0302	0.1188	0.0501
23	0.5997	0.0000	0.0000	0.0000	0.1080	0.2422	0.0501
24	0.1893	0.2294	0.0206	0.1997	0.0892	0.2216	0.0501
25	0.1671	0.4995	0.0802	0.1728	0.0302	0.0000	0.0501
26	0.4509	0.0152	0.1178	0.0911	0.1201	0.1547	0.0501
27	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501
28	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.0502
29	0.4392	0.2609	0.0031	0.1967	0.0349	0.0152	0.0501
30	0.5960	0.1038	0.1369	0.0811	0.0302	0.0018	0.0501
31	0.0298	0.4996	0.2002	0.1002	0.1200	0.0000	0.0501
32	0.3797	0.3199	0.0673	0.0000	0.0302	0.1528	0.0501
33	0.5299	0.0219	0.1901	0.0000	0.0590	0.1491	0.0501
34	0.3489	0.0000	0.1950	0.1049	0.0302	0.2709	0.0501
35	0.5997	0.1000	0.1239	0.0000	0.1201	0.0063	0.0501
36	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501
37	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501
38	0.0000	0.3198	0.1001	0.1997	0.0302	0.3002	0.0501
39	0.2439	0.2588	0.0160	0.1009	0.0302	0.3001	0.0501
40	0.0000	0.5000	0.0000	0.1998	0.0302	0.2199	0.0501
41	0.1901	0.2853	0.2001	0.0321	0.1200	0.1223	0.0501
42	0.4026	0.0000	0.0978	0.0780	0.0711	0.3003	0.0501
43	0.5539	0.0000	0.2001	0.1001	0.0958	0.0000	0.0501
44	0.2701	0.0000	0.1002	0.1998	0.0919	0.2879	0.0501
45	0.2141	0.2987	0.1910	0.1086	0.0483	0.0893	0.0501
46	0.0000	0.8102	0.0000	0.1002	0.0000	0.0000	0.0896
47	0.0000	0.4796	0.0000	0.1499	0.0000	0.3002	0.0704

EXHIBIT VI

Test Results and Elemental Compositions

Blend	MON	Density, g/mL 15.56 °C	Vapor Pressure, psi	Elemental Composition (mass fraction) Carbon	Hydrogen	Nitrogen	Oxygen
1	99.7	0.7501		0.8110	0.1374	0.0053	0.0463
2	104.8	0.7792		0.8521	0.1282	0.0197	0.0000
3	105.3	0.7996	3.17	0.8151	0.1213	0.0196	0.0439
4	103.9	0.7640		0.8455	0.1341	0.0204	0.0000
5	104.1	0.7687	2.88	0.8347	0.1321	0.0141	0.0192
6	106.0	0.7648		0.8445	0.1351	0.0204	0.0000
7	103.4	0.7388		0.8288	0.1428	0.0116	0.0168
8	105.0	0.7400		0.8214	0.1427	0.0211	0.0148
9	102.5	0.7625		0.8088	0.1311	0.0143	0.0459
10	103.9	0.7511		0.7973	0.1374	0.0186	0.0467
11	99.8	0.7572		0.8167	0.1318	0.0052	0.0463
12	101.1	0.7473		0.8202	0.1375	0.0054	0.0370
13	101.2	0.7376	5.24	0.8263	0.1423	0.0115	0.0200
14	104.0	0.7799		0.8092	0.1257	0.0200	0.0450
15	106.3	0.7551		0.8228	0.1366	0.0207	0.0200
16	102.8	0.7480		0.8494	0.1367	0.0138	0.0000
17	102.7	0.7281		0.7946	0.1465	0.0107	0.0482
18	99.6	0.7588		0.8501	0.1334	0.0067	0.0099
19	97.6	0.7197	5.77	0.8010	0.1469	0.0054	0.0467
20	104.2	0.7688		0.8008	0.1331	0.0203	0.0458
21	106.2	0.7654		0.7985	0.1351	0.0204	0.0460
22	100.5	0.7445		0.8394	0.1367	0.0053	0.0186
23	103.0	0.7373	5.64	0.7994	0.1430	0.0191	0.0385
24	103.3	0.7706		0.8191	0.1322	0.0151	0.0337
25	101.0	0.7476		0.8563	0.1384	0.0052	0.0000
26	104.0	0.7732		0.8270	0.1294	0.0202	0.0234
27	102.7	0.7484		0.8494	0.1367	0.0138	0.0000
28	106.0	0.7654		0.8445	0.1351	0.0204	0.0000
29	100.2	0.7387		0.8491	0.1424	0.0061	0.0024
30	97.6	0.7391		0.8552	0.1392	0.0053	0.0003
31	105.6	0.7824		0.8543	0.1257	0.0199	0.0000
32	98.8	0.7208		0.8231	0.1467	0.0054	0.0247
33	101.1	0.7497		0.8322	0.1343	0.0102	0.0232
34	98.8	0.7677		0.8252	0.1285	0.0051	0.0413
35	103.8	0.7491		0.8415	0.1367	0.0208	0.0010
36	103.0	0.7482		0.8494	0.1367	0.0138	0.0000
37	104.1	0.7642		0.8455	0.1341	0.0204	0.0000
38	100.6	0.7719		0.8195	0.1299	0.0051	0.0455
39	100.4	0.7374		0.8052	0.1419	0.0053	0.0475
40	102.0	0.7500	3.22	0.8215	0.1390	0.0052	0.0343
41	104.8	0.7771		0.8343	0.1272	0.0201	0.0184
42	101.5	0.7604		0.8084	0.1332	0.0122	0.0462
43	102.6	0.7722		0.8562	0.1276	0.0161	0.0000
44	102.9	0.7896		0.8171	0.1250	0.0152	0.0428
45	101.1	0.7653		0.8478	0.1303	0.0082	0.0136
46	98.2	0.7115	3.56	0.8475	0.1525	0.0000	0.0000
47	99.8	0.7347	4.05	0.8090	0.1432	0.0000	0.0477

APPENDIX C
STATISTICAL ANALYSIS
MON TEST RESULTS
PRESENTATION GIVEN AT SAE
GENERAL AVIATION CONFERENCE
APRIL 17, 2002

CRC Research Results Toward Development of Unleaded High Octane Aviation Gasoline

Fred Cornforth and Gary Hatfield, Phillips Petroleum Co.
Mical Renz, Dixie Services

Presentation for
SAE General Aviation Technology Conference and Exhibition
Wichita, Kansas April 17, 2002

Talk Outline

- CRC ULAvgas Working Group and the Work Charge
- Designed Experiments and this Design
- Results of this Experiment
- Next Steps

CRC Unleaded AVGAS Development Group

- Objective: conduct research and testing to facilitate development of a Hi Octane UL Avgas replacement for 100LL
- Industry activities launched in early 1990's, evolved into a major research initiative
- Today
  - 60 Members, > 30 organizations
  - Engine & airframe manufacturers, fuel producers, FAA, AOPA, EAA, GAMA, and other interested parties
- Incentive - GA fleet > 200,000 aircraft, many need Hi Octane
- Parallel activities include FAA sponsored research and company proprietary programs
- Much testing remains, including engine evaluation tests, elastomer compatibility, durability testing, service testing, and ultimately certification

Primary Matrix
CRC Unleaded AVGAS Development Group
Technically Viable (Octane) Base Fuels & Additives
September 7, 2000

Additive	(A) Aviation Alkylate	(B) Motor Alkylate*	(C) Super Alkylate	(D) Ethanol	(E) ETBE	Test Method
1) Super Alkylate	0 – 50% (vol)	0 – 50% (vol)	N/A	N/A	N/A	Deferred
2) Toluene	0 – 25 % (vol)	0 – 25% (vol)	0 – 25% (vol)	N/A	N/A	Deferred
3) ETBE	0 – 30% (vol)	0 – 30% (vol)	0 – 30% (vol)	N/A	N/A	Deferred
4) M-Toluidine*	0 – 10% (wgt)	0 – 10% (wgt)	0 – 10% (wgt)	N/A	N/A	Deferred
5) Ethanol *	0 – 5% (vol)	0 – 5% (vol)	0 – 5% (vol)	N/A	N/A	Deferred
6) MMT*	0 – 0.1 g/gal	0 – 0.1 g/gal	0 – 0.1 g/gal	N/A	N/A	Deferred
7) Isopentane	N/A	N/A	N/A	0 – 15% (vol)	N/A	Deferred
8) N-Butane	0 – 10% (vol)	0 – 10% (vol)	0 – 10% (vol)	N/A	0 – 5% (vol)	Deferred
9) Bio-Diesel	N/A	N/A	N/A	0 – 1% (vol)	N/A	Deferred

Notes: 1) * indicates non-consensus
2) Test method – MON, supercharge, full engine or other

MON Test Matrix
CRC Unleaded AVGAS Development Group
November 8, 2000

Additive	Base Fuel (A) Aviation Alkylate	(B) Motor Alkylate	(C) Super Alkylate
Super Alkylate	0 – 50% (vol)	0 – 50% (vol)	N/A
Toluene	0 – 25 % (vol)	0 – 25% (vol)	0 – 25% (vol)
ETBE	0 – 30% (vol)	0 – 30% (vol)	0 – 30% (vol)
M-Toluidine	0 – 10% (wgt)	0 – 10% (wgt)	0 – 10% (wgt)
Ethanol	0 – 5% (vol)	0 – 5% (vol)	0 – 5% (vol)
MMT	0 – 0.1 gMn/gal	0 – 0.1 gMn/gal	0 – 0.1 gMn/gal

Notes: 1) The above matrix was developed during November 8, 2000 Working Group Meeting
2) Test method – MON screening. Collaborative industry program.
3) Participants – Dixie Services, Phillips, Texaco, Ethyl, Exxon, Cessna, Chevron, & FAA Tech Center

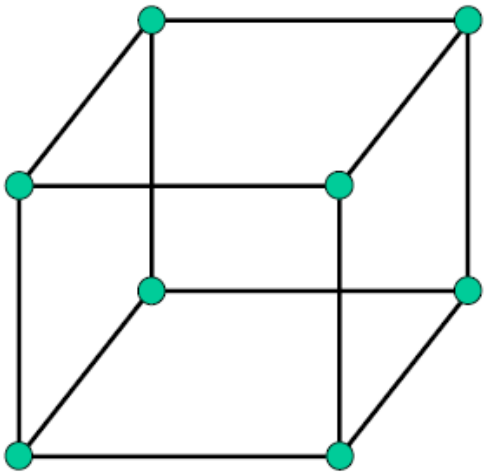
Acknowledgements

WILLIAM J. HUGHES TECHNICAL CENTER

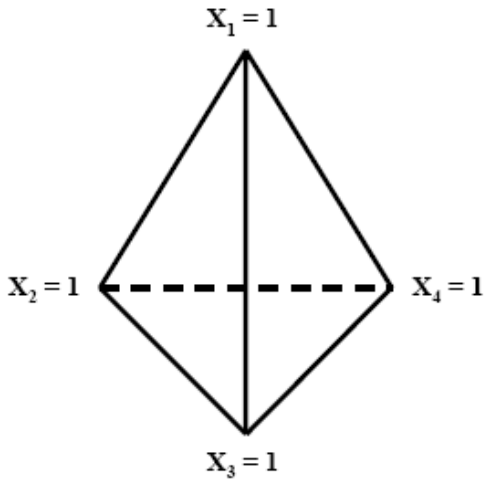
CRC UL AVGAS TASK GROUP

Atwood, Dave	FAA Tech Center
Byrnes, Skip	FAA Tech Center
Cornforth, Fred	Phillips Petroleum Co.
Gaughan, Roger	Exxon/Mobil
Giacobbe, Glen	Lyondell Chemical Co.
Gonzalez, Cesar	Cessna Aircraft
Hemighaus, Greg	Chevron Products Co.
Henderson, Doug	Ethyl Corporation
Renz, Mical	Dixie Services Inc.
Thompson, Randy	Phillips Petroleum
Valentine, Joe	Chevron Texaco Additives
Williams, Mark	Ultramar Diamond Shamrock
Wilkinson, Ron	Group Leader

Cubic Design for Independent Variables



Tetrahedron for Four Mixture Variables



MON Test Matrix
CRC Unleaded AVGAS Development Group
November 8, 2000

	Base Fuel		
Additive	(A) Aviation Alkylate	(B) Motor Alkylate	(C) Super Alkylate
Super Alkylate	0 – 50% (vol)	0 – 50% (vol)	N/A
Toluene	0 – 25 % (vol)	0 – 25% (vol)	0 – 25% (vol)
ETBE	0 – 30% (vol)	0 – 30% (vol)	0 – 30% (vol)
M-Toluidine	0 – 10% (vol)	0 – 10% vol)	0 – 10% (vol)
Ethanol	0 – 5% (vol)	0 – 5% (vol)	0 – 5% (vol)
MMT	0 – 0.1 gMn/gal	0 – 0.1 gMn/gal	0 – 0.1 gMn/gal

Notes: 1) The above matrix was developed during November 8, 2000 Working Group Meeting
2) Test method – MON screening. Collaborative industry program.
3) Participants – Dixie Services, Phillips, Texaco, Ethyl, Exxon, Cessna, Chevron, & FAA Tech Center

Program Used for Experimental Design

- Gosset used to develop I-optimal designs
  - Aviation Alkylate and Motor Alkylate Matrices
    - 7 variables, 75 mixtures including replicates
  - Super Alkylate Matrix
    - 6 variables, 52 mixtures including replicates
  - MMT treated as Process Variable

I-optimal designs minimize the average prediction variance

1/2 of Super Alkylate Design Showing Replicates

Super Alkylate	Toluene	ETBE	M-Toluidine	Ethanol	MMT	
0.350	0.250	0.300	0.100	0.000	0.000	
0.607	0.083	0.288	0.000	0.023	0.075	
0.700	0.000	0.300	0.000	0.000	0.000	
0.773	0.128	0.000	0.100	0.000	0.000	
0.482	0.208	0.187	0.085	0.038	0.000	
0.828	0.055	0.025	0.079	0.013	0.100	Duplicate
0.600	0.250	0.000	0.100	0.050	0.100	
0.650	0.125	0.150	0.050	0.025	0.050	Center point
0.810	0.156	0.000	0.017	0.017	0.052	
0.718	0.172	0.081	0.020	0.008	0.000	
0.965	0.000	0.000	0.035	0.000	0.017	
0.659	0.059	0.228	0.055	0.000	0.044	
0.438	0.146	0.300	0.100	0.017	0.049	Duplicate
0.774	0.000	0.196	0.018	0.012	0.100	
0.937	0.000	0.032	0.000	0.032	0.031	
0.650	0.238	0.056	0.057	0.000	0.054	
0.493	0.186	0.300	0.021	0.000	0.099	
0.600	0.000	0.300	0.100	0.000	0.100	
0.630	0.250	0.068	0.018	0.034	0.100	
0.710	0.185	0.000	0.067	0.039	0.055	
0.463	0.127	0.299	0.060	0.050	0.095	
0.804	0.053	0.052	0.056	0.036	0.000	
0.650	0.125	0.150	0.050	0.025	0.050	Center point
0.550	0.000	0.300	0.100	0.050	0.000	Duplicate
0.561	0.115	0.242	0.073	0.009	0.000	
0.531	0.250	0.210	0.000	0.009	0.033	Duplicate

Modeling of Data

- Statistica used to analyze data
- Multiple Regression to fit all mixture and mixture*process variable terms
- Forward Stepwise option used to develop parsimonious models
- Models similar for all matrices

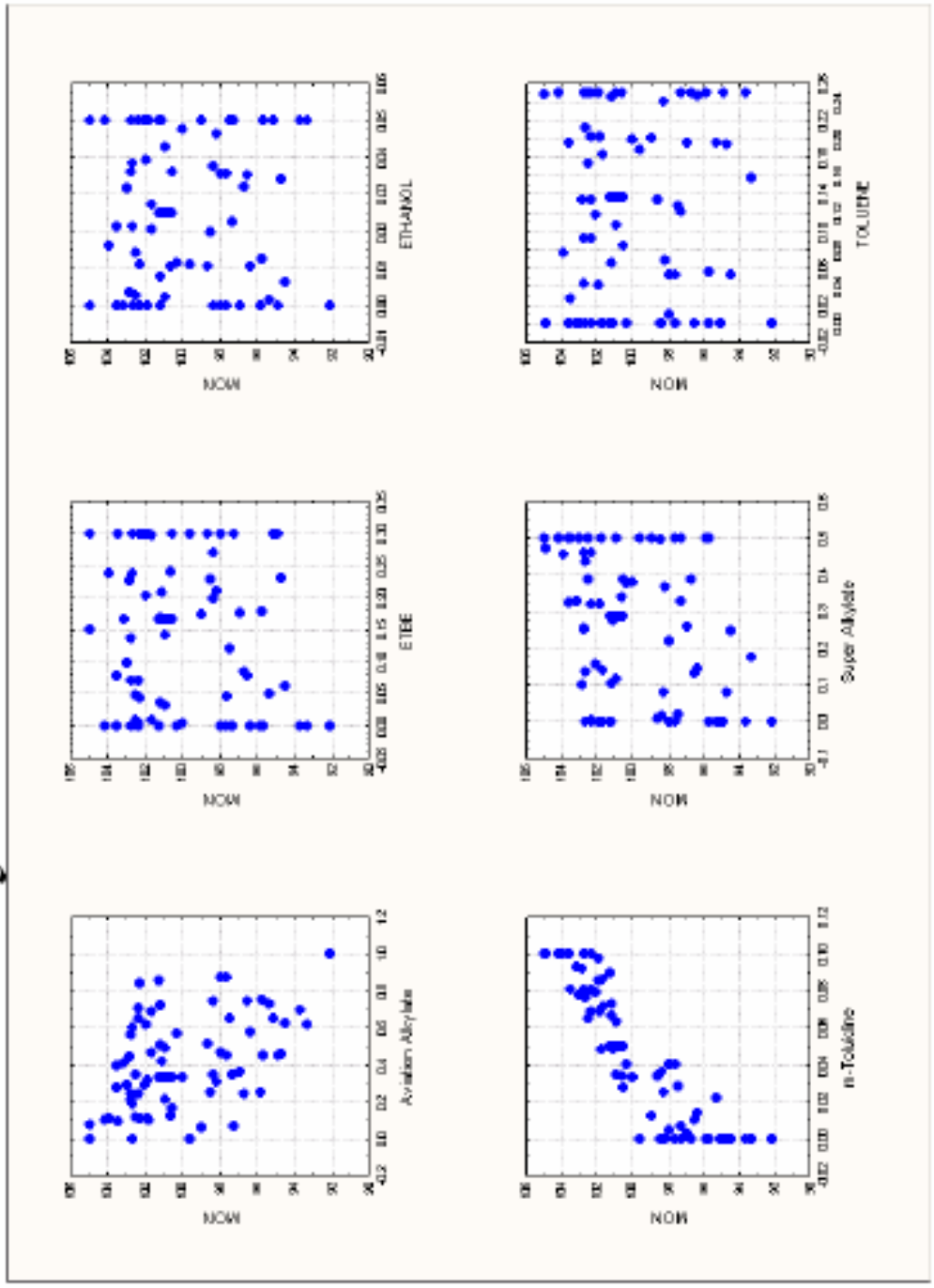
Coefficients for Regression Models

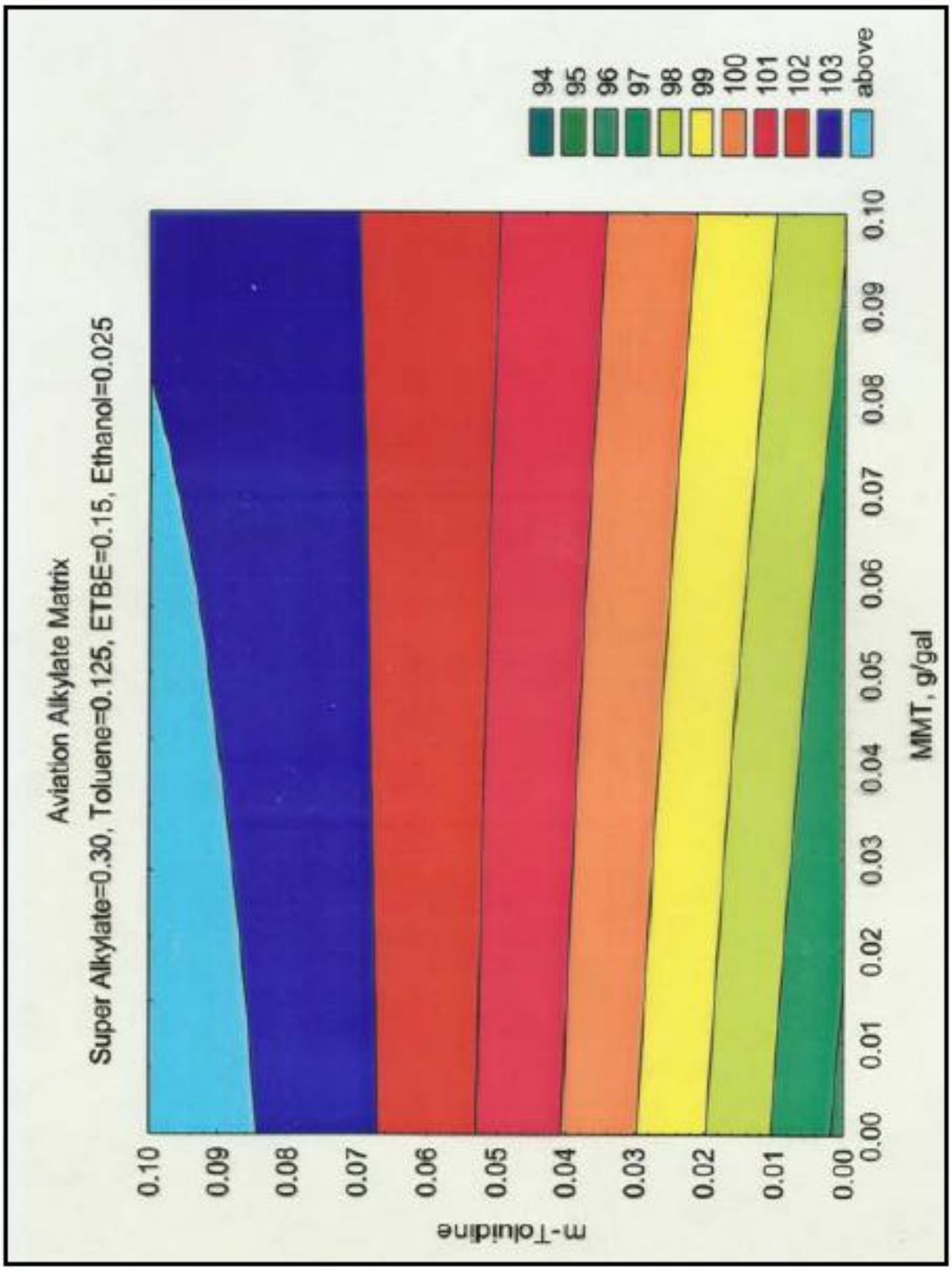
Variable	Matrix		
	Aviation Alkylate	Super Alkylate	Motor Alkylate
Aviation Alkylate (AvAlky)	92.000	N/A	N/A
Super Alkylate (SupAlky)	99.499	100.480	99.702
Motor Alkylate (MoAlky)	N/A	N/A	91.367
Toluene	92.697	94.428	92.340
ETBE	101.131	100.646	101.393
M-Toluidine (mToluidine)	-195.428	151.466	-166.555
Ethanol	95.240	94.269	95.701
MMT*AvAlky	21.138	N/A	N/A
MMT*SupAlky	13.653	7.437	14.244
MMT*MoAlky	N/A	N/A	21.810
MMT*Toluene			
MMT*ETBE			
MMT*MToluidine	-184.508	-123.838	-187.174
MMT*Ethanol			
AvAlky*MToluidine	434.984	N/A	N/A
SupAlky*MToluidine	393.428		359.464
MoAlky*MToluidine	N/A	N/A	402.424
Toluene*MToluidine	441.069	36.398	407.982
ETBE*MToluidine	357.427	-21.965	328.772
Ethanol*MToluidine	353.224		302.538

Goodness of Fit Statistics

Statistic	Matrix		
	Aviation Alkylate	Super Alkylate	Motor Alkylate
R^2	0.99999	0.99999	0.99999
Adjusted R^2	0.99999	0.99999	0.99999
Standard Deviation of Residuals	0.3567	0.2996	0.2922
Standard Deviation of Replicates	0.2518	0.2117	0.1533

MON by Mixture Variables

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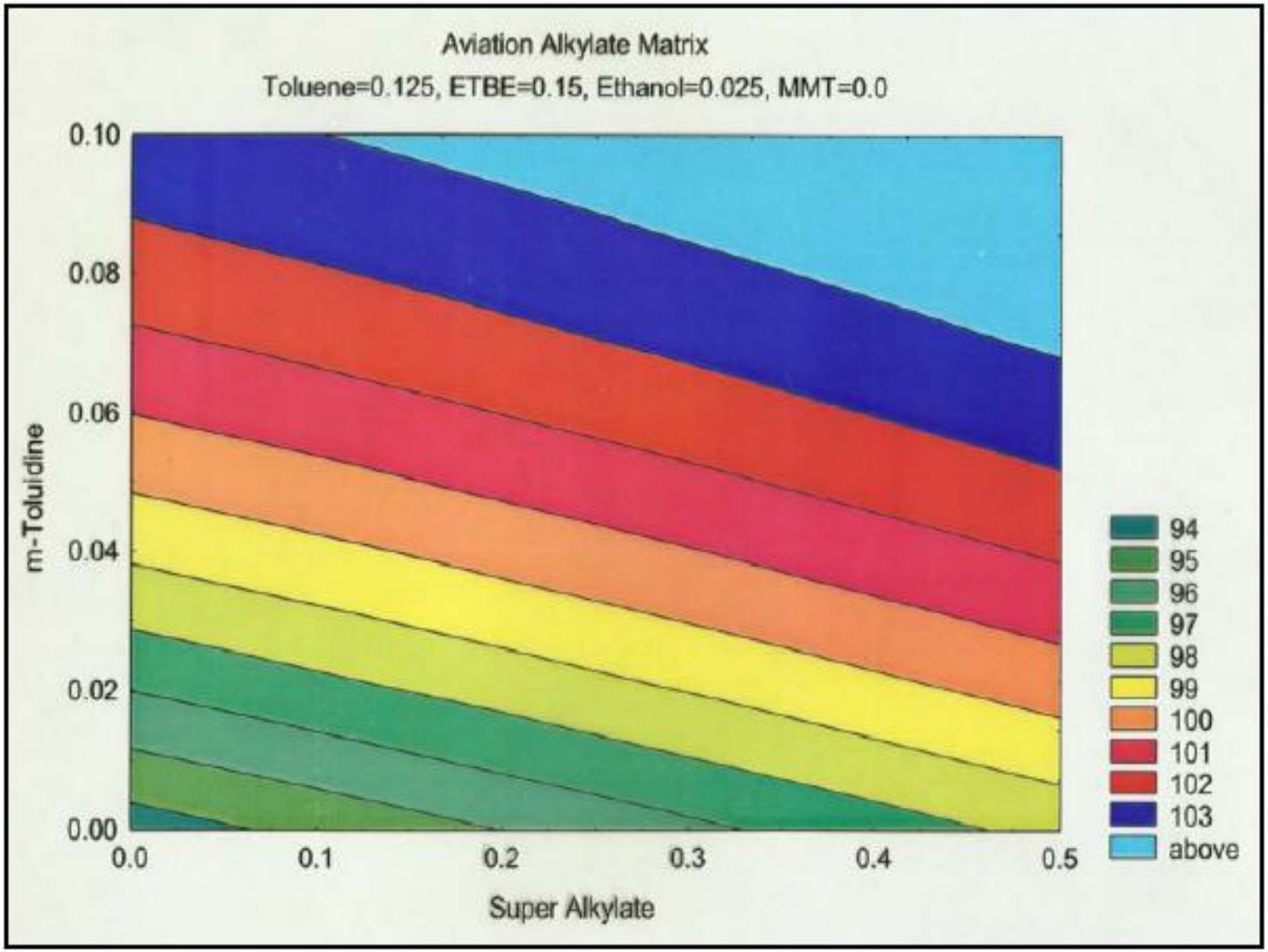
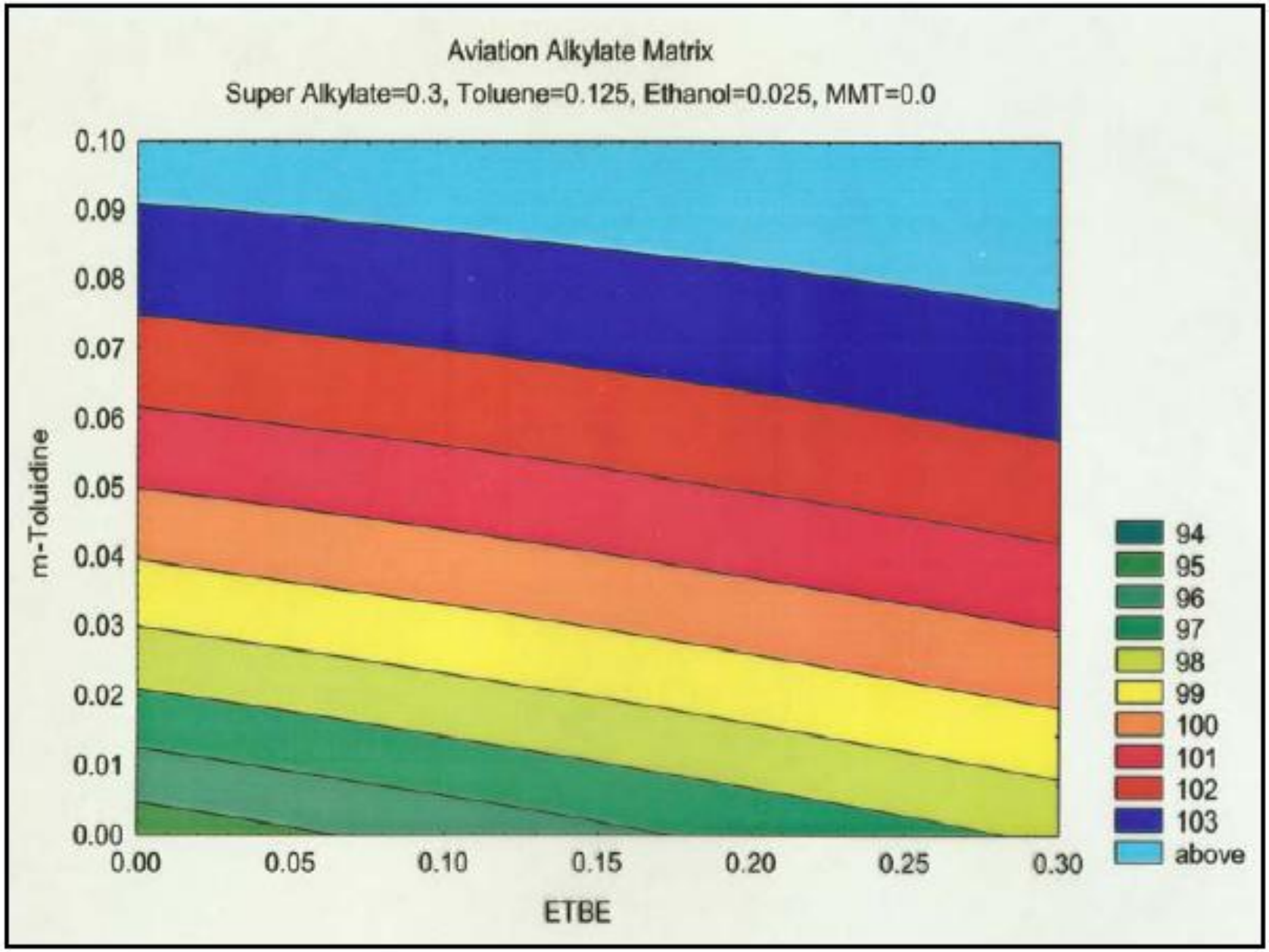
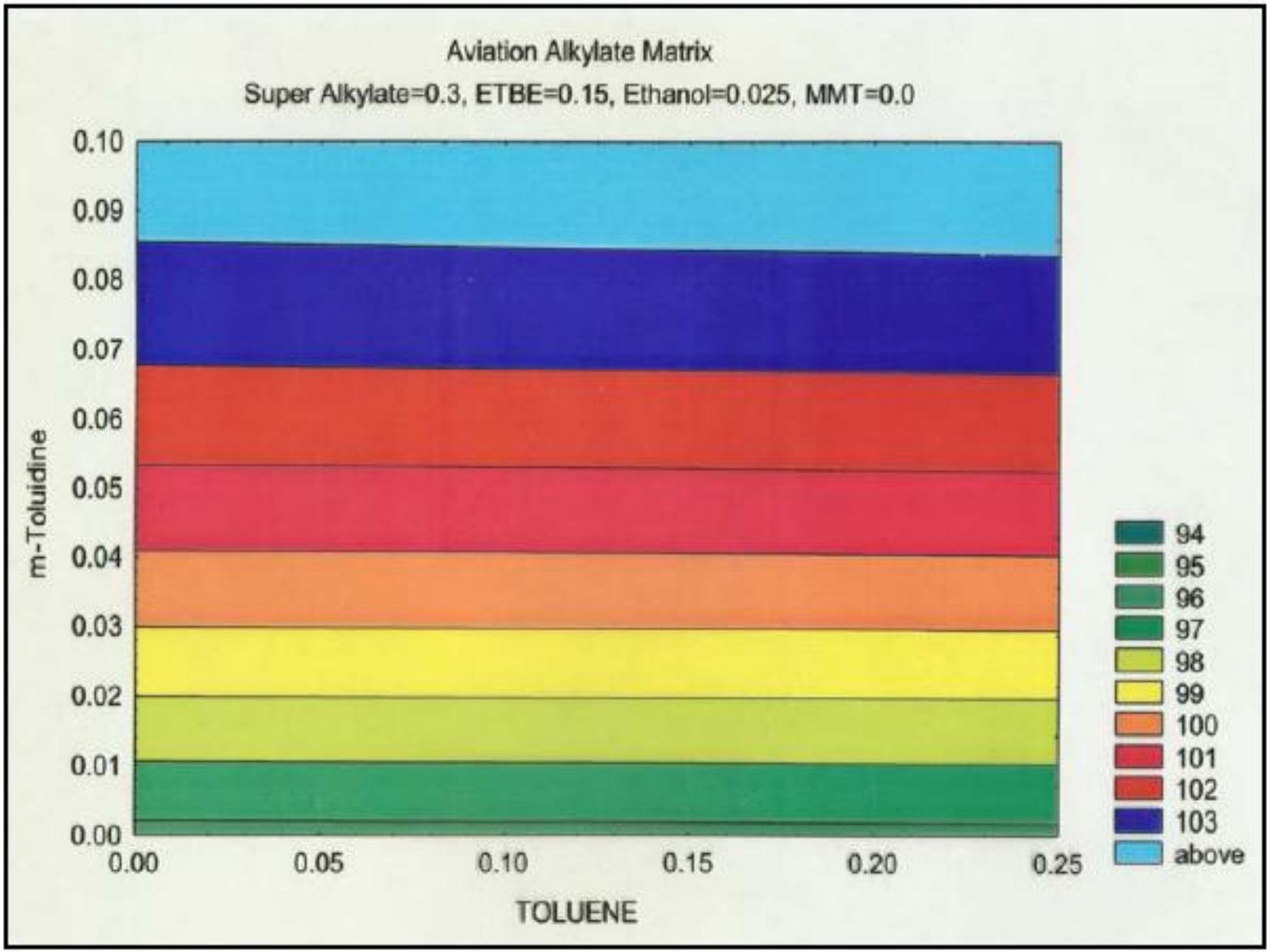
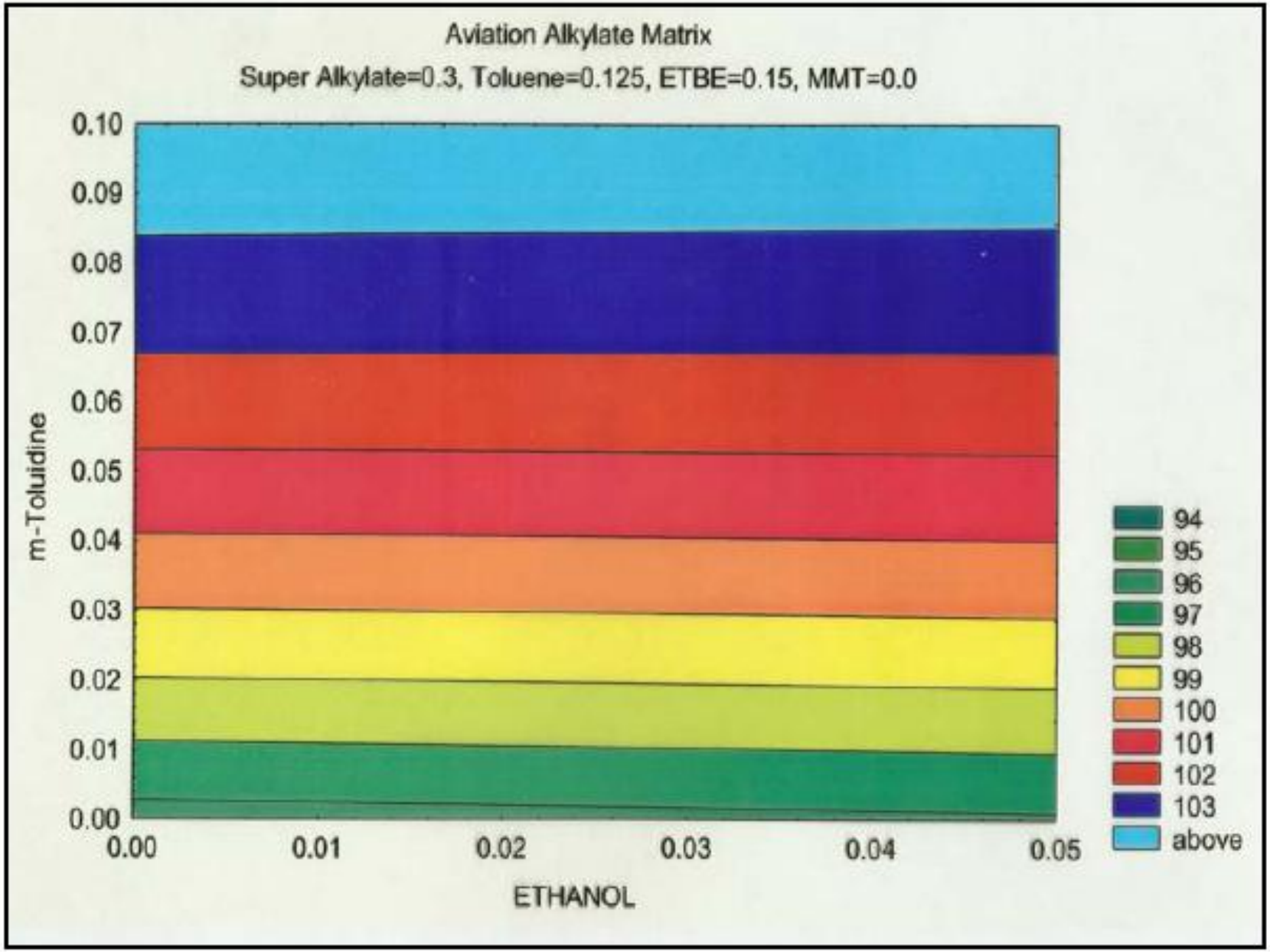
m-Toluidine
MMT, g/gal
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
94
95
96
97
98
99
100
101
102
103
above


Aviation Alkylate Matrix
Toluene=0.125, ETBE=0.15, Ethanol=0.025, MMT=0.0
m-Toluidine
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.1
0.2
0.3
0.4
0.5
Super Alkylate
94
95
96
97
98
99
100
101
102
103
above


Aviation Alkylate Matrix
Super Alkylate=0.3, Toluene=0.125, Ethanol=0.025, MMT=0.0
m-Toluidine
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.05
0.10
0.15
0.20
0.25
0.30
ETBE
94
95
96
97
98
99
100
101
102
103
above


Aviation Alkylate Matrix
Super Alkylate=0.3, ETBE=0.15, Ethanol=0.025, MMT=0.0
m-Toluidine
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.05
0.10
0.15
0.20
0.25
TOLUENE
94
95
96
97
98
99
100
101
102
103
above


Aviation Alkylate Matrix
Super Alkylate=0.3, Toluene=0.125, ETBE=0.15, MMT=0.0
m-Toluidine
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.00
0.01
0.02
0.03
0.04
0.05
ETHANOL
94
95
96
97
98
99
100
101
102
103
above

Summary of Component Effects on MON

- Effects of Components complicated by interactions
- For Alkylates Su Alky>Av Alky>Mo Alky
- M-Toluidine>ETBE>Toluene>Ethanol
- MMT ?
- Other considerations may supercede MON in final blends

APPENDIX D
TEST RESULTS
HOMOGENEITY TEMPERATURE EXPERIMENT
PHASE I BLENDS
PRESENTED AT AUGUST 30, 2001 CRC UL AVGAS MEETING

Homogeneity Temperatures for Aviation Alkylate Blends

BN	Temp	AvAlk	SuAlk	Tol	ETBE	Meta	EtOH	Mn
1	-69	0.296	0.156	0.118	0.300	0.079	0.050	0.085
2	-69	0.306	0.366	0.069	0.212	0.000	0.047	0.100
3	-69	0.514	0.008	0.134	0.300	0.034	0.011	0.041
4	-69	0.494	0.118	0.250	0.032	0.064	0.043	0.021
5	-69	0.061	0.500	0.201	0.174	0.013	0.050	0.000
6	-69	0.121	0.500	0.250	0.050	0.065	0.014	0.100
7	-69	0.250	0.500	0.250	0.000	0.000	0.000	0.000
8	-69	0.333	0.288	0.138	0.168	0.050	0.025	0.050
9	-33	0.871	0.000	0.053	0.000	0.041	0.036	0.000
10	-18	0.725	0.106	0.065	0.037	0.067	0.000	0.100
11	-69	0.444	0.100	0.134	0.227	0.092	0.004	0.000
12	-69	0.073	0.328	0.250	0.300	0.000	0.050	0.033
13	-51	0.247	0.458	0.093	0.071	0.081	0.050	0.056
14	-33	0.711	0.001	0.134	0.004	0.100	0.050	0.000
15	-69	0.210	0.251	0.250	0.139	0.100	0.050	0.100
16	-69	0.650	0.000	0.000	0.300	0.000	0.050	0.000
17	-69	0.700	0.000	0.250	0.000	0.000	0.050	0.100
18	-69	0.215	0.500	0.107	0.141	0.035	0.002	0.048
19	-69	0.336	0.378	0.200	0.005	0.033	0.048	0.100
20	-51	0.693	0.000	0.183	0.010	0.086	0.027	0.100
21	-69	0.278	0.326	0.197	0.078	0.100	0.022	0.000
22	-33	0.346	0.387	0.174	0.009	0.080	0.003	0.021
23	-69	0.333	0.288	0.138	0.168	0.050	0.025	0.050
24	-51	0.100	0.500	0.250	0.000	0.100	0.050	0.000
25	-69	0.000	0.500	0.189	0.300	0.000	0.011	0.100
26	-69	0.333	0.288	0.138	0.168	0.050	0.025	0.050
27	-69	0.244	0.389	0.250	0.085	0.000	0.032	0.040
28	-69	0.453	0.500	0.000	0.047	0.000	0.000	0.100
29	-69	0.347	0.079	0.241	0.271	0.025	0.038	0.100
30	-69	0.461	0.079	0.195	0.231	0.000	0.034	0.000
31	-33	0.292	0.500	0.000	0.099	0.078	0.032	0.000
32	0	0.574	0.375	0.000	0.000	0.040	0.012	0.045
33	-33	0.650	0.000	0.250	0.000	0.100	0.000	0.033
34	-69	0.107	0.321	0.202	0.300	0.069	0.000	0.100
35	-69	0.466	0.219	0.010	0.300	0.005	0.000	0.082
36	-69	0.253	0.497	0.000	0.230	0.000	0.020	0.027
37	-69	0.364	0.260	0.197	0.177	0.003	0.000	0.065
38	-33	0.871	0.000	0.053	0.000	0.041	0.036	0.000
39	-69	0.743	0.133	0.000	0.078	0.010	0.035	0.078
40	-69	0.652	0.021	0.127	0.121	0.029	0.050	0.052
41	-69	0.314	0.000	0.250	0.300	0.086	0.050	0.000
42	-69	0.193	0.136	0.250	0.300	0.100	0.022	0.054
43	-69	0.748	0.015	0.000	0.200	0.037	0.000	0.000
44	-69	0.450	0.000	0.250	0.300	0.000	0.000	0.000
45	-69	0.164	0.388	0.084	0.300	0.028	0.036	0.000
46	-69	0.583	0.144	0.248	0.000	0.015	0.011	0.085
47	-69	0.333	0.288	0.138	0.168	0.050	0.025	0.050
48	-69	0.753	0.000	0.056	0.178	0.000	0.013	0.100
49	-69	1.000	0.000	0.000	0.000	0.000	0.000	0.051
50	-69	0.078	0.472	0.000	0.300	0.100	0.050	0.000
51	0	0.564	0.257	0.043	0.000	0.100	0.036	0.065
52	-69	0.729	0.000	0.197	0.051	0.022	0.002	0.000
53	-69	0.333	0.288	0.138	0.168	0.050	0.025	0.050
54	-69	0.092	0.500	0.027	0.300	0.081	0.000	0.000
55	15	0.400	0.500	0.000	0.000	0.100	0.000	0.092
56	-69	0.111	0.457	0.078	0.238	0.100	0.016	0.100
57	-69	0.000	0.435	0.212	0.239	0.076	0.039	0.041
58	-69	0.101	0.500	0.000	0.300	0.049	0.050	0.100
59	-69	0.471	0.139	0.000	0.298	0.071	0.021	0.040
60	-69	0.127	0.338	0.250	0.241	0.034	0.011	0.000

Homogeneity Temperatures for Aviation Alkylate Blends

BN	Temp	AvAlk	SuAlk	Tol	ETBE	Meta	EtOH	Mn
61	-69	0.600	0.000	0.000	0.300	0.100	0.000	0.100
62	0	0.842	0.002	0.000	0.045	0.100	0.011	0.027
63	-69	0.348	0.500	0.122	0.000	0.007	0.023	0.056
64	-69	0.616	0.176	0.158	0.000	0.000	0.050	0.001
65	-69	0.000	0.500	0.250	0.151	0.100	0.000	0.015
66	0	0.860	0.000	0.000	0.000	0.090	0.050	0.100
67	-51	0.247	0.458	0.093	0.071	0.081	0.050	0.056
68	-33	0.413	0.328	0.000	0.166	0.093	0.000	0.069
69	-69	0.418	0.275	0.000	0.208	0.049	0.050	0.002
70	-69	0.505	0.000	0.245	0.169	0.073	0.008	0.078
71	-69	0.629	0.250	0.053	0.062	0.000	0.006	0.000
72	-69	0.450	0.500	0.000	0.000	0.000	0.050	0.000
73	-69	0.333	0.288	0.138	0.168	0.050	0.025	0.050
74	-69	0.618	0.000	0.042	0.203	0.097	0.039	0.054
75	-69	0.107	0.321	0.202	0.300	0.069	0.000	0.100

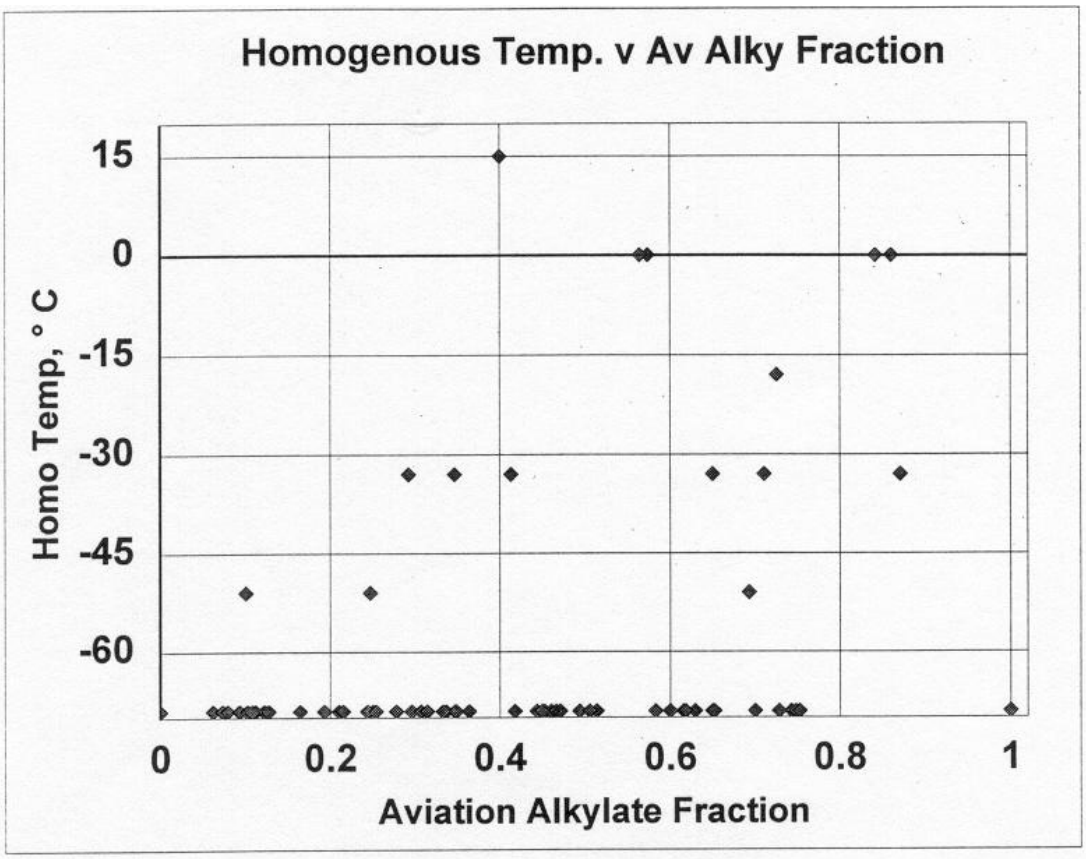
Homogeneity Temperatures of -51 °C and Higher

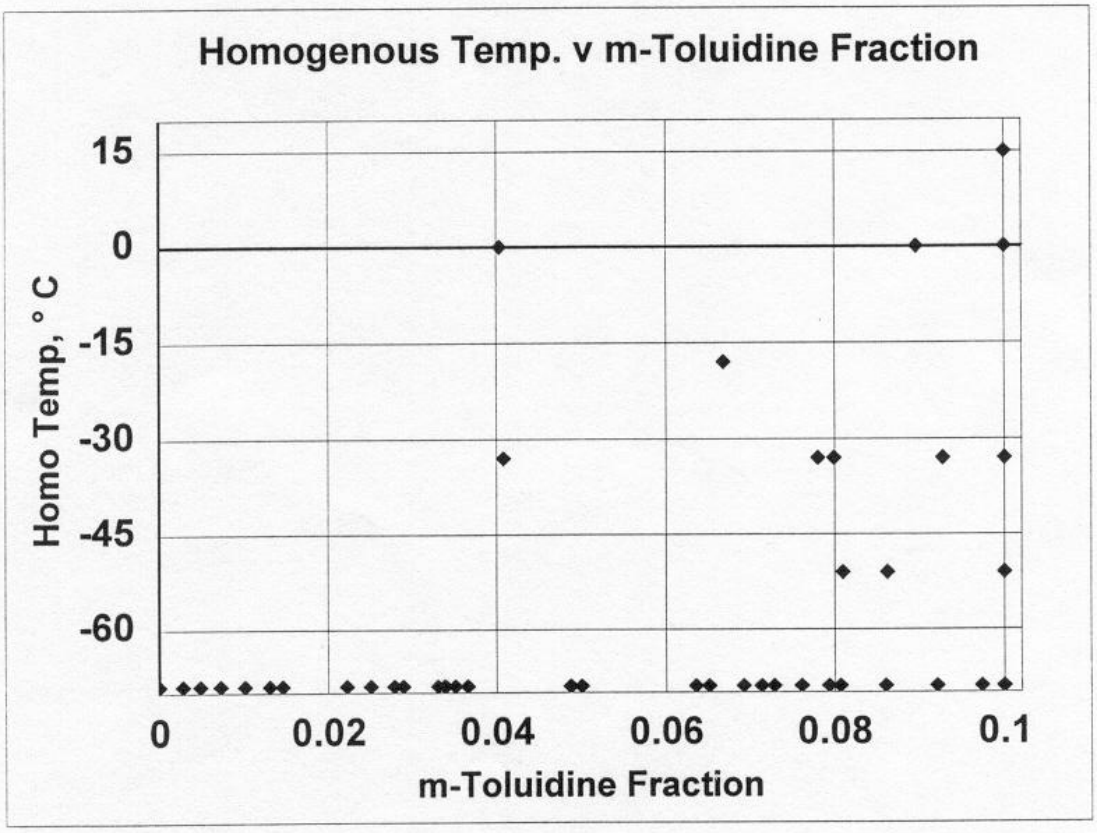
listed in order of blend number

BN	Temp	AvAlk	SuAlk	Tol	ETBE	Meta	EtOH
9	-33	0.871	0.000	0.053	0.000	0.041	0.036
10	-18	0.725	0.106	0.065	0.037	0.067	0.000
13	-51	0.247	0.458	0.093	0.071	0.081	0.050
14	-33	0.711	0.001	0.134	0.004	0.100	0.050
20	-51	0.693	0.000	0.183	0.010	0.086	0.027
22	-33	0.346	0.387	0.174	0.009	0.080	0.003
24	-51	0.100	0.500	0.250	0.000	0.100	0.050
31	-33	0.292	0.500	0.000	0.099	0.078	0.032
32	0	0.574	0.375	0.000	0.000	0.040	0.012
33	-33	0.650	0.000	0.250	0.000	0.100	0.000
38	-33	0.871	0.000	0.053	0.000	0.041	0.036
51	0	0.564	0.257	0.043	0.000	0.100	0.036
55	15	0.400	0.500	0.000	0.000	0.100	0.000
62	0	0.842	0.002	0.000	0.045	0.100	0.011
66	0	0.860	0.000	0.000	0.000	0.090	0.050
67	-51	0.247	0.458	0.093	0.071	0.081	0.050
68	-33	0.413	0.328	0.000	0.166	0.093	0.000

listed in order of decreasing homogeneity temperature

BN	Temp	AvAlk	SuAlk	Tol	ETBE	Meta	EtOH
55	15	0.400	0.500	0.000	0.000	0.100	0.000
66	0	0.860	0.000	0.000	0.000	0.090	0.050
62	0	0.842	0.002	0.000	0.045	0.100	0.011
32	0	0.574	0.375	0.000	0.000	0.040	0.012
51	0	0.564	0.257	0.043	0.000	0.100	0.036
10	-18	0.725	0.106	0.065	0.037	0.067	0.000
9	-33	0.871	0.000	0.053	0.000	0.041	0.036
38	-33	0.871	0.000	0.053	0.000	0.041	0.036
14	-33	0.711	0.001	0.134	0.004	0.100	0.050
33	-33	0.650	0.000	0.250	0.000	0.100	0.000
68	-33	0.413	0.328	0.000	0.166	0.093	0.000
22	-33	0.346	0.387	0.174	0.009	0.080	0.003
31	-33	0.292	0.500	0.000	0.099	0.078	0.032
20	-51	0.693	0.000	0.183	0.010	0.086	0.027
67	-51	0.247	0.458	0.093	0.071	0.081	0.050
13	-51	0.247	0.458	0.093	0.071	0.081	0.050
24	-51	0.100	0.500	0.250	0.000	0.100	0.050


Homogenous Temp. v Av Alky Fraction
Homo Temp, ° C
15
0
-15
-30
-45
-60
0
0.2
0.4
0.6
0.8
1
Aviation Alkylate Fraction


Homogenous Temp. v m-Toluidine Fraction
Homo Temp, ° C
15
0
-15
-30
-45
-60
0
0.02
0.04
0.06
0.08
0.1
m-Toluidine Fraction

APPENDIX E
UNPUBLISHED CRC REPORT

AN INVESTIGATION INTO HIGH (100 MON) & MID (91 MON) OCTANE AVGAS DETONATION CHARACTERISTICS IN A FULL SIZE ENGINE

BY ALISDAIR Q. CLARK BSC PHD

VERSION 2.0, DATED OCTOBER 11, 2005

An Investigation into High (100 MON) and Mid (91 MON) Octane AVGAS Detonation Characteristics in a Full Size Aviation Engine Version 2.0 October 2005

Summary

The detonation (knock) characteristics of a matrix of leaded and unleaded test fuels covering high (100 MON) and mid (91 MON) octane AVGAS have been evaluated in a Lycoming IO540 engine. Under the test conditions, the high octane study demonstrated significant benefits from the presence of TEL with unleaded fuels requiring ca. +3 MON for equivalence. Accepting a 0.057 gPb/l variance between test fuels, Supercharge also showed some impact on performance. Results for the mid octane study were mixed and further work is required. Inlet air and cylinder head temperature were found to have significant influence on engine octane requirement.

1. Introduction

Spark ignition aviation piston engines rely heavily on fuel octane quality to provide high performance and knock free operation. Aviation gasoline (AVGAS) Grade 100LL currently meets this requirement. However, AVGAS 100LL contains the octane enhancement additive tetraethyl lead (TEL) and the Aviation Industry wishes to move to a viable unleaded alternative. This is a challenging program given the high quality of the current fuel. ASTM specifications for AVGAS were developed over 50 years ago and rely on the standard Industry octane tests of MON (currently ASTM D 2700) and Supercharge (ASTM D 909). The relevance of such tests and the impact of AVGAS lead content on current aviation engine performance requires evaluation. An understanding of these parameters is vital to ensure correct decisions can be taken with respect to unleaded fuels. In support of the CRC program, a matrix of fuels of different lead content, MON and Supercharge have been prepared and evaluated by the FAA in a full size engine. Air BP contributed 5 fuel formulations to the program covering both high and mid octane AVGAS. Additional fuels were supplied by ExxonMobil, Cessna and Phillips. Studies focused on the following areas:

(1) To determine if leaded and unleaded fuels can be successfully compared in a full size aviation engine with the minimum of hysterisis.
(2) To evaluate the effect of lead content, MON and Supercharge on high octane (100 MON) AVGAS performance.
(3) To evaluate the effect of lead content and MON on mid octane (91 MON) AVGAS performance.

This report details the program, results and conclusions.

2. Test Facility

A full size Lycoming IO540 fuel injected, normally aspirated aviation engine installed at the FAA Technical Center in Atlantic City USA, was utilized for the test program. The engine configuration is representative of a large proportion of current performance engines used in General Aviation and is known to be octane sensitive. The installation is well documented and features advanced instrumentation to ensure conditions are suitably severe and repeatable. Two different systems for knock detection, operating in parallel, are utilized:

- Pressure Transducer
  A direct method utilizing cylinder pressure measurements.
- Force Transducer
  An indirect method utilizing relief of spark plug force on a washer.

Reference to both systems is made within this report but no statistical analysis to correlate measurements between each system has been performed.

3. Fuels

9 fuels were supplied:

• High Octane Study	
- Leaded 100/130 Base-line AVGAS	Cessna (ex. Phillips)
- Leaded 100/100 AVGAS	BP
- Unleaded 100 MON Amine AVGAS	ExxonMobil
- Unleaded 104 MON Amine AVGAS	ExxonMobil
- Unleaded Iso-octane primary reference fuel	Phillips
• Mid Octane Study	
- Leaded 91/98 Base-line AVGAS	BP
- Unleaded 91/98 AVGAS	BP
- Unleaded 93 MON AVGAS	BP
- Unleaded 95 MON AVGAS	BP

Fuel properties are provided in Tables 1 and 2. The two base-line leaded AVGAS blends were formulated to represent as closely as possible the minimum octane quality permissible by ASTM D 910. Survey data suggests market AVGAS is generally of far higher quality than the minimum specification. No metal additives, such as Methylcyclopentadienyl Manganese Tricarbonyl (MMT), were used in the unleaded formulations.

Table 1: High Octane Study Test Fuels

	Units	Iso-Octane	W02/575	100LL	100 Amine	104 Amine
Description		Unleaded 100/100 PRF *	Leaded 100/100	Leaded 100/130 Base-line	Unleaded 100 Amine	Unleaded 104 Amine
MON		100.0	100.0	100.3	100	104
Supercharge		100.0	99	131.5	>161	>161
Lead	gPb/liter	0.00	0.501	0.568		
D1319 FIA Aromatics	% v/v	0.0	0.3	12.0		
D1319 FIA Olefins	% v/v	0.0	0.3	0.8		
D1319 FIA Saturates	% v/v	100.0	99.4	87.2		
D3338 Specific Energy	MJ/kg	44.345	44.533	43.659		
D381 Existent Gum (Air)	mg/100ml	-	0	-		
IP365 Composite Density	kg/m3	694.0	684.5	720.2		
D86 Initial Boiling Point	Deg C	99.2	36.3	-		
D86 Final Boiling Point	Deg C	99.2	110.5	-		
D86 Loss	% v/v	-	0.6	-		
D86 Recovery	% v/v	-	98.7	-		
D86 Residue	% v/v	-	0.7	-		
D86 10% Evaporated	Deg C	-	68.6	-		
D86 40% Evaporated	Deg C	-	92.4	-		
D86 50% Evaporated	Deg C	-	96.4	-		
D86 90% Evaporated	Deg C	-	99.2	-		
D86 Sum of 10% and 50% Evaporated temps	Deg C	-	165.0	-		
D873 16Hr Accelerated Gum	mg/100ml	-	0	-		
D873 Lead Precipitate	mg/100ml	-	0	-		
IP16 Freeze point	Deg C	<-80	<-80	-		
IP154 Copper Corrosion 2Hrs @100 Deg C	-	-	1b	-		
IP289 Water Reaction Interface Rating	-	-	1b	-		
IP289 Water Reaction Volume change	-	-	2	-		
Vapor Pressure	kPa	11.8	44.5	39.6		
Sulfur (D2622mod)	% w/w	-	0.0010	-		

* API / Defined Properties

Table 2: Mid Octane Study Test Fuels

Property	Units	W02/420	W02/422	W02/421	W02/579
Description		Unleaded 91/98	Leaded 91/98	Unleaded 93	Unleaded 95
MON		91.2	91.4	93.2	95.0
Supercharge		98	96	99	99
Lead	gPb/liter	0.00	0.56	0.00	0.00
D1319 FIA Aromatics	% v/v	7.2	6.9	6.5	7.4
D1319 FIA Olefins	% v/v	0.6	0.5	0.6	0
D1319 FIA Saturates	% v/v	92.2	92.6	92.9	92.6
D3338 Specific Energy	MJ/kg	44.040	44.053	44.086	44.071
D381 Existent Gum (Air)	mg/100ml	1	2	1	<1
IP365 Composite Density	kg/m3	702.5	703.0	700.9	698.8
D86 Initial Boiling Point	Deg C	31.8	40.0	39.7	32.5
D86 Final Boiling Point	Deg C	131.5	143.8	123.4	119.5
D86 Loss	% v/v	0.9	0.7	0.6	0.5
D86 Recovery	% v/v	98.0	98.1	98.3	99.0
D86 Residue	% v/v	1.1	1.2	1.1	0.5
D86 10% Evaporated	Deg C	63.7	64.7	67.1	69.5
D86 40% Evaporated	Deg C	96.2	94.0	96.2	96.0
D86 50% Evaporated	Deg C	100.0	98.9	99.3	98.5
D86 90% Evaporated	Deg C	106.6	110.6	104.0	101.0
D86 Sum of 10% and 50% Evaporated temps	Deg C	163.7	163.6	166.4	168.0
D873 16Hr Accelerated Gum	mg/100ml	2	3	3	1
D873 Lead Precipitate	mg/100ml	0	0	0	0
IP16 Freeze point	Deg C	<-80	<-80	<-80	<-60
IP154 Copper Corrosion 2Hrs @100 Deg C	-	1a	1a	1a	1
IP289 Water Reaction Interface Rating	-	1	1	1	1b
IP289 Water Reaction Volume change	-	0	0	0	0
Vapor Pressure	kPa	(49.1) 46.5 rpt	43.3	45.1	41.1
Sulfur (D2622mod)	% w/w	0.0004	<0.0010	0.0011	<0.0010

4. Test Program

Generally, two routes are available for fuel/engine evaluation:

(1) A fuel may be assessed as fit for purpose for a given engine/installation. i.e. a determination made regarding engine octane requirement, fuel system susceptibility to vapor lock etc.

(2) A fuel may be compared against a fuel of known properties to assess if performance is better or worse under severe, controlled conditions.

The former method tends to be used for engine development and for changes to an approved fuel for aircraft type e.g. STC. The latter method is used for refinery production control to maintain fuel octane quality e.g. ASTM D 2700 MON and ASTM D 909 Supercharge testing.

For the current programme, method (2) was selected where fuels were compared to 'base-line' leaded AVGAS formulations in a representative, octane sensitive, full size aviation engine. This procedure was adopted in an effort to capture a large proportion of engine/airframe installations but must not be taken as completely universal given the great variation in design. For the high octane study, engine conditions were set to give a more severe operating environment than normally achievable, such that both test and reference AVGAS formulations could be made to knock in a similar manner to Co-ordinated Fuels Research (CFR) engine tests. To allow the engine to operate for the mid-octane study, the severity of intake air temperature/cylinder head temperature was reduced from 104 ºF/475 ºF to 62 ºF/420 ºF respectively. For all tests it must be noted that the objective was to compare fuels under set conditions and not to exactly match the test conditions used in ASTM D 2700 MON and ASTM D 909 Supercharge. Thus, any differences in fuel ranking due to laboratory and full size engine tests could be identified.

Fuels were evaluated by knock limited lean out at fixed engine speed/power.
Four engine speed/power settings were selected:

- 100% Wide Open Throttle (WOT) power at 2700 rpm.
- 85% of WOT power at 2600 rpm
- 75% WOT power at 2450 rpm
- 65% WOT power at 2350 rpm

Conditions were achieved as follows:

The 100% WOT power was determined by firstly setting, and then optimizing, the full rich fuel mass flow rate in accordance with the engine manufactures' instructions at the fixed speed of 2700 rpm. The 85%, 75% and 65% power settings could then be calculated. To obtain lower power settings, the engine RPM was selected and fixed. The manifold absolute air pressure was then adjusted with the mixture setting to achieve the desired power at full rich mass fuel flow. The fuel flow was then leaned while maintaining the manifold pressure until light knock was detected. This procedure gave a plot of mass fuel flow/power at the point of light knock. The degree of enleanment possible with each AVGAS was indicative of fuel anti-knock performance. Full details are available elsewhere [1].

To ensure that results were meaningful, engine operating parameters were carefully controlled/monitored. e.g. inlet oil temperature; cylinder head temperature; RPM (appropriate for power setting); ignition timing; intake air temperature; humidity. Appropriate corrections were also applied to parameters, such as power output, to account for operating conditions. Only chosen variable parameters such as fuel flow were varied in a systematic manner to take the engine to the point of light knock. Fuels were tested to a set regime with a number of repeat measurement performed at the end of the program to determine repeatability/hysterisis.

Full details of the test protocol are available elsewhere [2].

6. Results and Analysis

6.1 Control of Engine Environment

Data were analyzed to determine the variability of conditions for both the high and mid range octane studies, Appendix 1, to ensure adequate engine control and consistent results. The minimum, average and maximum result for each engine control parameter are presented in Tables 3 and 4 respectively.

Results indicate good control of critical engine parameters with little variance between minimum and maximum recorded values. A minor exception was noted for the humidity data where T2-54 E to J exceeded the range of 0 to 2 Grains Moisture/lb dry air. Point T2-54F covered a light knock point for the 104 amine fuel and at 13.3 Grains Moisture/lb dry air gave a nominal change in humidity of 5 % at 105 ºF. This point has been highlighted in further analysis. Overall, engine operating conditions were appropriate for the studies and allowed a fair comparison of fuel performance.

Additional engine parameters recorded during the test program, including exhaust gas temperatures, are provided in Appendix 2.

Table 3: High Octane Study Engine Parameters

165 Data Points

Variance in RPM				
	2700 RPM	2600 RPM	2450 RPM	2350 RPM
Minimum	2700	2600	2450	2350
Average	2700.7	2600.8	2450.9	2350.9
Maximum	2701	2601	2451	2351
Min Max Range +/-	0.5	0.5	0.5	0.5

Variance in Other Engine Parameters – Inclusive of all RPM Settings				
	Intake Air Temp ºF	Oil Temp ºF	Oil Press Psig	Humidity ratio @ meter. Grains Moist. / lb air
Minimum	97	226	60	0
Average	104	236	63	2
Maximum	106	247	67	17*
Min Max Range +/-	4.5	10.5	3.5	8.5*

	Cyl. Head 1 ºF	Cyl. Head 2 ºF	Cyl. Head 3 ºF	Cyl. Head 4 ºF	Cyl. Head 5 ºF	Cyl. Head 6 ºF
Minimum	436	416	437	417	470	432
Average	451	437	448	432	475	453
Maximum	466	452	460	454	483	464
Min Max Range +/-	15.0	18.0	11.5	18.5	6.5	16.0

* The majority of results fell within the range 0 to 2 Grains Moisture/lb dry air. Only T2-54 E to J exceeded these values giving a nominal change in humidity of 5 % at 105 ºF. Result T2-54 F covered a light knock point for the 104 amine fuel and this point has been highlighted in any further analysis.

Table 4: Mid Octane Study Engine Parameters

73 Data Points

Variance in RPM				
	2700 RPM	2600 RPM	2450 RPM	2350 RPM
Minimum	2701	2601	2451	2351
Average	2702.0	2601.6	2451.1	2351.7
Maximum	2703	2603	2453	2352
Min Max Range +/-	1	1	1	0.5

Variance in Other Engine Parameters – Inclusive of all RPM Settings				
	Intake Air Temp °F	Oil Temp °F	Oil Press psig	Humidity ratio @ meter. Grains Moist. / lb air
Minimum	59	229	62	1.00
Average	62	235	64	1.00
Maximum	66	240	68	1.00
Min Max Range +/-	3.5	5.5	3	0.00

	Cyl. Head 1 °F	Cyl. Head 2 °F	Cyl. Head 3 °F	Cyl. Head 4 °F	Cyl. Head 5 °F	Cyl. Head 6 °F
Minimum	382	368	379	363	408	387
Average	392	376	388	370	414	396
Maximum	412	384	408	377	420	402
Min Max Range +/-	15.0	8.0	14.5	7.0	6.0	7.5

6.2 Knock Analysis

Knock limits for the pressure and force transducer systems were as follows:

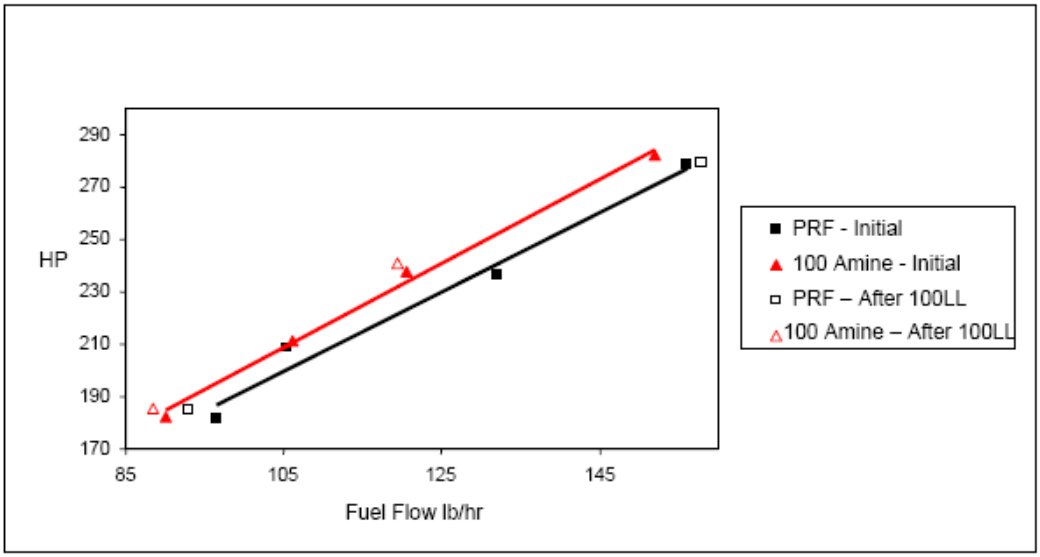
- Pressure Transducer
  Light Knock 10 – 40
  Medium Knock 40 – 100
  Heavy Knock >100
- Force Transducer
  Knock => 100

The first detection of light knock on any of the engine cylinders was taken as the point at which the engine had reached knock limited power for a set fuel flow. Both the pressure and force transducer systems were generally found to be in good agreement and the average power output/fuel flow was calculated from the data in the case of disparity. An exception to the above were tests relating to the 104 amine unleaded fuel. Here the force transducer data appeared inconsistent and the pressure transducer data alone was utilized. Knock analysis data is provided in Appendix 3.

6.3 Repeatability / Hysterisis

As reported in Section 4, a number of detonation points were re-measured on completion of the test program and these data were compared to earlier measurements. This procedure was used to ensure the engine had not been irreversibly effected when running leaded fuel. Results, presented in Figure 1, demonstrate good repeatability and no/minimal hysterisis. This demonstrated that under the test conditions the performance of leaded and unleaded fuels could be successfully compared in the full size engine.

Figure 1: Knock Limited Power/Fuel Flow Measurements for the Primary Reference Fuel (PRF) and 100 MON Amine Unleaded Fuels Before and After Engine Operation on Leaded AVGAS 100LL Base-Line Fuel.



6.4 High Octane Study - MON

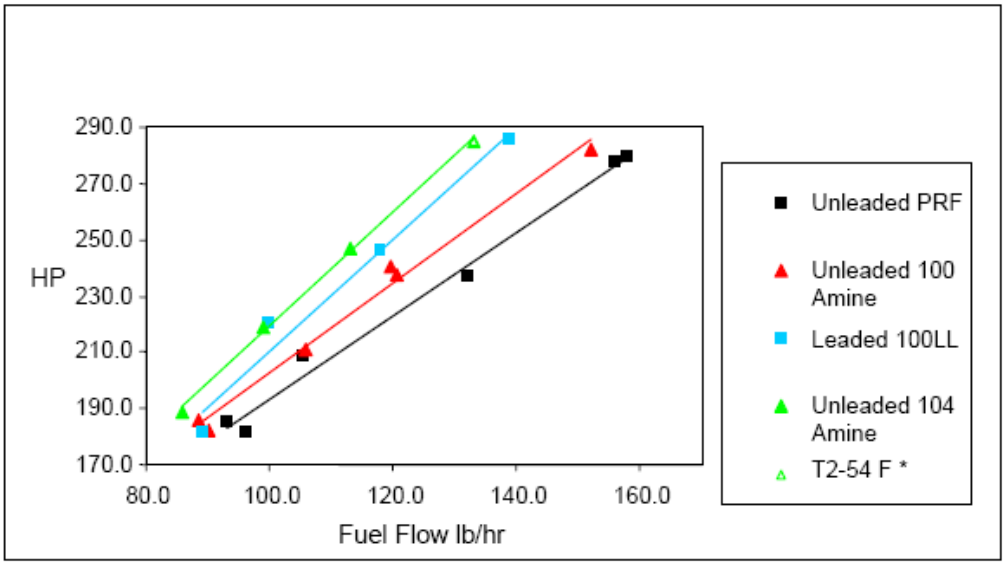
A comparison of the knock limited power output versus engine enleanment was undertaken for the fuels listed in Table 5.

Table 5: High Octane Fuel Matrix – Lean Out Study

	Leaded 100LL	Unleaded PRF Iso-Octane	Unleaded 100 Amine	Unleaded 104 Amine
MON	100.3	100.0	100	104
Supercharge	132	100	>161	>161
TEL gPb/liter	0.568	0.000	0.000	0.000

Data are presented graphically in Figure 2.

Figure 2: A Comparison of Knock Limited Power Output versus Fuel Flow for the High Octane Fuel Matrix



* As reported in Section 6.1.1 point T2-54 F, at 13.3 Grains Moisture/lb dry air, exceeded the range of 0 to 2 Grains Moisture/lb dry air recorded for the other knock data points.

Under the test conditions, results indicate:

- The leaded base-line AVGAS 100LL offered better engine octane satisfaction across a range of fuel flow when compared to the unleaded fuels of similar MON and either low (100 PN) or high (>161 PN) Supercharge.
- The unleaded fuel of 104 MON and >161 PN supercharge offered better engine octane satisfaction across a range of fuel flow when compared to leaded base-line AVGAS 100LL.
- Linear interpolation between fuels suggests that, ignoring Supercharge effects, an unleaded fuel of about 103 MON is required to match the anti-knock performance of the base-line AVGAS 100LL in this study.

Similar trends have been observed in CRC programs examining a matrix of high octane unleaded fuels [1,3,4], Cessna/BP work [5,6] and earlier CFR research [7]. However CRC data also indicates some fuels are exceptions to this trend, in particular those containing the metal additive Methylcyclopentadienyl Manganese Tricarbonyl (MMT), where there is some similarity to leaded fuels. This may be due to the formation of a manganese oxide radical quenching cloud within the cylinder, in a similar manner to the mode of operation of TEL [8,9,10]. There is also some evidence [3] that suggests MMT knock suppression characteristics improve with the accumulation of time of operation exposure to the additive. This may not have been observed for the fuels containing TEL due to the presence of the ethylene dibromide scavenger which assists in removing lead oxide deposits from the chamber.

6.5 High Octane Study - Supercharge

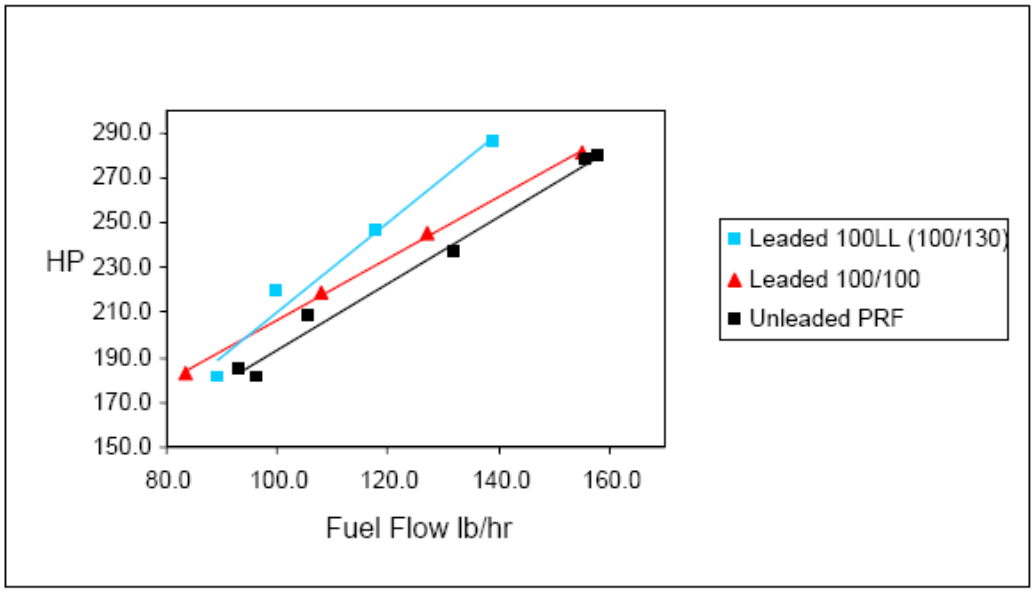
A comparison of the knock limited power output versus engine enleanment was undertaken for the fuels listed in Table 6.

Table 6: High Octane Fuel Study – Effect of Supercharge Matrix

	Leaded 100LL	Leaded 100/100	Unleaded PRF Iso-Octane
MON	100.3	100.0	100.0
Supercharge	132	99	100
TEL gPb/liter	0.568	0.501	0.000

Data are presented graphically in Figure 3.

Figure 3: Effect of Supercharge and Fuel Flow on Knock Limited Power



Under the test conditions:

- At high engine power output the 0.568 gPb/l 100/130 AVGAS offered better engine octane satisfaction when compared to a 0.501 gPb/l 100/100 AVGAS and a 100/100 PRF.
- At low engine power output, any differences between fuels became less clear.

These data suggest fuel Supercharge may become increasingly important as engine power output is raised and the fuel stressed to a greater extent. However, it should also be noted that there was some variance in the TEL content of the leaded fuels which could have influenced results. In general, these observations are in agreement with the development of supercharged aviation engines but are not applicable to all current engine types as determined elsewhere [5]. This suggests a 'spectrum' of engine supercharge requirement exists ranging from little/no reliance to significant importance.

6.6 Mid Octane Study

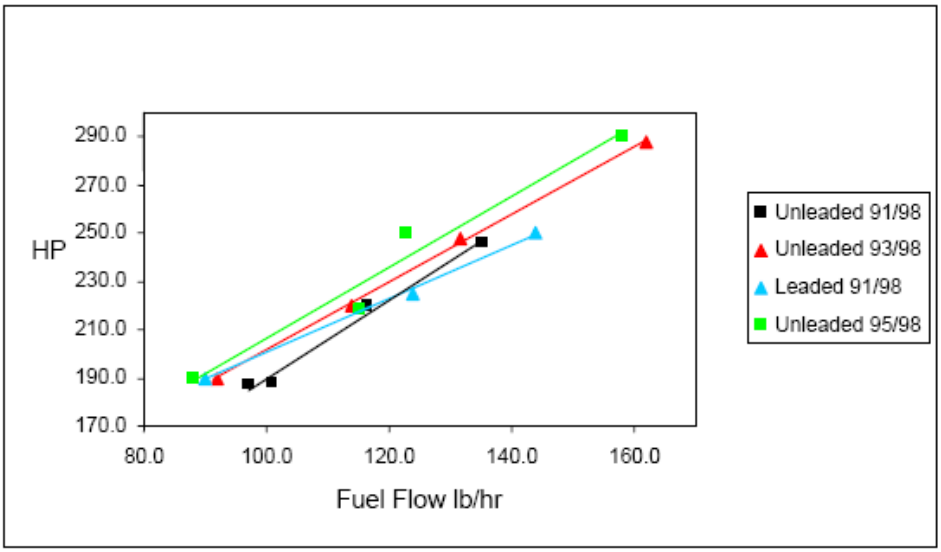
A comparison of the knock limited power output versus engine enleanment was undertaken for the fuels listed in Table 7.

Table 7: Mid Octane Fuel Matrix

	Leaded 91/98	Unleaded 91/98	Unleaded 93/98	Unleaded 95/98
MON	91.4	91.2	93.2	95.0
Supercharge	96	98	99	99
TEL gPb/liter	0.56	0.000	0.000	0.000

Data a presented graphically in Figure 4.

Figure 4: A Comparison of Knock Limited Power Output versus Fuel Flow for the Mid Octane Fuel Matrix



Under the test conditions, results indicate:

- Testing of 91/98 AVGAS has proved more challenging on the full size engine available.
- The unleaded 93/98 and 95/98 AVGAS data appears consistent with the High Octane study.
- The 95/98 unleaded AVGAS offered better engine octane satisfaction across a range of fuel flow when compared a 93/98 unleaded AVGAS.
- The leaded 91/98 and unleaded 91/98 AVGAS data appears inconsistent with the High Octane study.
- Caution should be exercised evaluating the current information.

Given the success of the High Octane Study in differentiating between fuels, the results from the Mid Octane Study were surprising. A possible explanation may lie in the reduced intake air temperature necessary to allow the engine to operate. The lower temperature may not have sufficiently stressed the fuels to highlight differences. A further investigation using an engine designed for 91/98 AVGAS under appropriate conditions would be advantageous.

6.7 Engine Operating Conditions / Fuel Octane Quality

As reported in Section 4 reducing intake air/cylinder head temperatures from 104 ºF/475 ºF to 62 ºF/420 ºF respectively allowed the mid octane fuels to be tested on same engine as the high octane fuels. The success of this approach suggests the importance of these parameters on aviation engine octane requirement. As observed in Section 6.1.6, there is the possibility that fuels perform differently following such changes. Therefore, it is important to make conditions as representative and severe as possible in fuel/engine knock evaluation.

7. Conclusions

7.1 A matrix of leaded and unleaded test fuels covering high (100 MON) and mid (91 MON) octane AVGAS have been prepared.

7.2 Tests featuring a normally aspirated, fuel injected Lycoming IO540 engine have sought to determine the effect of fuel octane quality and lead content on full size engine performance under carefully controlled conditions.

7.3 Results have demonstrated good control of engine conditions, good repeatability and little/no effect from testing leaded and unleaded fuels in the same engine.

7.4 Results for the high octane AVGAS study have indicated, under the test conditions:

- A 0.568 gPb/l100/130 AVGAS offered better engine octane satisfaction across a range of fuel flow when compared to unleaded fuels of similar MON and either low (100 PN) or high (>161 PN) Supercharge.
- Linear interpolation between fuels suggests that, ignoring Supercharge, an unleaded (no metallic additives) fuel of about 103 MON was required to match the anti-knock performance of the leaded AVGAS in the test engine.
- At high engine power output the 0.568 gPb/l 100/130 AVGAS offered better engine octane satisfaction when compared to a 0.501 gPb/l 100/100 AVGAS and a 100/100 PRF.

7.5 Results for the mid octane AVGAS study have indicated, under the test conditions:

- A 95/98 unleaded AVGAS offered better engine octane satisfaction across a range of fuel flow when compared a 93/98 unleaded AVGAS.
- Data for a 0.56 gPb/l 91/98 AVGAS and a 91/98 unleaded AVGAS appeared inconsistent when compared to the high octane studies.
- Further work is recommended using an engine specifically designed for 91/98 AVGAS.

7.6 Changes to intake air and cylinder head temperature had a significant effect on the octane requirement of the test engine allowing both high and mid range fuels to be tested.

8. Acknowledgement

Air BP wish to thank the FAA Technical Center for the full scale engine testing, Cessna Aircraft Company for the supply of Base Line 100/130 AVGAS, ExxonMobil for the supply of the Amine unleaded fuels, Chevron-Phillips Chemical Company for the supply of Iso-Octane primary reference fuel and the CRC for their support and suggestions.

9. References

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October 11th 2005

APPENDIX F

UNPUBLISHED CRC REPORT

AN INVESTIGATION INTO MID (91/98) OCTANE AVGAS DETONATION CHARACTERISTICS IN A FULL SIZE ENGINE

BY ALISDAIR Q. CLARK BSC PHD

VERSION 3.0, DATED APRIL 26, 2007

An Investigation into Mid (91/98) Octane AVGAS Detonation Characteristics in a Full Size Aviation Engine
Draft - Version 3.0 April 2007

Summary
The detonation characteristics of leaded and unleaded AVGAS in the mid (91 MON/98 Supercharge) octane range have been evaluated in a Lycoming IO320-B engine. Under the test conditions, the leaded Avgas provided more anti-detonation performance versus an unleaded Avgas of similar laboratory MON and Supercharge. Further comparison with unleaded fuels of 93 and 94 MON suggested that to achieve a similar performance to the leaded Avgas an unleaded product might require approximately +2 MON at 98 ON Supercharge.

1. Introduction

Spark ignition aviation piston engines rely heavily on fuel octane quality to provide high performance and detonation free operation. Aviation gasoline (AVGAS) Grade 100LL currently meets this requirement. However, 100LL AVGAS contains the octane enhancement additive tetraethyl lead (TEL) and the Aviation Industry wishes to move to a viable unleaded alternative. One option is to adopt a fuel of lower octane quality and rely on advances in engine technology to help recoup the deficit in thermal efficiency. A potential Mid-Grade product, 91/98 AVGAS, was featured in ASTM D 910 up until the 1960's and was recently re-introduced in 2001. In support of the CRC, a program of work has been undertaken to assess the anti-detonation performance of leaded / unleaded 91/98 AVGAS in a full size aviation engine. The objective was to determine if the presence of TEL significantly influenced the anti-detonation behavior of 91/98 AVGAS in a similar manner to that already determined for 100LL AVGAS. This report details the program, results and conclusions.

2. Test Facility

A full size Lycoming IO320-B fuel injected, normally aspirated aviation engine installed at the FAA Technical Center in Atlantic City NJ, was utilized for the test program. The engine was originally certified on Grade 91/96 ASTM D 910 leaded AVGAS [1] and the configuration is typical of such engines used in General Aviation:
Power output: 160 bhp
Compression Ratio: 8.5:1
Cylinders: 4
The engine installation and test proceedure are well documented, following guidelines developed by the Coordinating Research Council / ASTM [2]. Advanced instrumentation ensures conditions are suitably severe and repeatable, with a pressure transducer detonation detection system directly measuring pressure fluctuations in each engine cylinder.

3. Fuels

4 Avgas blends were supplied by Air BP and a 94 MON Primary Reference Fuel was supplied by the FAA:

- Leaded 91/98 Base-line AVGAS
- Unleaded 91/98 AVGAS
- Unleaded 93/98 AVGAS
- Unleaded 94/98 AVGAS
- Unleaded 94 PRF

Fuel properties are given in Table 1. Every effort was made to ensure the base-line leaded and unleaded 91/98 formulations were as close to ASTM D 910 minimum octane requirements as possible. However, to achieve 98 ON Supercharge it was necessary to increase MON by ca. 0.8 ON. The unleaded 93/98 and 94/98 fuels met all AVGAS

specifications except for vapor pressure which exceeded specification by 1.1 and 1.7 kPa respectively and loss which exceeded specification by 0.2% v/v for the 94/98 fuel only. Again, some compromise was necessary to achieve the required octane quality for the test. No metal additives, such as Methylcyclopentadienyl Manganese Tricarbonyl (MMT), were used in the unleaded formulations. During the preparation of all the unleaded fuels it was noted that meeting the minimum 98 ON Supercharge requirement was extremely difficult and the addition of aromatics gave lower octane enhancement than expected.

Table 1: Test Fuels

Fuel		Leaded 91/98	Unleaded 91/98	Unleaded 93/98	Unleaded 94/98	PRF 94
Analysis	Units	W04/674	W06/057#6	W06/387	W06/386	PRF94
MON ‡	ON	91.9 / 91.8‡‡	91.8	93.2	94.1	94.0*
Supercharge ‡	ON	98	98	98	98	94*
Copper Corr. 2 hrs. at 100 ºC		1	1A	1A	1A	
Density at 15 ºC	kg/L	0.7156	0.7236	0.7141	0.714	
I.B.P.	°C	35.8	37.0	34.4†	34.3†	
10% v evap. at	°C	68.2	65.5	61.2†	60.6†	
40% v evap. at	°C	94.3	96.5	93.2†	93.9†	
50% v evap. at	°C	97.1	99.0	98.5†	98.7†	
90% v evap. at	°C	101.5	102.0	101.4†	101.2†	
End Point	°C	115	111.0	112.8†	109.9†	
Sum of 10% & 50% Evap	°C	165.3	164.5	159.7†	159.4†	
Recovery	% (v/v)	98.8	99.0	97.6†	97.4†	
Residue	% (v/v)	1.0	0.4	0.9†	0.9†	
Loss	% (v/v)	0.2	0.6	1.5†	1.7†	
Freezing Point	°C	<-60.0	<-70	<-80	<-80	
Potential Gum	Mg/100ml	<1.0	3	6	5	
Precipitate	Mg/100ml	<1.0	0.1	-	-	
Specific Energy (Net)	MJ/kg	43.64	43.58	43.54	43.58**	
Sulfur Content	% (m/m)	<0.01	<0.001	<0.001	<0.001	
Lead	gPb/liter	0.502	0	0	0	
Interface Rating		1B	1B	1	1	
Volume Change	ml	0	0.0	0	0	
Vapor Pressure at 37.8 ºC	kPa	42.5	42.9	50.1†	50.7†	

‡ MON and Supercharge measurements all performed by Dixie Testing Services for repeatability.
‡‡ Measured in duplicate.
* Defined by ASTM D 2700, ASTM D 909.
** Calculated from chemical composition and API calorific value data.
† Average of 2 determinations.

4. Test Program

Generally, two routes are available for fuel/engine evaluation:

(1) A fuel may be assessed as fit for purpose for a given engine/installation. i.e. a determination made regarding engine octane requirement, fuel system susceptibility to vapor lock etc.
(2) A fuel may be compared against a fuel of known properties to assess if performance is better or worse under severe, controlled conditions.

The former method tends to be used for engine development or to establish if a fuel is suitable for a particular aircraft type i.e. Supplementary Type Certificate approval. The latter method is used for refinery production control, for example, to ensure a fuel meets or exceeds a minimum octane specification by ASTM D 2700 MON and ASTM D 909 Supercharge testing. For the current program, method (2) was selected where fuels were compared to the base-line leaded AVGAS formulation in a representative full size aviation engine. This procedure was adopted to determine if the test fuels could match the

performance of the leaded AVGAS in a realistic environment typical of a large proportion of engine/airframe instillations. However, it must not be taken as completely universal given the wide variation of engine design seen in the market. Conditions were set to give a severe and repeatable operating environment at the limits of normal operation, such that both test and reference AVGAS formulations could be made to detonate in a similar manner to Co-coordinated Fuels Research (CFR) engine tests. For all tests it should be noted that the objective was to compare fuels under set conditions and not to exactly match the test conditions used in ASTM D 2700 MON and ASTM D 909 Supercharge. Thus, any differences in fuel ranking due to laboratory and full size engine tests could be identified.

Fuels were evaluated by detonation limited lean out at fixed engine speed/power.
Four engine speed/power settings were selected:

- 100% Wide Open Throttle (WOT) power at 2700 rpm.
- 85% of WOT power at 2600 rpm
- 75% WOT power at 2450 rpm
- 65% WOT power at 2350 rpm

Conditions were achieved as follows:
The 100% WOT power was determined by firstly setting, and then optimizing, the full rich fuel mass flow rate in accordance with the engine manufactures' instructions at the fixed speed of 2700 rpm. The 85%, 75% and 65% power settings could then be calculated. To obtain lower power settings, the engine RPM was selected and fixed. The manifold absolute air pressure was then adjusted with the mixture setting to achieve the desired power at full rich mass fuel flow. The fuel flow was then leaned while maintaining the manifold pressure until light detonation was detected. This procedure gave a plot of mass fuel flow/power at the point of light detonation. The degree of enleanment possible with each AVGAS was indicative of fuel anti-detonation performance. Full details are available elsewhere [3].

To ensure that results were meaningful, engine operating parameters were carefully controlled/monitored. e.g. inlet oil temperature; cylinder head temperature; RPM (appropriate for power setting); ignition timing; intake air temperature; humidity. Appropriate corrections were also applied to parameters, such as power output, to account for operating conditions. Only chosen parameters such as fuel flow were varied in a systematic manner to take the engine to the point of light detonation. Fuels were tested to a set regime with a number of repeat measurement performed throughout the program to determine repeatability/hysterisis. The following running order was adopted:

- Unleaded AVGAS
- Unleaded Primary Reference Fuel
- Unleaded AVGAS
- Leaded AVGAS
- Unleaded Primary Reference Fuel

5. Results and Analysis

On completion of the engine tests a considerable amount of data (2.5 GB) was captured. To help analysis only results at the point of light detonation are presented, this representing the critical engine condition for the study.

5.1 Control of Engine Environment

Data were analyzed to determine the variability in test conditions, Appendix 1, to ensure adequate engine control and consistency. The minimum, average and maximum result for each engine control parameter is presented in Table 2. Results indicate good control of critical parameters with little variance between minimum and maximum recorded values. Given the consistent operating environment a fair comparison of fuel performance was possible. Additional engine parameters recorded during the test program, including exhaust gas temperatures, are provided in Appendix 2.

Table 2: Engine Parameters

89 Data Points

Variance in RPM				
	2700 RPM	2600 RPM	2450 RPM	2350 RPM
Minimum	2699	2600	2449	2349
Average	2700.0	2600.3	2450.0	2350.0
Maximum	2701	2601	2451	2351
Min Max Range +/-	1	0.5	1	1
Variance in Other Engine Parameters – Inclusive of all RPM Settings				
	Intake Air Temp °F	Oil Temp °F	Oil Press psig	Humidity ratio @ meter. Grains Moist. / lb air
Minimum	102	226	56	1.0
Average	102.9	235.1	58.3	1.48
Maximum	104	248	61	1.7
Min Max Range +/-	1	11	2.5	0.35
	Cyl. Head 1 °F	Cyl. Head 2 °F	Cyl. Head 3 °F	Cyl. Head 4 °F
Minimum	443	465	464	463
Average	453.9	476.0	475.7	473.1
Maximum	462	483	483	485
Min Max Range +/-	9.5	9	9.5	11

5.2 Detonation Analysis

Detonation limits for the pressure transducer system were set as follows:

- Light Detonation 10 – 40
- Medium Detonation 41 – 100
- Heavy Detonation >100

The onset of light detonation in any of the engine cylinders was taken as the point at which the engine had reached detonation limited power for a set fuel flow. Detonation analysis, fuel flow and power output data are provided in Appendix 3.

5.3 Repeatability / Hysterisis

As reported in Section 4, a number of detonation points were re-measured throughout the test program and these data were compared to earlier measurements where possible. This procedure was used to ensure the engine had not been irreversibly effected during the study and when running the leaded fuel. Results, presented in Figures 1 and 2, show good repeatability and no/minimal hysterisis. This procedure demonstrated that under the test conditions the performance of leaded and unleaded fuels could be successfully compared in the full size engine.

Figure 1: Detonation Limited Power/Fuel Flow Measurements for the 91/98 Unleaded AVGAS at Start and Finish of Unleaded Fuels Testing

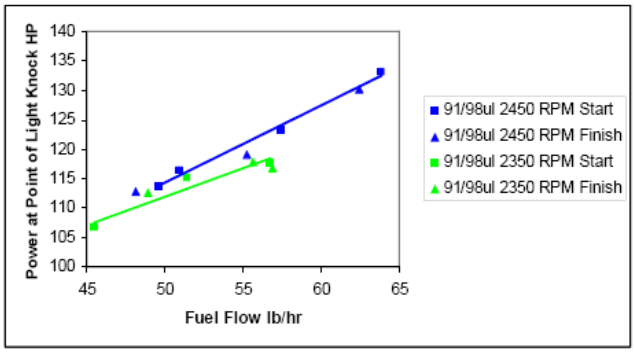
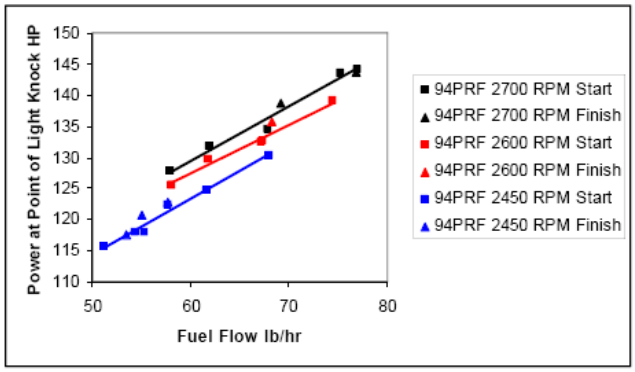


Figure 2: Detonation Limited Power/Fuel Flow Measurements for the 94 Primary Reference Fuel Prior and Post Leaded 91/98 AVGAS Testing



5.4 Leaded / Unleaded Fuel Comparison

A comparison of the detonation limited power output versus engine enleanment was undertaken for the fuels listed in Table 3.

Table 3: Leaded / Unleaded AVGAS Comparison

	Leaded 91/98 AVGAS	Unleaded 91/98 AVGAS	Unleaded 93/98 AVGAS	Unleaded 94/98 AVGAS
MON	91.9, 91.8*	91.8	93.2	94.1
Supercharge	98	98	98	98
TEL gPb/liter	0.502	0.000	0.000	0.000

* Measured in duplicate.

Data are presented graphically in Figures 3 to 6.

Figure 3: A Comparison of Detonation Limited Power Output versus Fuel Flow for Leaded and Unleaded AVGAS at 2350 RPM

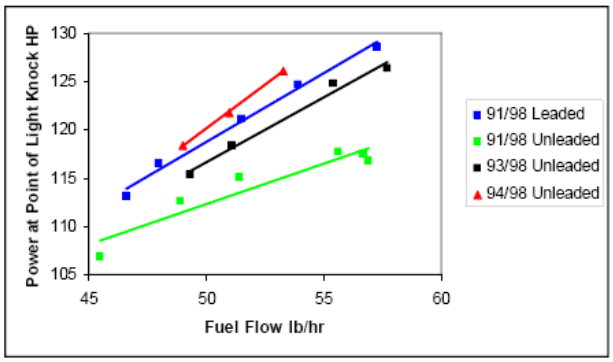


Figure 4: A Comparison of Detonation Limited Power Output versus Fuel Flow for Leaded and Unleaded AVGAS at 2450 RPM

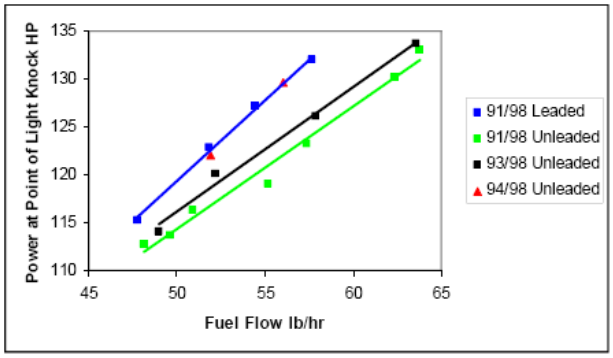


Figure 5: A Comparison of Detonation Limited Power Output versus Fuel Flow for Leaded and Unleaded AVGAS at 2600 RPM

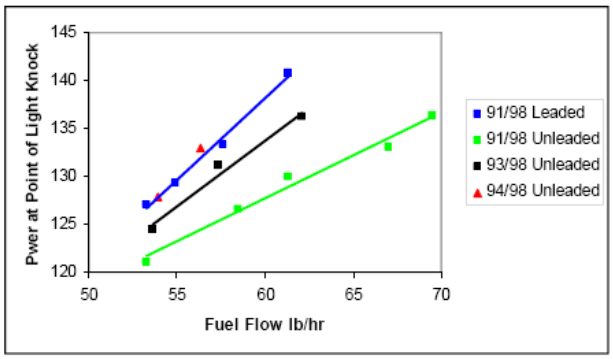
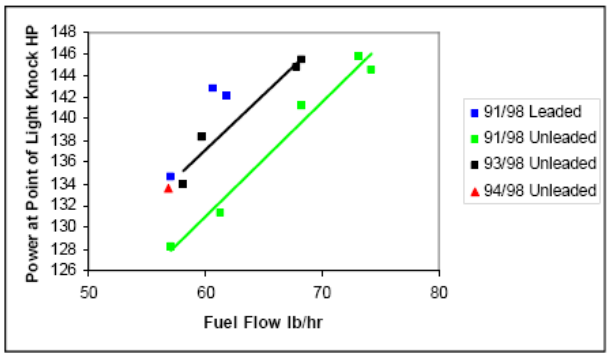


Figure 6: A Comparison of Detonation Limited Power Output versus Fuel Flow for Leaded and Unleaded AVGAS at 2700 RPM



Under the test conditions, results indicate:

- The leaded base-line AVGAS offered better engine octane satisfaction across a range of fuel flows when compared to the unleaded AVGAS of similar MON and Supercharge.
- At 2450 and 2600 RPM the leaded base-line AVGAS offered similar engine octane satisfaction across a range of fuel flows to the 94/98 unleaded AVGAS. Given that the measured MON of the leaded fuel was 91.8 ON, this would indicate that an unleaded fuel of about +2 MON is required to achieve similar engine octane satisfaction at 98 ON Supercharge.

Similar trends have been observed in CRC programs examining a matrix of high octane leaded/unleaded fuels [3,4,5,6], Cessna/BP work [7,8] and earlier CFR research [9]. The performance of the leaded fuel may be due to the mode of operation of TEL [10,11,12]. The reaction to form a radical quenching cloud on combustion may accelerate under the more severe combustion environment of the full size engine, with two flame fronts/large chamber, and offer benefits compared to an unleaded fuel of similar laboratory octane.

5.5 94 Primary Reference Fuel

A comparison of the detonation limited power output versus engine enleanment was undertaken for the fuels listed in Table 4.

Table 4: 94 Primary Reference Fuel Comparison

	Leaded 91/98 AVGAS	Unleaded 91/98 AVGAS	Unleaded 94 PRF
MON	91.9, 91.8*	91.8	94.0**
Supercharge	98	98	94**
TEL gPb/liter	0.502	0.000	0.000

* Measured in duplicate
** Defined by ASTM D 2700, ASTM D 909

Data are presented graphically in Figure 8 to 11.

Figure 8: A Comparison of Detonation Limited Power Output versus Fuel Flow for 94 PRF, Leaded and Unleaded AVGAS at 2350 RPM

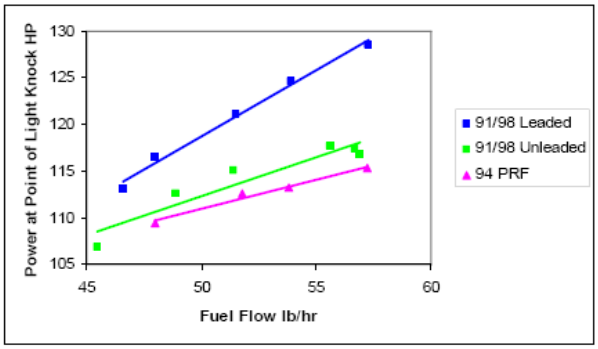


Figure 9: A Comparison of Detonation Limited Power Output versus Fuel Flow for 94 PRF, Leaded and Unleaded AVGAS at 2450 RPM

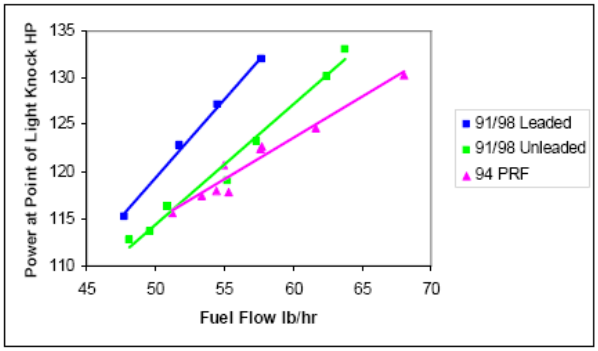


Figure 10: A Comparison of Detonation Limited Power Output versus Fuel Flow for 94 PRF, Leaded and Unleaded AVGAS at 2600 RPM

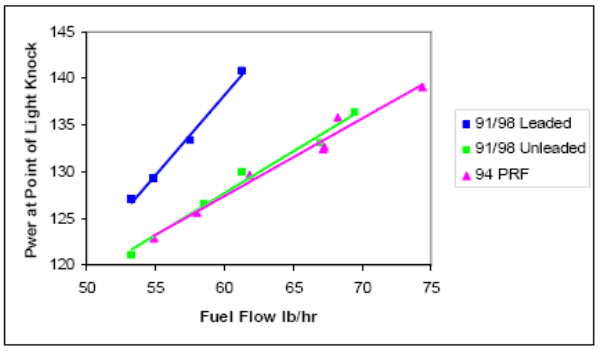
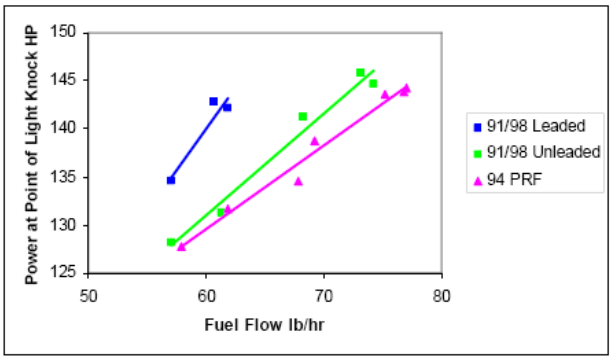


Figure 11: A Comparison of Detonation Limited Power Output versus Fuel Flow for 94 PRF, Leaded and Unleaded AVGAS at 2700 RPM



Under the test conditions:

- The 94 Primary Reference Fuel offered lower or similar engine octane satisfaction across a range of fuel flows when compared to the unleaded 91/98 AVGAS.
- The 94 Primary Reference Fuel offered significantly lower engine octane satisfaction across a range of fuel flows when compared to the leaded 91/98 AVGAS.

These data are in agreement with earlier CRC studies [6] where a 100 MON (iso-octane) Primary Reference Fuel offered lower engine octane satisfaction versus AVGAS formulations. Given that the current fuel was of 94 MON the difference versus the unleaded 91/98 AVGAS is surprising and might be due to one, or a combination of, effects:

- Supercharge - The PRF would have a Supercharge rating of only 94 ON versus the 98 ON of the AVGAS formulations.
- Volatility – The PRF would have a limited volatility range versus the AVGAS formulations and this might effect combustion performance.
- Degradation - Some form of degradation may have occurred to the PRF during storage.

While the current study can not resolve this issue, it should be noted that for full size engine research, AVGAS prepared within the spirit of ASTM D 910 appears to offer the most useful base-line of true operational performance based on this and earlier studies.

6. Conclusions

6.1 A matrix of leaded and unleaded AVGAS formulations in the mid-octane 91 MON / 98 Supercharge range have been prepared.

6.2 Tests featuring a normally aspirated, fuel injected Lycoming IO320 engine have sought to determine the effect of fuel lead content and octane quality on full size engine performance under carefully controlled conditions.

6.3 Results have demonstrated good control of engine conditions, good repeatability and little/no effect from the short-term testing of leaded and unleaded fuels in the same engine.

6.4 Under the test conditions:

- A leaded AVGAS, 0.502 gPb/l 91.8 MON 98 ON Supercharge, offered more full size engine octane satisfaction over a range of fuel flows than an unleaded AVGAS of similar laboratory octane quality.
- Comparison with two further unleaded AVGAS formulations of 93.2/98 and 94.1/98 MON/Supercharge quality suggested that about +2 MON was required for an unleaded fuel to match the leaded AVGAS at 98 ON Supercharge.
- A 94 MON, 94 Supercharge unleaded Primary Reference Fuel was found to offer lower/similar engine octane satisfaction compared to the 91.8 MON 98 ON Supercharge unleaded AVGAS. While comparable effects have been seen in earlier studies the reason for the poor performance of the reference fuel remains unexplained. This may be due to Supercharge, volatility, fuel stability or other reasons.

- Leaded AVGAS, prepared within the spirit of ASTM D 910, appears to offer the most realistic base-line fuel for full size engine studies where a product of similar anti-detonation performance is sought.

7. Acknowledgement

Air BP wish to thank Dixie Testing Services for help with the manufacture and laboratory analysis of the test fuels, the FAA Technical Center for the full scale engine testing, and the CRC for their support and suggestions.

8. References

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[6] An Investigation into High (100 MON) and Mid (91 MON) Octane AVGAS Detonation Characteristics in a Full Size Aviation Engine. A Q Clark. CRC Report October 2005.

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Alisdair Clark BP
April 26th 2007

APPENDICES

Key to Appendices

9198l	Leaded 91/98 AVGAS
9198ul	Unleaded 91/98 AVGAS
9398ul	Unleaded 93/98 AVGAS
9498ul	Unleaded 94/98 AVGAS
94prf	Unleaded 94 Primary Reference Fuel
MAP	Manifold absolute pressure inHg
RPM	Revolutions per minute
LCBHP	Pressure, temperature and humidity corrected power
FF	Fuel flow, lbs/hr
IAT	Inlet air temperature ºF
CHT1	Cylinder 1 head temperature, Cylinder #1 ºF
CHT2	Cylinder 2 head temperature ºF
CHT3	Cylinder 3 head temperature ºF
CHT4	Cylinder 4 head temperature ºF
EGT1	Cylinder 1 Exhaust gas temperature ºF
EGT2	Cylinder 2 Exhaust gas temperature ºF
EGT3	Cylinder 3 Exhaust gas temperature ºF
EGT4	Cylinder 4 Exhaust gas temperature ºF
OILT	Oil inlet temperature from oil cooler ºF
OILP	Oil pressure (psig)
HumT	Air inlet temperature at humidity measuring device
Humrtio	Humidity ration at humidity measuring device
KNS cyl1	Cylinder 1 Detonation sensor
KNS cyl2	Cylinder 2 Detonation sensor
KNS cyl3	Cylinder 3 Detonation sensor
KNS cyl4	Cylinder 4 Detonation sensor
TORK	Shaft torque ft Lbs
BHP	Raw power HP
TCBHP	Inlet air temperature corrected power
BMEP	Brake mean effective pressure psi
FFG	Fuel flow, gal/hr
BSFC	Brake specific fuel consumption (Lbs/BHP Hr)
IAP	Inlet air pressure inHg
CowlT	Cowling air temperature ºF
CowlP	Cowling air pressure in H2O
FuelT	Fuel temp prior to fuel distribution manifold (ºF)
Fdens	Fuel density at same location (Lbs/gal)
CalcA/F	Calculated Air to fuel ratio (Kairflow/FF)

APPENDIX G
CRC Unleaded AVGAS Phase III Research
Regression Analysis of Engine Test Results
November 24, 2009

HATS STATS LLC
Gary Hatfield
1305 W 9th Ave
Stillwater, OK 74074

CRC Unleaded AVGAS Phase III Research Results
Regression Analysis of Engine Test Results
November 24, 2009

EXECUTIVE SUMMARY

Regression models were successfully developed for all responses. Only four blend components appear in every model as linear terms. These are Aviation Alkylate, Super Alkylate, *tert*-Butyl Benzene, and ETBE. The quadratic term for *meta*-Toluidine x ETBE appears in 14 of the 16 models. The special-cubic term for Aviation Alkylate x Super Alkylate x meta-Toluidine appears in 10 of the 16 models. Even though the linear terms for meta-Toluidine and Toluene do not appear in every model, they appear in every model as quadratic or special cubic terms.

Four responses have Mean Squared Error (MSE) that are significantly larger than Pure Error variance. MON has MSE about five times larger than Pure Error, Fuel Flow at 2450 rpm has MSE 10 times larger than Pure Error, Equivalence Ratio at 2450 rpm has MSE about five times larger than Pure Error, and BSFC at 2450 rpm has MSE about eight times larger than Pure Error. For MON, this could be an indication that extraneous variables are contributing to total variation. For Fuel Flow at 2450 rpm, Equivalence Ratio at 2450 rpm, and BSFC at 2450 rpm, their estimates of Pure Error are a lot smaller than estimates for other rpm levels. The MSE of these three responses is similar to Pure Error for the other rpm levels.

A measure of the quality of an empirical model is the ratio of MSE to the variance of a response. The MSEs for the various final models ranges from 1.5 percent to 5.4 percent of response variance. All of the models do an excellent job of explaining observed variation.

The philosophy of parsimonious models addresses the issue of missing data. Even though there are several blends with missing response values for the highest rpm setting, fewer explanatory variables helps to compensate for fewer observations.

The assumptions for regression analysis are met by all responses. The residuals exhibit constant variance and are from a normal distribution.

There are not any blends that consistently appear as the minimum or maximum standardized residuals for the final models. There are also not any standardized residuals that are smaller than -3.0 or larger than +3.0.

1.0INTRODUCTION

Regression analysis is a useful statistical tool for developing empirical models. The relationship between two or more explanatory variables is used to predict a response variable. Underlying assumptions in regression analysis are that the residuals are from a normal distribution and their variance is constant, or homogeneous.

2.0 BACKGROUND

The CRC Unleaded AVGAS Phase III Research Project to investigate engine octane response to fuel composition variables used a mixture experiment designed to estimate all linear, quadratic, and selected cubic effects. The design points (blends) were generated using Gosset, a general-purpose program for constructing experimental designs, during summer YR2005. The fuel composition of the 45 design points, as well as all responses analyzed, are given in Attachment I.

Replicated points were included to estimate Pure Error variance, which is the basis for determining the quality of regression models. Pure Error variance is the pooled variance of the replicates. Three groups of points were replicated. Group 1 consists of Blends 16, 27, and 36, Group 2 consists of blends 6 and 28, and Group 3 consists of Blends 4 and 37. Estimates of Pure Error variance and associated degrees of freedom are given in Table 1. Fuel composition for these blends is given in Table 2.

Table 1
Pure Error Variance Estimates

Response	**MON**	**Avg FF**	**FF2350**	**FF2450**	**FF2600**	**FF2700**
Est. Pure Error Variance	0.01667	4.09858	2.2039	0.3773	6.8067	20.0067
Degrees of Freedom	4	3	4	4	3	3
Response	**Avg EqR**	**EqR2350**	**EqR2450**	**EqR2600**	**EqR2700**	
Est. Pure Error Variance	0.000151	0.000181	0.0000865	0.00031	0.000507	
Degrees of Freedom	3	4	4	3	3	
Response	**Avg BSFC**	**BSFC2350**	**BSFC2450**	**BSFC2600**	**BSFC2700**	
Est. Pure Error Variance	0.0000441	0.0000398	0.00000567	0.00010722	0.00011933	
Degrees of Freedom	3	4	4	3	3	

Table 2
Fuel Composition of Replicated Points Used to Estimate Pure Error

Group	**Blend**	**AvAlky**	**SupAlky**	**Toluene**	**t-Bt_Bnz**	**m-Tol**	**ETBE**	**i-Pen**
1	**16**	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501
1	**27**	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501
1	**36**	0.2949	0.3949	0.1482	0.0321	0.0798	0.0000	0.0501
2	**6**	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.0502
2	**28**	0.1298	0.5001	0.0000	0.1998	0.1201	0.0000	0.0502
3	**4**	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501
3	**37**	0.5998	0.0171	0.0130	0.1998	0.1201	0.0000	0.0501

3.0 OBJECTIVES

Conduct regression analyses of fuel composition variables against engine octane response for Phase III blends 1-45. Responses of interest include fuel ASTM MON rating, engine BSFC at knock on-set, engine fuel flow at knock on-set, and equivalence ratio at knock on-set which were obtained at four power settings.

4.0 REGRESSION METHODOLOGY

Regression analyses were conducted using standard statistical software (STATISTICA and SAS). Models were developed for each response at each power setting, as well as for the average over the four different power settings. Models for mixture data do not have an intercept term since the total proportion of all components sum to a constant value. I investigated models comprised of linear effects; linear and quadratic effects; linear, quadratic, and selected cubic effects; and various methods of stepwise regression to develop the best, statistically valid, parsimonious models. The stepwise methods included stepwise with various values for variables to enter or be removed from the model. forward selection with various values for variables to enter the model, and backward elimination with various values for variables to stay in the model. For modeling responses based on mixture experiments, I prefer those based on the backward elimination method. The final models define the relationship between fuel composition and full-scale engine detonation characteristics.

Reported results include the use of acronyms and various terms that are described as follows.

Response variable – a variable that is measured or tested for each given blend. Regression analysis is performed on this variable in order to predict its values or explain its variation as a function of the explanatory variables. For example, MON is a response variable.

Explanatory variable – a blend component that is by itself, or in conjunction with one or two other components, to investigate linear, quadratic and special cubic effects. For example, Aviation Alkylate is a linear explanatory variable and Aviation Alkylate x Super Alkylate is a quadratic explanatory variable.

Observed value – the measured or tested value of a response variable for a given blend. For example, a MON of 99.7 is observed for Blend 1.

Predicted value – the estimated value of a response variable for a given blend.

Residual – the difference between an observed value and predicted value for a given blend.

Standardized residual – a residual divided by its standard error. Standardizing results in residuals that have a standard normal distribution, thus around 95% of standardized residuals will be between -2.0 and +2.0 and over 99% will be between -3.0 and +3.0. This facilitates the identification of potential outliers or blends for which a model is having difficulty predicting an observed value.

Mean Squared Error (MSE) – The Mean Squared Error for a regression model is an unbiased estimate of the common variance of the residuals. It is based on the residuals and the degrees of freedom associated with estimating the common variance. For mixture data, this degrees of freedom is n-p, where n is the number of observations and p is the number of variables in the model. It is a measure of how close the predicted values are to observed values.

Degrees of freedom – the amount of independent information available to estimate a quantity of interest. A larger degrees of freedom implies more information is available, thus leading to more precise estimates.

Model building procedures include:

Fixed Model – all explanatory variables of interest are included in the model. For example, the linear model contains all linear explanatory variables.

Forward Selection – start without any explanatory variables in the model and add only significant variables one at a time.

Backward Elimination – start with all explanatory variables in the model and remove non-significant variables one at a time.

Stepwise – start without any explanatory variables in the model and add only significant variables one at a time; however, after a variable is added, all variables currently in the model are checked for significance and non-significant variables are removed one at a time.

For each response, the following is provided:

- The stepwise technique used to select the explanatory variables for the final model.
- The final model is given as a function of the explanatory variables using the following notation:
    - AVALK = Aviation Alkylate, SUALK = Super Alkylate, TOL = Toluene, tBB = *tert*-Butyl Benzene, and mT = *meta*-Toluidine.
    - Higher order terms are denoted with a small "x". For example: AVALK x SUALK.
    - A large "X" is used to indicate multiplication between an effect and its coefficient. For example: AVALK x tBB X 22.441.
- A brief description of the model and associated summary statistics, including a p-value for the Shapiro-Wilk test for normality of the residuals. The null hypothesis for this test is that the residuals are from a normal distribution, therefore we fail to reject for large p-values.
- A table that gives coefficients for linear, quadratic, special cubic, the final model, and goodness of fit statistics such as number of explanatory variables, MSE, minimum and maximum standardized residuals. For models based on mixture experiments, the sign of a coefficient for higher order terms tells us if the explanatory variables are synergistic (the coefficient has a positive sign) or antagonistic (the coefficient has a negative sign). The residuals given in all tables are standardized for ease of interpretation, these are *not* raw residuals. Large standardized residuals, say those less than -3.0 or greater than +3.0, are an indication of potential outliers. None of the responses have observations that are potential outliers.
- A graph of observed versus predicted values to assess goodness of fit.
- A graph of observed versus predicted values with 95% confidence interval for an individual predicted value to assess the reliability of predictions and model performance.
- A graph of raw residuals versus predicted values to assess the homogeneity of variance assumption
- A normal probability plot of residuals to assess the normality assumption.

The statistical significance of each regression coefficient is denoted using the following legend:

**** Significant at the 0.001 level
*** Significant at the 0.01 level
** Significant at the 0.05 level
* Significant at the 0.10 level
No asterisks Not significant at any of the above levels

This allows the importance of each explanatory variable to be determined quite readily.

4.1 MON Regression Analysis

The best model for MON was selected using Backward Elimination with a significance level to stay of 0.10.

MON Model

MON = (AVALK X 97.552) + (SUALK X 108.72342) + (TOL X 111.67524) +
(tBB X 104.73734) + (mT X 117.41574) + (ETBE X 99.65123) -
(AVALK x SUALK X 8.1114) + (AVALK x tBB X 22.441) +
(AVALK x mT X 80.69856) + (AVALK x ETBE X 9.07637) –
(SUALK x TOL X 32.39934) + (SUALK x mT X 63.32299) –
(tBB x mT X 50.59123) + (mT x ETBE X 42.17913) +
(AVALK x SUALK x TOL X 43.14445) –
(AVALK x TOL x tBB X 172.44862) + (TOL x tBB x mT X 557.42779) +
(tBB x mT x ETBE X 173.54337)

This model has 18 variables and a MSE = 0.08185 with 27 degrees of freedom. This MSE is about five time bigger than Pure Error, which is 0.01667. The smallest residual is -2.362 for Blend 34 and the largest residual is 2.537 for Blend 39. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.8565, thus confirming they are from a normal distribution.

Table 3
MON Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	101.21****	98.63****	96.24****	97.55200****
Super Alkylate	x2	105.68****	107.09****	106.64****	108.72342****
Toluene	x3	101.36****	115.94****	115.42****	111.67524****
tert-Butyl Benzene	x4	105.30****	98.14****	98.09****	104.73734****
meta-Toluidine	x5	160.01****	92.67	110.73**	117.41574****
ETBE	x6	103.22****	97.07****	100.74****	99.65123****
	x1*x2		-2.20	-11.58	-8.11140****
	x1*x3		-15.34	6.39	
	x1*x4		16.75	38.62**	22.44100****
	x1*x5		101.37	96.92	80.69856****
	x1*x6		10.69	10.76	9.07637****
	x2*x3		-27.44	-23.52	-32.39934****
	x2*x4		8.74	19.85	
	x2*x5		83.60	75.52	63.32299****
	x2*x6		5.54	2.66	
	x3*x4		-14.12	20.35	
	x3*x5		71.33	-46.53	
	x3*x6		-10.31	-23.23	
	x4*x5		52.38	-65.39	-50.59123**
	x4*x6		25.86	0.81	
	x5*x6		85.30	39.14	42.17913*
	x1*x2*x3			44.26	43.14445**
	x1*x2*x4			6.98	
	x1*x2*x5			30.77	
	x1*x2*x6			18.39	

	x1*x3*x4			-258.07**	-172.44862****
	x2*x3*x4			-102.13	
	x3*x4*x5			840.31**	557.42779***
	x3*x5*x6			190.48	
	x4*x5*x6			235.87	173.54337**
	# Variables	6	21	30	18
	MSE	0.18794	0.14008	0.09734	0.08185
	Obs/Min Std Res	30/-2.807	9/-2.746	30/-2.606	34/-2.362
	Obs/Max Std Res	33/2.592	33/2.874	18/2.193	39/2.537

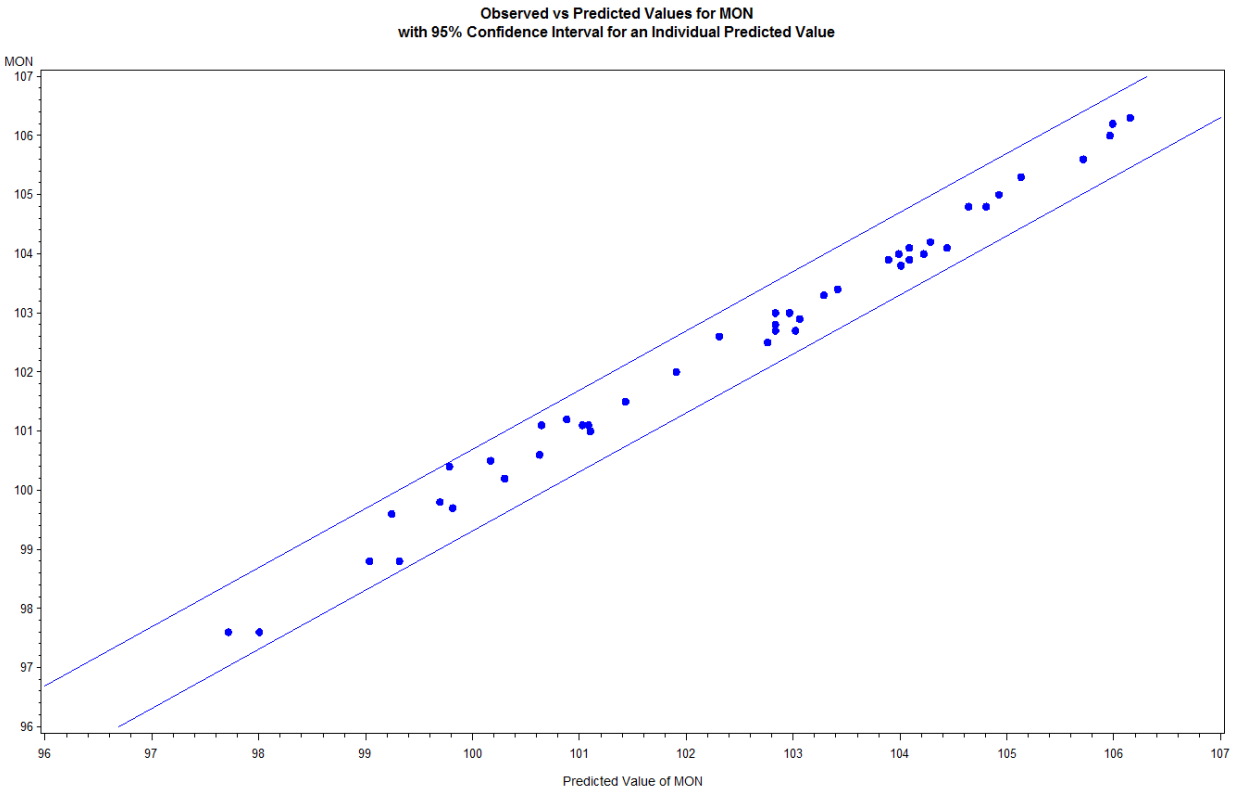

Figure 1 Observed versus Predicted Values for MON with 95% Confidence Interval for an Individual Predicted Value

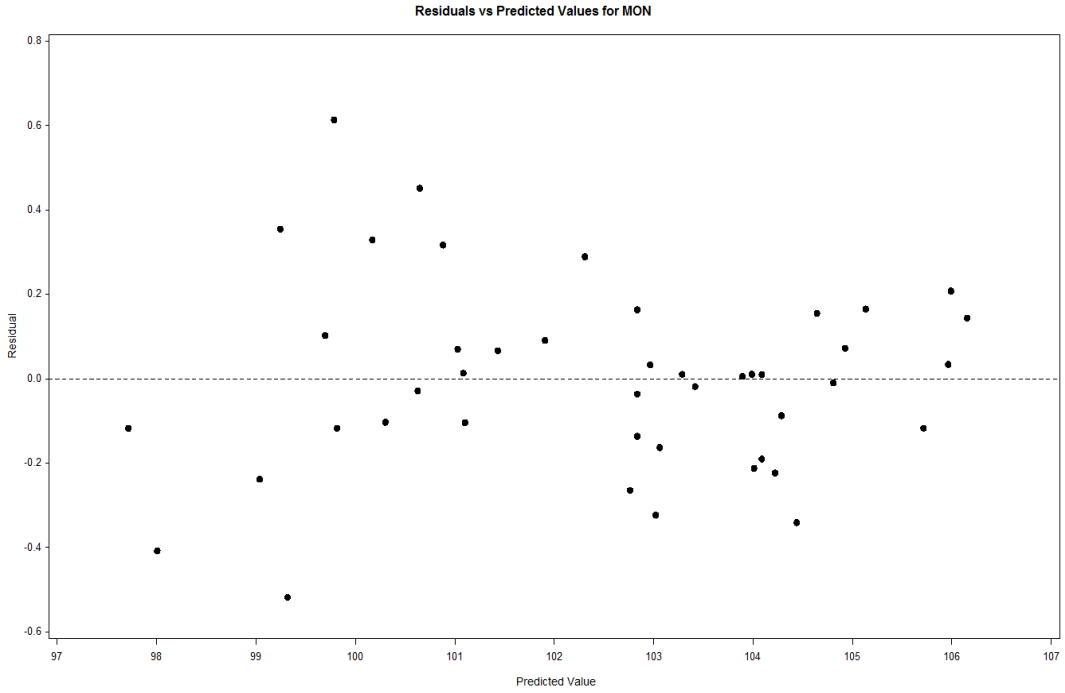

Figure 2 Residual versus Predicted Values for MON

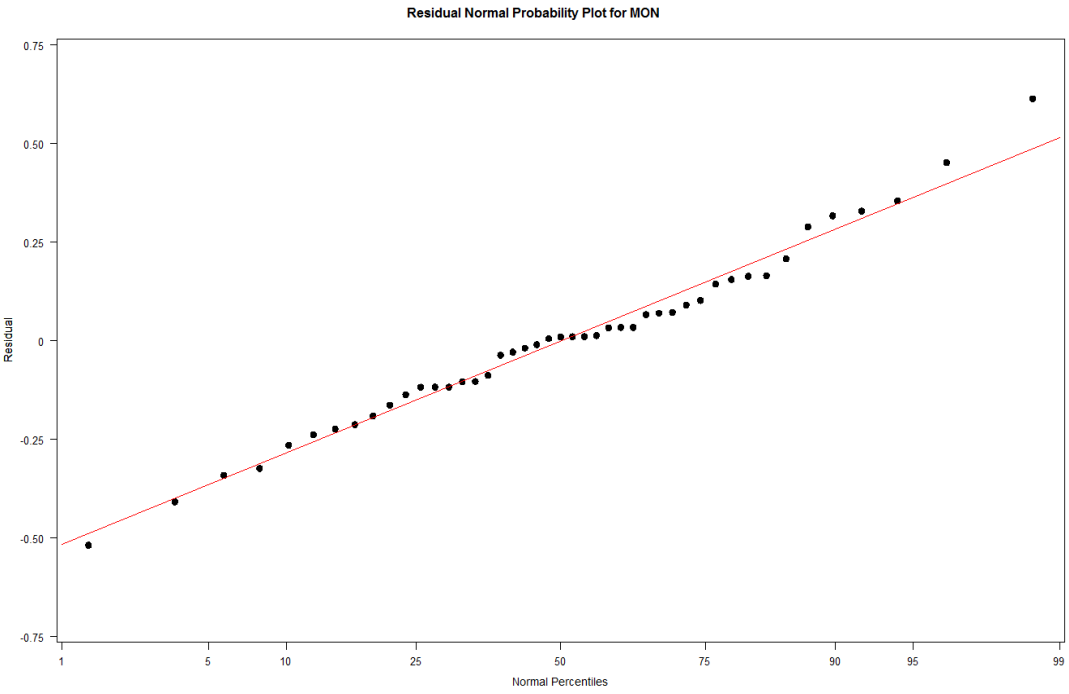

Figure 3 Normal Probability Plot of MON Residuals

4.2 Average Fuel Flow Regression Analysis

The best model for Average Fuel Flow was selected using Backward Elimination with a significance level to stay of 0.10 and the additional requirement that the six linear terms remain in the model.

Average Fuel Flow Model

AvgFF = (AVALK X 143.58957) + (SUALK X 103.73815) + (TOL X 128.39692) +
(tBB X 159.37483) - (mT X 95.25733) + (ETBE X 149.58962) +
(AVALK x SUALK X 100.20032) - (AVALK x tBB X 63.06916) +
(SUALK x TOL X 78.07939) + (SUALK x ETBE X 64.86165) –
(AVALK x SUALK x mT X 711.46666) –
(AVALK x SUALK x ETBE X 216.96122) +
(AVALK x TOL x tBB X 290.17490)

This model has 13 variables and a MSE = 2.32925 with 24 degrees of freedom. This MSE is similar to Pure Error, which is 4.098576. The smallest residual is -1.516 for Blend 4 and the largest residual is 1.93 for Blend 37. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.7057, thus confirming they are from a normal distribution.

Table 4
Average Fuel Flow Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	142.94****	159.33****	139.54****	143.58957****
Super Alkylate	x2	126.26****	121.86****	93.41***	103.73815****
Toluene	x3	149.39****	65.19	71.81	128.39692****
tert-Butyl Benzene	x4	143.59****	127.82*	180.31*	159.37483****
meta-Toluidine	x5	-123.65****	125.26	503.79	-95.25733****
ETBE	x6	152.36****	163.10****	176.19***	149.58962****
	x1*x2		12.27	122.05	100.20032****
	x1*x3		72.58	133.40	
	x1*x4		-39.18	-73.76	-63.06916***
	x1*x5		-399.02	-642.88	
	x1*x6		-55.48	-8.80	
	x2*x3		142.96	209.26	78.07939***
	x2*x4		21.89	16.69	
	x2*x5		-397.16	-497.83	
	x2*x6		-4.23	52.15	64.86165***
	x3*x4		135.55	-170.58	
	x3*x5		-127.48	-1135.60	
	x3*x6		82.60	5.16	
	x4*x5		-85.24	-986.36	
	x4*x6		12.89	-113.78	
	x5*x6		-211.05	-1044.03	
	x1*x2*x3			-70.42	
	x1*x2*x4			-1.69	
	x1*x2*x5			-1163.70	-711.46666****
	x1*x2*x6			-222.29	-216.96122**
	x1*x3*x4			575.20	290.17490*
	x2*x3*x4			93.20	

	x3*x4*x5			2171.19	
	x3*x5*x6			1986.00	
	x4*x5*x6			1832.06	
	# Variables	6	21	30	13
	MSE	4.21803	3.65984	3.61279	2.32925
	Obs/Min Std Res	7/-2.430	10/-2.050	7/-1.794	4/-1.516
	Obs/Max Std Res	9/2.022	9/2.339	25/1.773	37/1.93

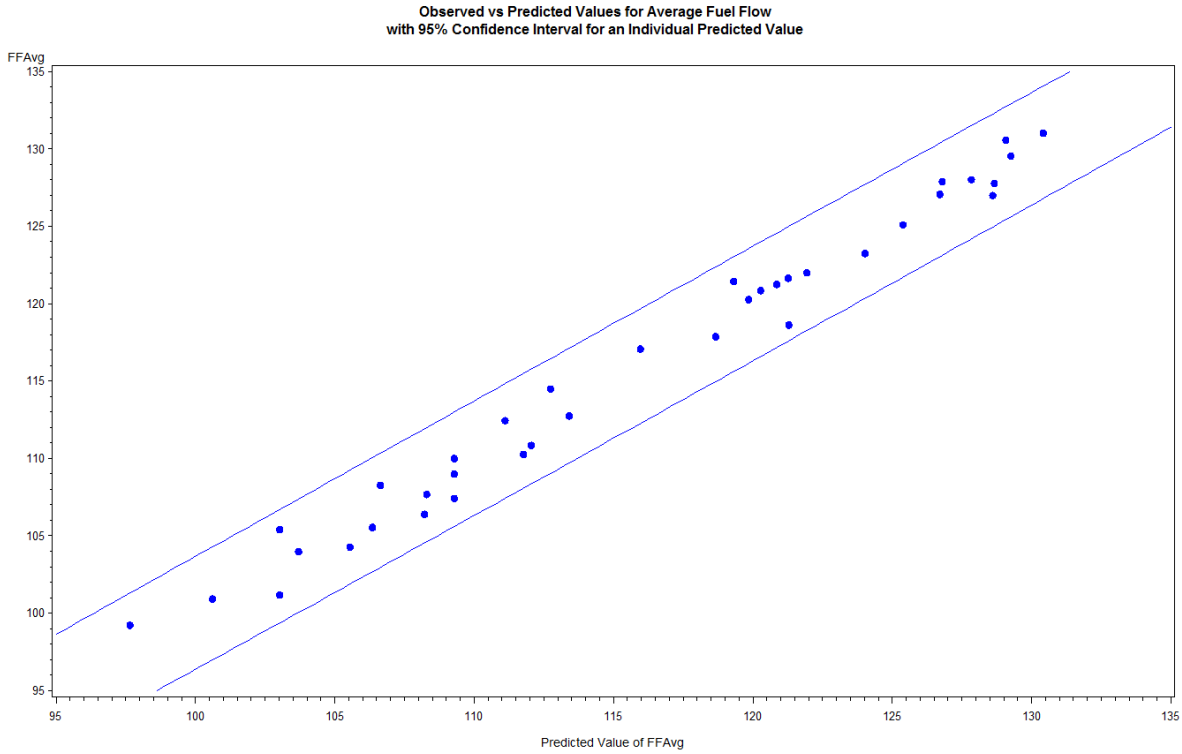

Figure 4 Observed versus Predicted Values for Average Fuel Flow with 95% Confidence Interval for an Individual Predicted Value

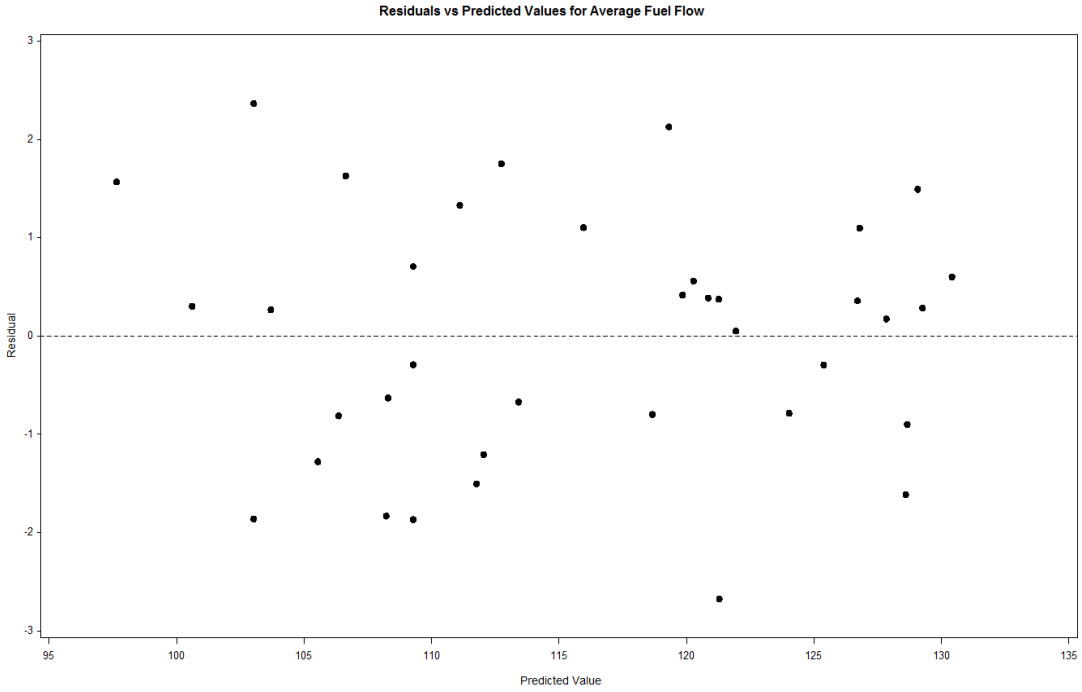

Figure 5 Residual versus Predicted Values for Average Fuel Flow

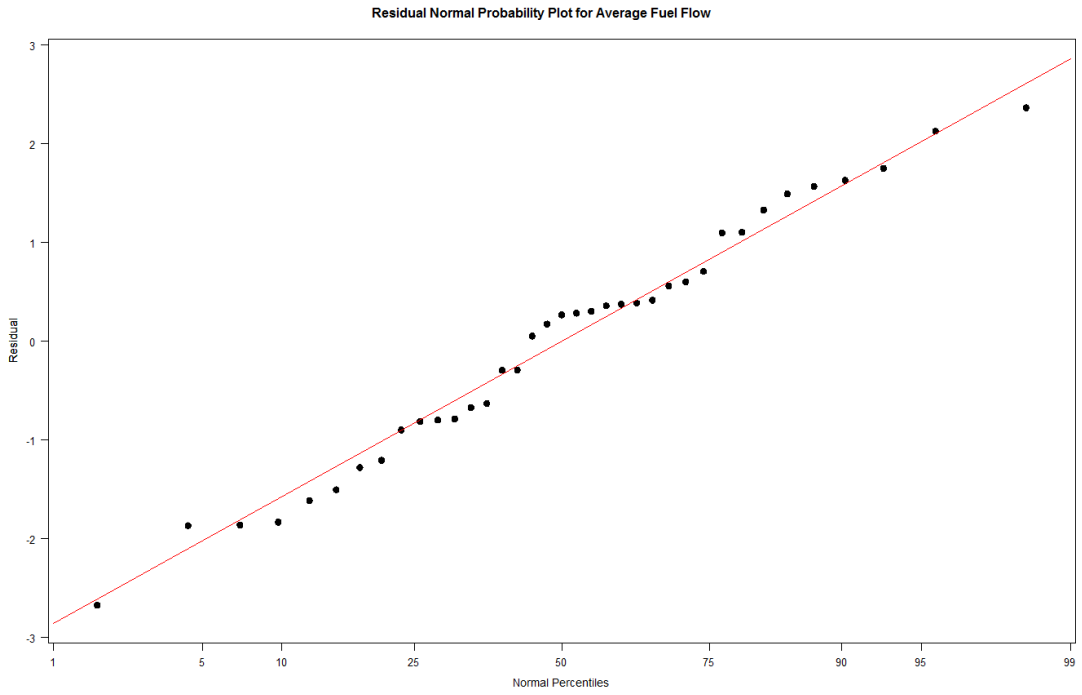

Figure 6 Normal Probability Plot of Average Fuel Flow Residuals

4.3 Fuel Flow at 2350 rpm Regression Analysis

The best model for Fuel Flow at 2350 rpm was selected using Backward Elimination with a significance level to stay of 0.10.

Fuel Flow at 2350 rpm Model

FF_{2350} = (AVALK X 119.68130) + (SUALK X 85.71555) +
(tBB X 106.99535) + (ETBE X 134.76866) +
(AVALK x SUALK X 36.66789) + (AVALK x TOL X 128.16674) -
(AVALK x tBB X 56.30614) - (AVALK x mT X 96.82942) -
(AVALK x ETBE X 37.57537) + (SUALK x TOL X 213.00542) +
(TOL x ETBE X 148.6928) - (mT x ETBE X 220.80871) +
(AVALK x SUALK x tBB X 225.31392) –(AVALK x SUALK x mT X 850.44891) +
(AVALK x TOL x tBB X 612.271) – (TOL x tBB x mT X 1143.13555) +
(tBB x mT x ETBE X 900.37832)

This model has 17 variables and a MSE = 1.60656 with 26 degrees of freedom. This MSE is similar to Pure Error, which is 2.2039. The smallest residual is -2.369 for Blend 7 and the largest residual is 2.064 for Blend 25. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.5898, thus confirming they are from a normal distribution.

Table 5
Fuel Flow at 2350 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	113.15***	123.51****	112.84****	119.68130****
Super Alkylate	x2	99.00***	94.32****	79.40****	85.71555****
Toluene	x3	119.02***	5.23	-20.13	
tert-Butyl Benzene	x4	115.86***	40.61	112.63**	106.99535****
meta-Toluidine	x5	-102.32***	228.07	443.73	
ETBE	x6	120.53***	133.04****	144.68****	134.76866****
	x1*x2		-2.70	57.83	36.66789**
	x1*x3		152.04	177.47**	128.16674****
	x1*x4		75.20	-26.40	-56.30614***
	x1*x5		-482.59	-569.77**	-96.82942****
	x1*x6		-38.54	-15.74	-37.57537****
	x2*x3		198.14**	254.21***	213.00542****
	x2*x4		109.05	17.68	
	x2*x5		-433.32	-450.60	
	x2*x6		-7.77	21.34	
	x3*x4		138.80	58.68	
	x3*x5		-306.38	-581.02	
	x3*x6		118.62	116.63	148.6928****
	x4*x5		-131.84	-757.94*	
	x4*x6		70.56	-82.00	
	x5*x6		-350.91	-975.73**	-220.80871****
	x1*x2*x3			-27.85	
	x1*x2*x4			208.17	225.31392***
	x1*x2*x5			-1048.00**	-850.44891****
	x1*x2*x6			-22.39	

	x1*x3*x4			686.10	612.27100****
	x2*x3*x4			144.04	
	x3*x4*x5			-1954.96	-1143.13555**
	x3*x5*x6			954.24	
	x4*x5*x6			2366.55*	900.37832***
	# Variables	6	21	30	17
	MSE	4.06753	3.74906	1.93195	1.60656
	Obs/Min Std Res	7/-2.017	10/-2.026	7/-2.083	7/-2.369
	Obs/Max Std Res	24/1.872	24/2.13	17/2.018	25/2.064

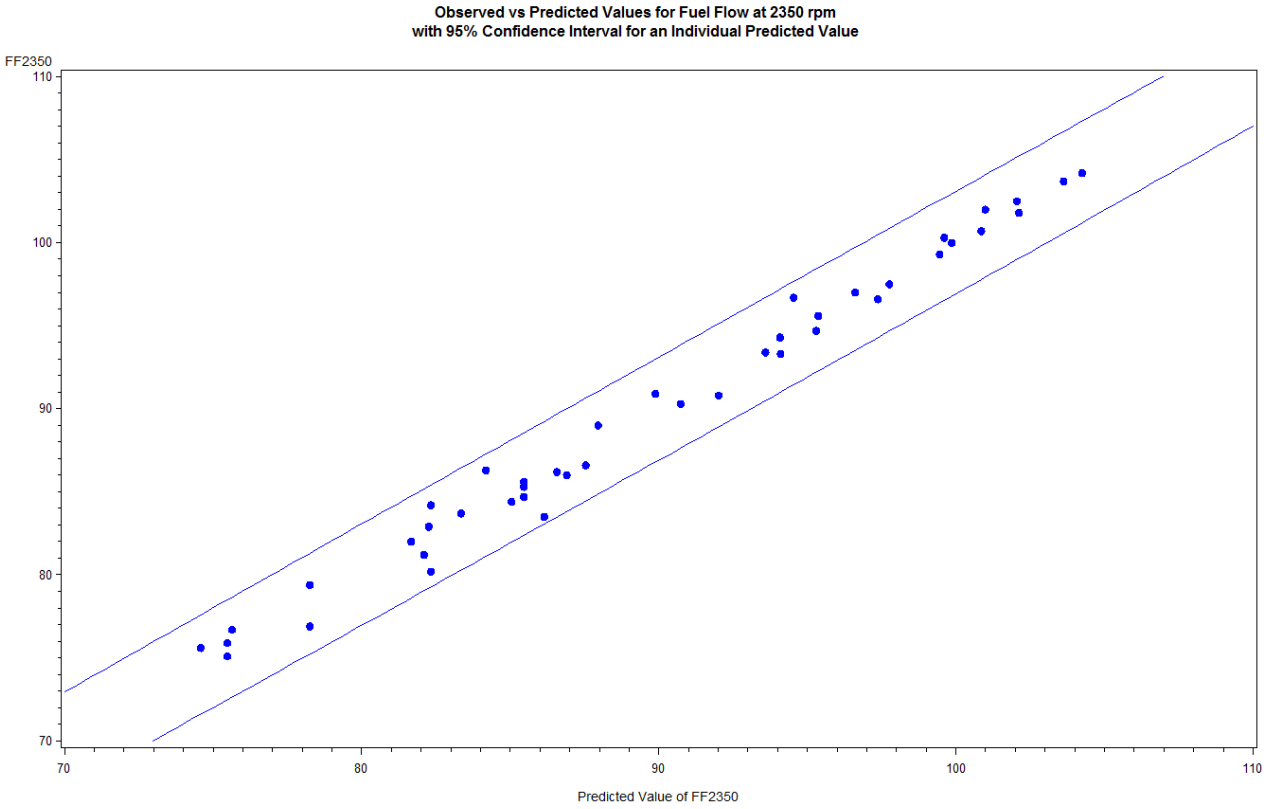

Figure 7 Observed versus Predicted Values for Fuel Flow at 2350 rpm with 95% Confidence Interval for an Individual Predicted Value

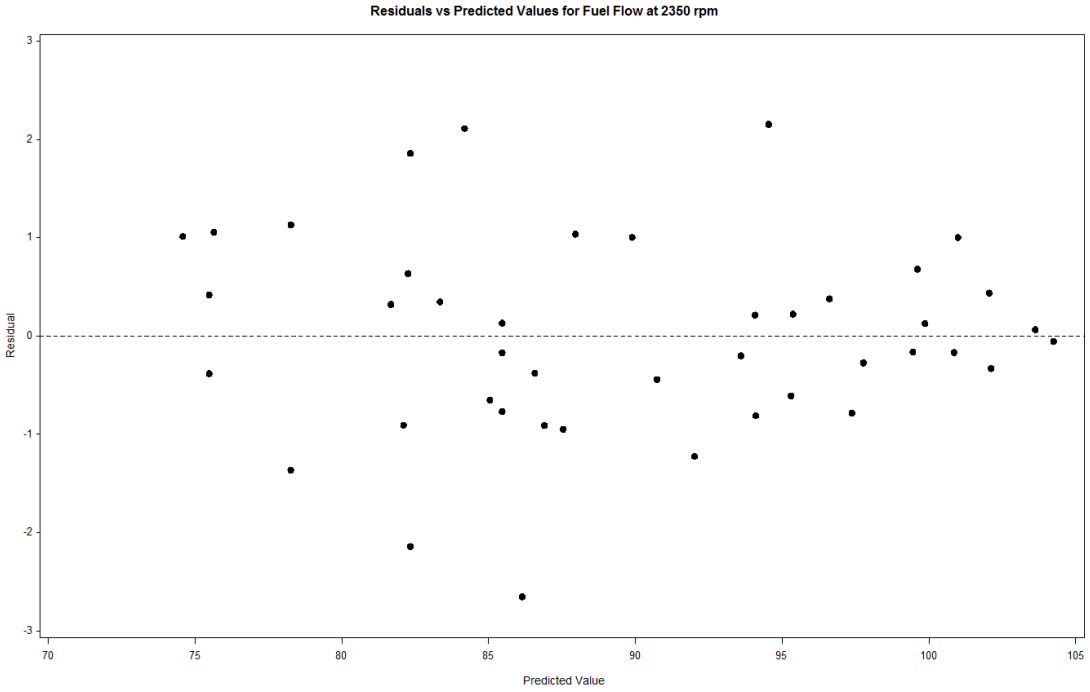

Figure 8 Residual versus Predicted Values for Fuel Flow at 2350

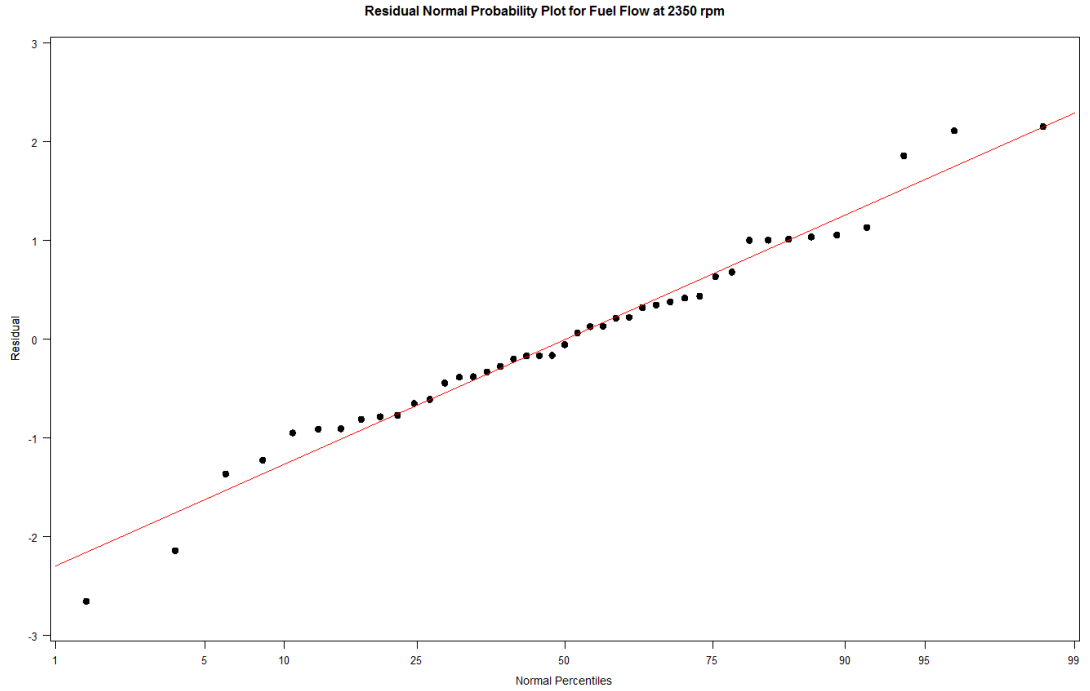

Figure 9 Normal Probability Plot of Fuel Flow at 2350 rpm Residuals

4.4 Fuel Flow at 2450 rpm Regression Analysis

The best model for Fuel Flow at 2450 rpm was selected using Backward Elimination with a significance level to stay of 0.05.

Fuel Flow at 2450 rpm Model

FF_{2450} = (AVALK X 124.90383) + (SUALK X 112.12693) +
(TOL X 142.96247) + (tBB X 129.86625) + (ETBE X 146.21969) +
(AVALK x SUALK X 45.54588) - (TOL x mT X 311.6288) -
(tBB x mT X 303.68769) - (mT x ETBE X 334.10026) -
(AVALK x SUALK x mT X 827.55787) +
(tBB x mT x ETBE X 1461.6769)

This model has 11 variables and a MSE = 3.86202 with 32 degrees of freedom. This MSE is over 10 times larger than Pure Error, which is 0.377303. The smallest residual is -1.986 for Blend 5 and the largest residual is 2.509 for Blend 9. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.7598, thus confirming they are from a normal distribution.

Table 6
Fuel Flow at 2450 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	131.90****	139.66****	117.10****	124.90383****
Super Alkylate	x2	116.96****	121.77****	86.66****	112.12693****
Toluene	x3	131.41****	99.77	94.78	142.96247****
tert-Butyl Benzene	x4	134.29****	95.23	179.44**	129.86625****
meta-Toluidine	x5	-118.14****	229.77	382.81	
ETBE	x6	140.06****	157.69****	186.60****	146.21969****
	x1*x2		-15.97	127.46*	45.54588***
	x1*x3		57.78	91.63	
	x1*x4		20.49	-62.53	
	x1*x5		-441.16	-356.28	
	x1*x6		-48.23	-20.52	
	x2*x3		77.42	182.70	
	x2*x4		27.55	7.08	
	x2*x5		-433.28	-265.87	
	x2*x6		-38.83	0.62	
	x3*x4		-10.49	-307.12	
	x3*x5		-510.22	-1025.02	-311.62880***
	x3*x6		18.31	-68.75	
	x4*x5		-279.58	-1037.91	-303.68769****
	x4*x6		93.99	-132.95	
	x5*x6		-439.61	-1122.60**	-334.10026****
	x1*x2*x3			-186.48	
	x1*x2*x4			-71.75	
	x1*x2*x5			-1441.58***	-827.55787****
	x1*x2*x6			-120.00	
	x1*x3*x4			972.42	
	x2*x3*x4			11.91	
	x3*x4*x5			404.91	

	x3*x5*x6			1888.93	
	x4*x5*x6			2844.80**	1461.67690****
	# Variables	6	21	30	11
	MSE	5.40044	6.13772	4.15317	3.86202
	Obs/Min Std Res	2/-2.942	2/-2.619	2/-2.589	5/-1.986
	Obs/Max Std Res	26/2.002	26/2.489	31/2.246	9/2.509

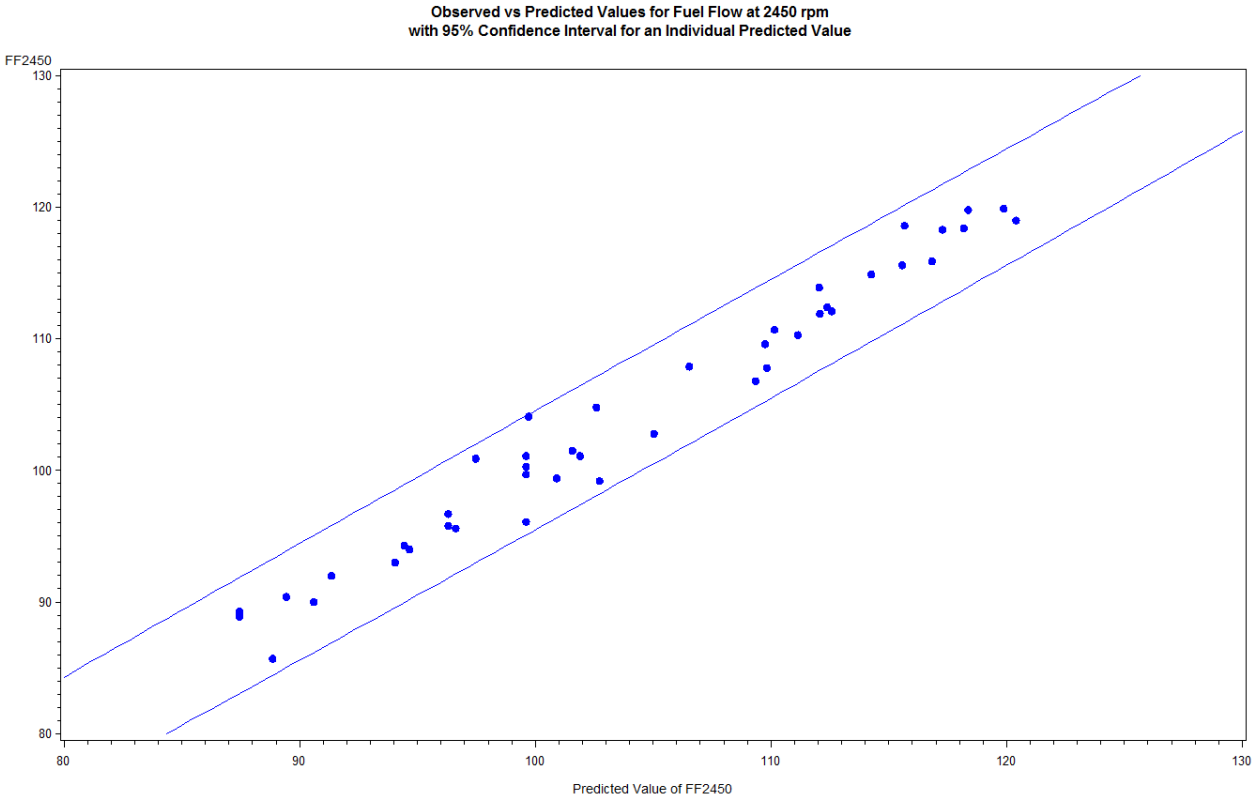

Figure 10 Observed versus Predicted Values for Fuel Flow at 2450 rpm with 95% Confidence Interval for an Individual Predicted Value

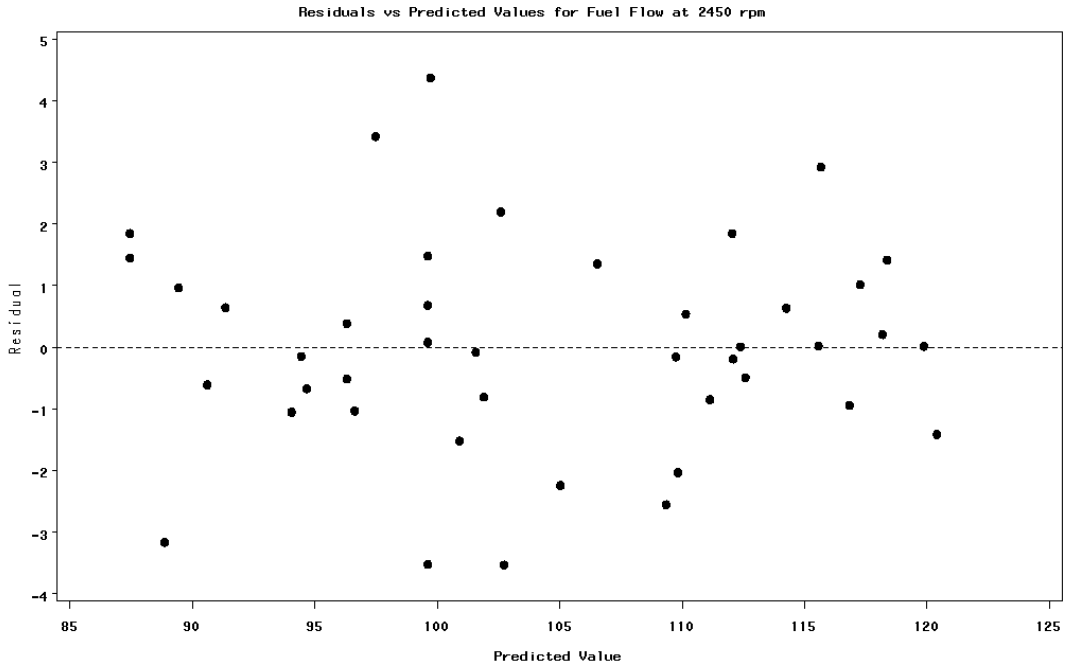

Figure 11 Residual versus Predicted Values for Fuel Flow at 2450 rpm

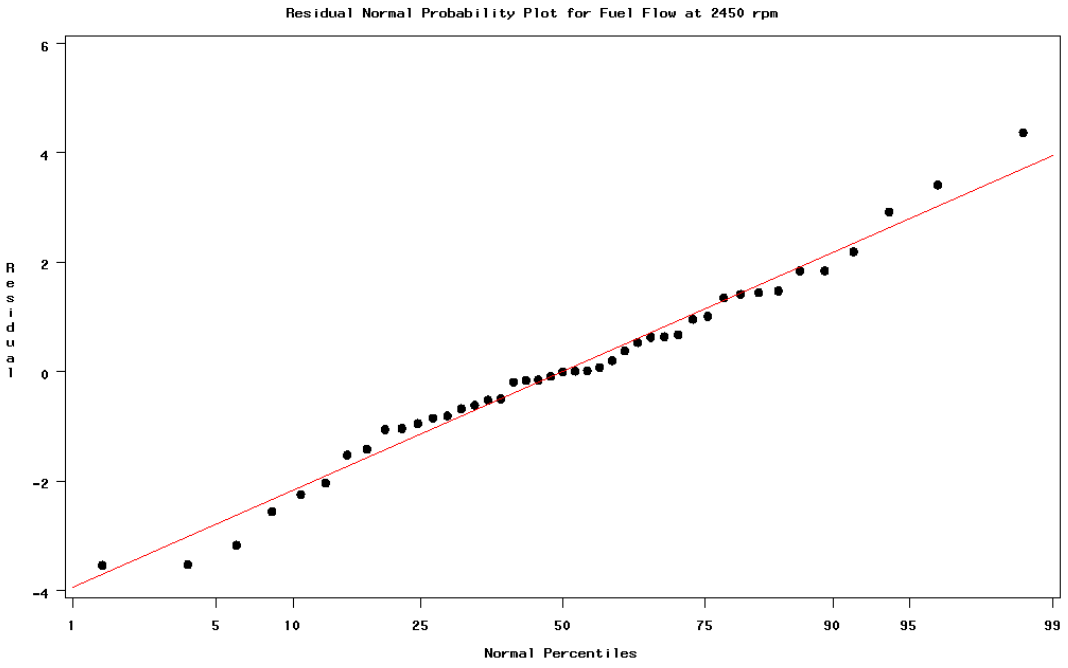

Figure 12 Normal Probability Plot of Fuel Flow at 2450 rpm Residuals

4.5 Fuel Flow at 2600 rpm Regression Analysis

The best model for Fuel Flow at 2600 rpm was selected using Backward Elimination with a significance level to stay of 0.10.

Fuel Flow at 2600 rpm Model

FF_{2600} = (AVALK X 139.26252) + (SUALK X 107.49561) +
(tBB X 181.33597) + (ETBE X 185.09003) +
(AVALK x SUALK X 148.60072) + (AVALK x TOL X 177.38091) -
(AVALK x tBB X 101.88822) + (SUALK x TOL X 295.75976) –
(TOL x tBB X 452.00205) + (TOL x ETBE X 210.17655) –
(tBB x mT X 178.58576) – (mT x ETBE X 380.36609) –
(AVALK x SUALK x TOL X 393.01563) - (AVALK x SUALK x mT X 1193.10580) -
(AVALK x SUALK x ETBE X 208.28648) + (AVALK x TOL x tBB X 1777.21517) +
(SUALK x TOL x tBB X 827.79872)

This model has 17 variables and a MSE = 3.76114 with 25 degrees of freedom. This MSE is similar to Pure Error, which is 6.806744. The smallest residual is -2.214 for Blend 16 and the largest residual is 1.730 for Blend 30. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.5065, thus confirming they are from a normal distribution. .

Table 7

Response: Fuel Flow at 2600 rpm

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	152.18****	149.84****	143.68****	139.26252****
Super Alkylate	x2	134.02****	128.43****	107.77****	107.49561****
Toluene	x3	153.97****	77.82	79.55	
tert-Butyl Benzene	x4	151.82****	179.82**	244.80**	181.33597****
meta-Toluidine	x5	-137.32****	371.75	556.43	
ETBE	x6	159.01****	184.73****	163.94****	185.090003****
	x1*x2		3.97	167.88*	148.60072****
	x1*x3		122.78	85.49	177.38091****
	x1*x4		-31.14	-201.22	-101.88822***
	x1*x5		-600.19	-720.02	
	x1*x6		-11.22	37.27	
	x2*x3		153.22	184.10	295.75976****
	x2*x4		9.26	-116.73	
	x2*x5		-621.60	-654.22	
	x2*x6		-23.62	55.67	
	x3*x4		72.39	-544.65	-452.00205**
	x3*x5		-606.97	-780.69	
	x3*x6		45.11	116.70	210.17655****
	x4*x5		-684.16	-819.78	-178.58576*
	x4*x6		-97.89	-34.75	
	x5*x6		-668.70	-992.41	-380.36609****
	x1*x2*x3			-368.23	-393.01563**
	x1*x2*x4			54.77	
	x1*x2*x5			-1327.39**	-1193.10580****
	x1*x2*x6			-329.78	-208.28648**

	x1*x3*x4			1856.90*	1777.21517****
	x2*x3*x4			1018.14	827.79872**
	x3*x4*x5			-1466.42	
	x3*x5*x6			-27.55	
	x4*x5*x6			-176.64	
	# Variables	6	21	30	17
	MSE	6.08057	7.61649	5.6082	3.76114
	Obs/Min Std Res	3/-2.544	3/-2.886	3/-2.084	16/-2.214
	Obs/Max Std Res	9/2.175	9/3.168	8/2.179	30/1.730

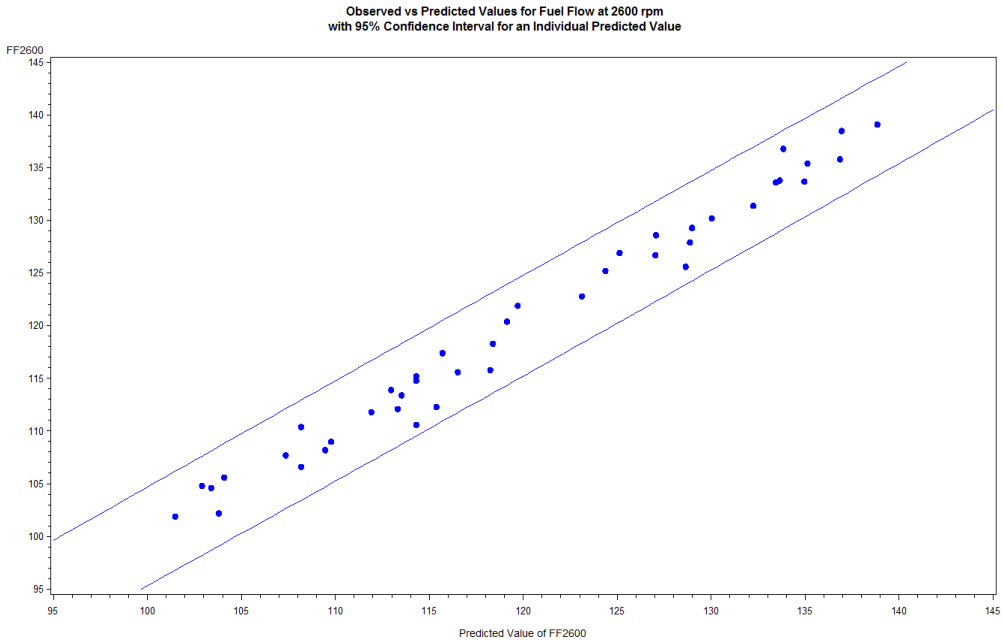

Figure 13 Observed versus Predicted Values for Fuel Flow at 2600 rpm with 95% Confidence Interval for an Individual Predicted Value

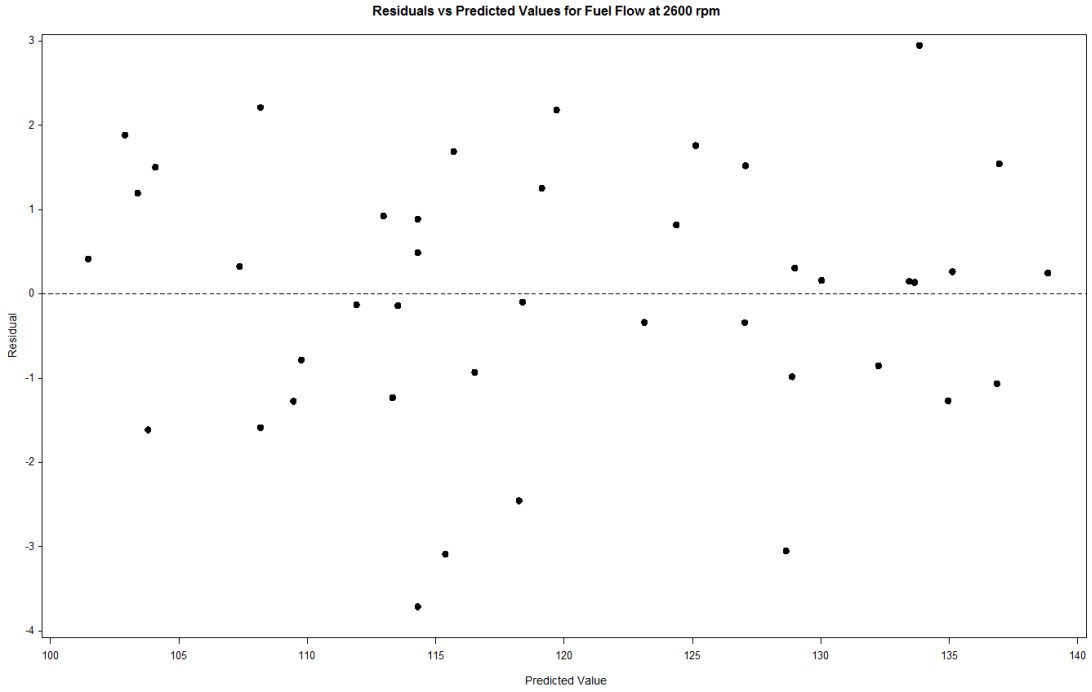

Figure 14 Residual versus Predicted Values for Fuel Flow at 2600 rpm

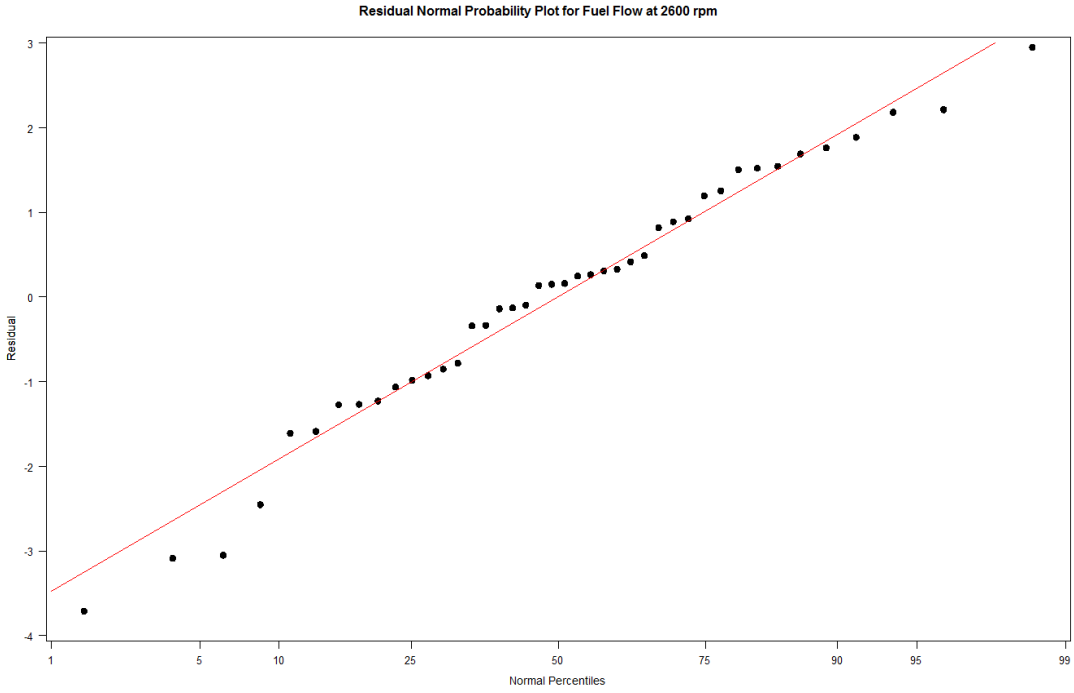

Figure 15 Normal Probability Plot of Fuel Flow at 2600 rpm Residuals

4.6 Fuel Flow at 2700 rpm Regression Analysis

The best model for Fuel Flow at 2700 rpm was selected using Backward Elimination with a significance level to stay of 0.05.

Fuel Flow at 2700 rpm Model

FF_{2700} = (AVALK X 202.55859) + (SUALK X 148.65063) +
(TOL X 155.82497) + (tBB X 181.05937) + (ETBE X 197.73358) -
(AVALK x tBB X 95.59542) - (AVALK x mT X 328.62687) –
(AVALK x ETBE X 84.43984) + (SUALK x TOL X 84.48035) –
(SUALK x mT X 243.10139)

This model has 10 variables and a MSE = 6.07291 with 27 degrees of freedom. This MSE is similar to Pure Error, which is 20.00673. The smallest residual is -2.685 for Blend 4 and the largest residual is 2.261 for Blend 37. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.6538, thus confirming they are from a normal distribution. .

Table 8
Fuel Flow at 2700 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	175.27****	206.76****	192.40****	202.55859****
Super Alkylate	x2	156.65****	149.93****	126.52**	148.65063****
Toluene	x3	192.06****	126.51	150.88	155.82497****
tert-Butyl Benzene	x4	169.69****	221.10**	224.40	181.05937****
meta-Toluidine	x5	-137.87****	-268.04	48.82	
ETBE	x6	188.26****	189.46****	203.85**	197.73358****
	x1*x2		30.34	104.51	
	x1*x3		-20.27	25.71	
	x1*x4		-176.29	-121.98	-95.59542***
	x1*x5		-26.55	-281.53	-328.62687****
	x1*x6		-92.75	-64.37	-84.43984****
	x2*x3		96.59	135.03	84.48035***
	x2*x4		-77.25	0.15	
	x2*x5		-32.82	-190.52	-243.10139****
	x2*x6		8.58	54.91	
	x3*x4		105.47	21.87	
	x3*x5		510.54	-449.64	
	x3*x6		62.75	-58.04	
	x4*x5		337.02	-393.33	
	x4*x6		-56.06	-149.37	
	x5*x6		404.13	-211.74	
	x1*x2*x3			3.58	
	x1*x2*x4			-118.86	
	x1*x2*x5			-574.90	
	x1*x2*x6			-197.73	
	x1*x3*x4			-206.92	
	x2*x3*x4			-294.70	
	x3*x4*x5			3693.84	
	x3*x5*x6			1840.14	

	x4*x5*x6			1272.02	
	# Variables	6	21	30	10
	MSE	10.60629	6.96339	13.74118	6.07291
	Obs/Min Std Res	7/-2.308	4/-2.541	4/-1.83	4/-2.685
	Obs/Max Std Res	30/2.122	37/2.568	37/1.968	37/2.261

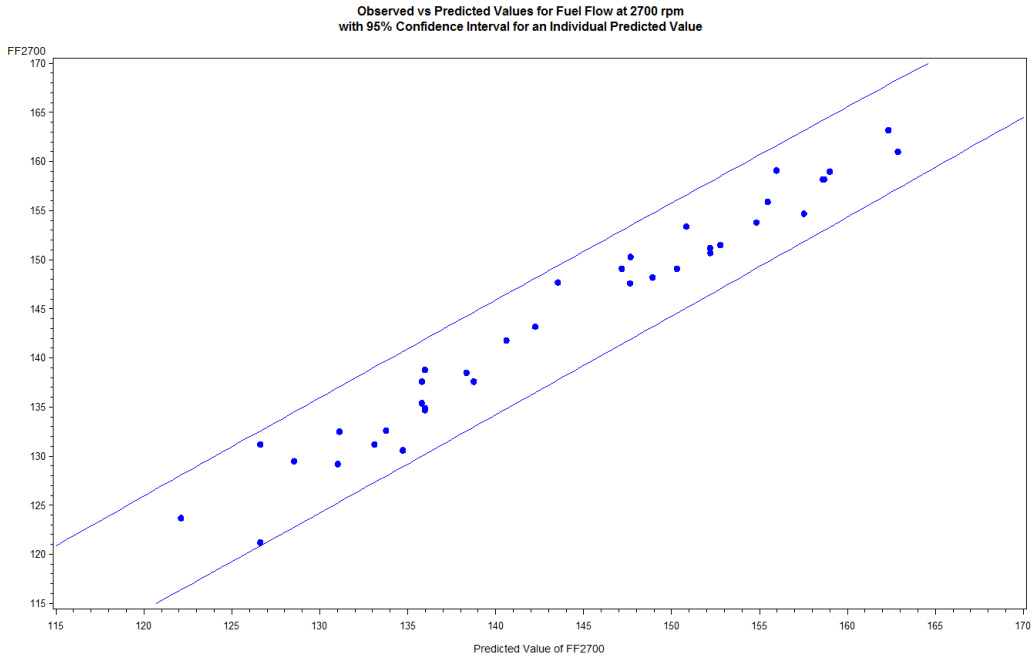

Figure 16 Observed versus Predicted Values for Fuel Flow at 2700 rpm with 95% Confidence Interval for an Individual Predicted Value

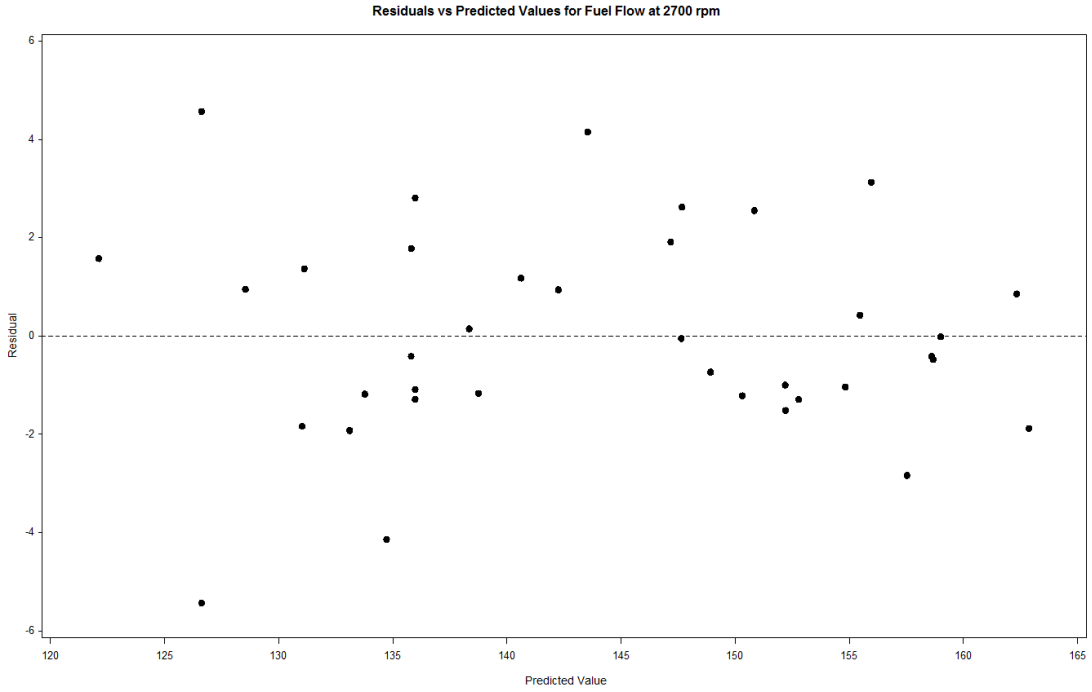

Figure 17 Residual versus Predicted Values for Fuel Flow at 2700 rpm

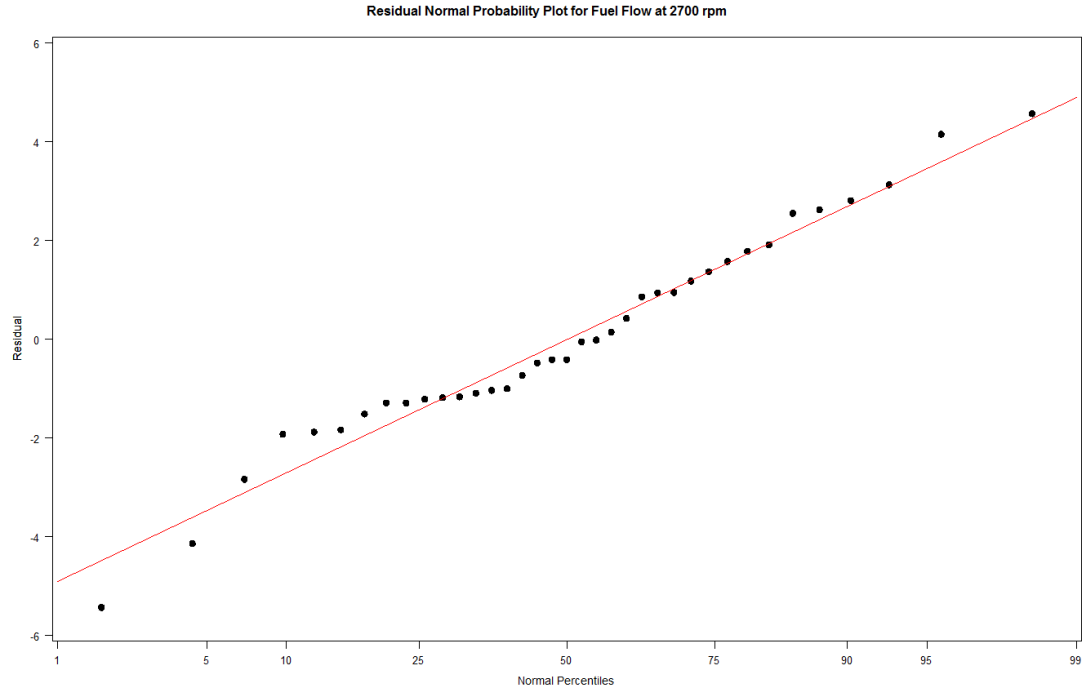

Figure 18 Normal Probability Plot of Fuel Flow at 2700 rpm Residuals

4.7 Average Equivalence Ratio Regression Analysis

The best model for Average Equivalence Ratio was selected using Backward Elimination with a significance level to stay of 0.05.

Average Equivalence Ratio Model

AvgEqR= (AVALK X 1.56777) + (SUALK X 1.17043) +
(TOL X 1.22585) + (tBB X 1.53896) + (ETBE X 1.50289) +
(AVALK x SUALK X 0.44285) -
(AVALK x tBB X 0.73864) - (AVALK x mT X 1.50843) –
(AVALK x ETBE X 0.41227) + (SUALK x TOL X 0.50763) –
(mT x ETBE X 1.35653) – (AVALK x SUALK x mT X 6.76337)

This model has 12 variables and a MSE = 0.00019491 with 25 degrees of freedom. This MSE is similar to Pure Error, which is 0.000151. The smallest residual is -1.938 for Blend 38 and the largest residual is 2.050 for Blend 30. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.3186, thus confirming they are from a normal distribution. .

Table 9
Average Equivalence Ratio Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	1.46****	1.59****	1.44	1.56777****
Super Alkylate	x2	1.31****	1.28****	1.05	1.17043****
Toluene	x3	1.45****	0.53	0.83	1.22585****
tert-Butyl Benzene	x4	1.41****	1.17**	1.44	1.53896****
meta-Toluidine	x5	-0.96****	1.07	5.21	
ETBE	x6	1.39****	1.43****	1.62	1.50289****
	x1*x2		0.06	0.85	0.44285***
	x1*x3		0.93	1.38	
	x1*x4		-0.15	-0.15	-0.73864****
	x1*x5		-3.21	-6.19	-1.50843****
	x1*x6		-0.40	-0.22	-0.41227***
	x2*x3		1.35	1.58	0.50763***
	x2*x4		0.30	0.48	
	x2*x5		-3.06	-3.97	
	x2*x6		0.02	0.21	
	x3*x4		1.03	-1.91	
	x3*x5		-0.38	-13.28	
	x3*x6		1.10	-0.34	
	x4*x5		-0.89	-10.49	
	x4*x6		0.57	-0.10	
	x5*x6		-1.98	-10.64	-1.35653***
	x1*x2*x3			0.38	
	x1*x2*x4			-0.29	
	x1*x2*x5			-12.39*	-6.76337****
	x1*x2*x6			-0.92	
	x1*x3*x4			2.70	
	x2*x3*x4			2.22	
	x3*x4*x5			36.09	

	x3*x5*x6			28.59	
	x4*x5*x6			14.80	
	# Variables	6	21	30	12
	MSE	0.00028232	0.00025813	0.00024285	0.00019491
	Obs/Min Std Res	7/-2.012	19/-2.025	7/-2.152	38/-1.938
	Obs/Max Std Res	30/2.581	9/2.333	25/2.043	30/2.050

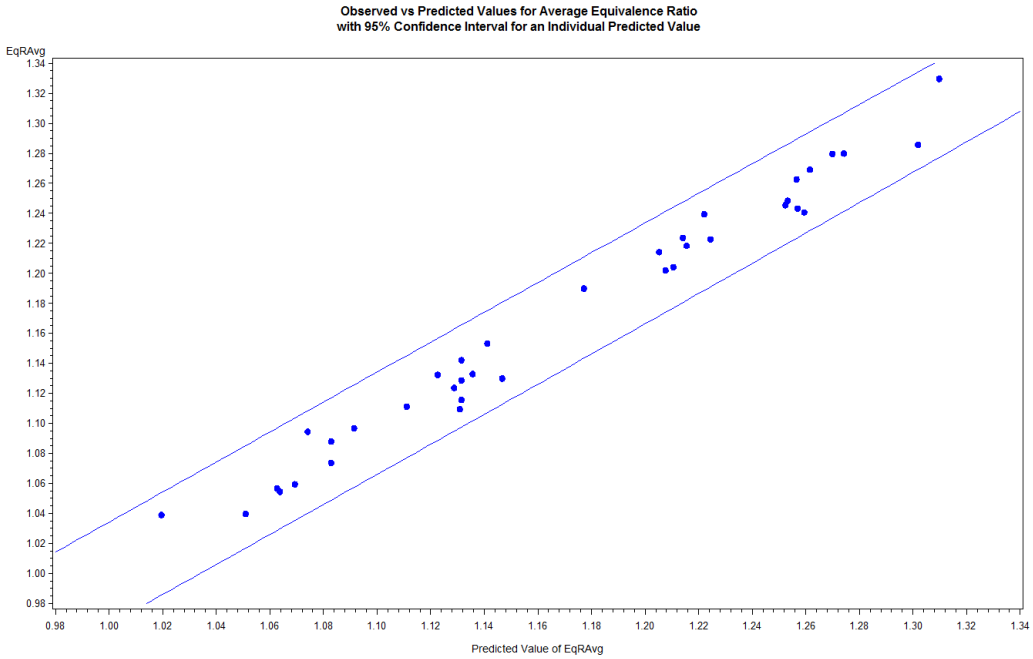

Figure 19 Observed versus Predicted Values for Average Equivalence Ratio with 95% Confidence Interval for an Individual Predicted Value

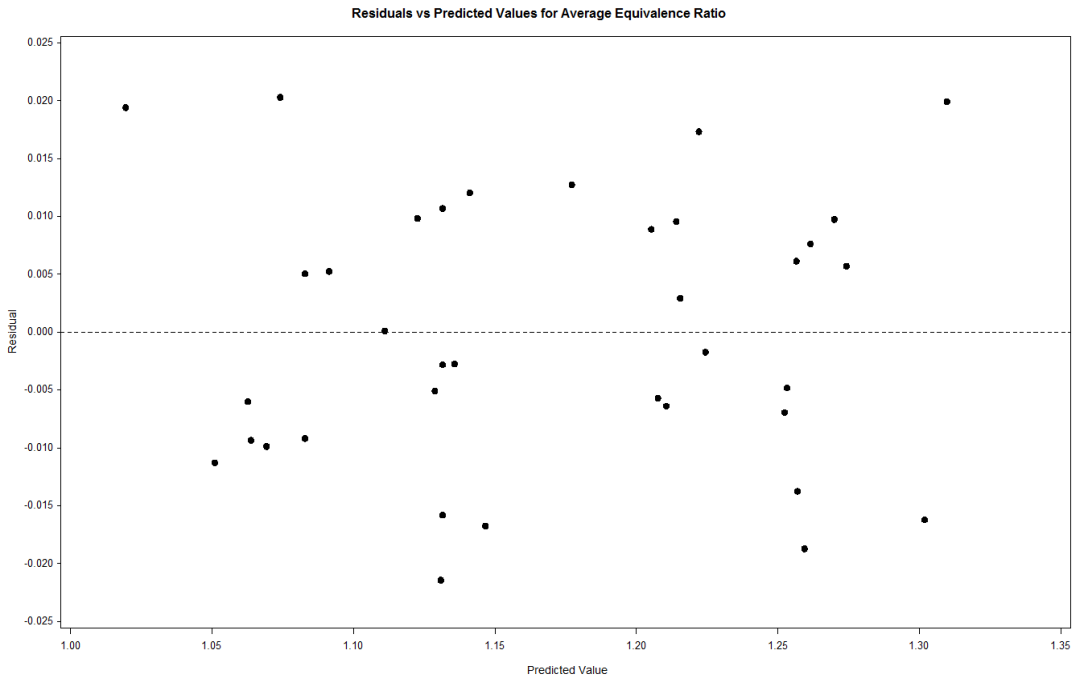

Figure 20 Residual versus Predicted Values for Average Equivalence Ratio

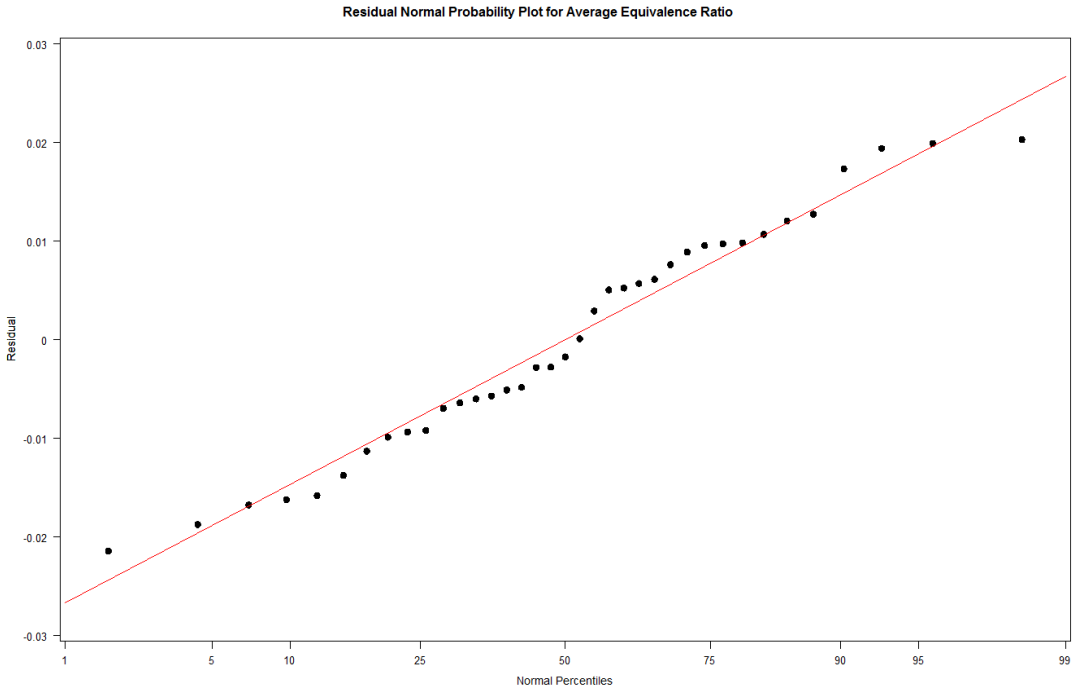

Figure 21 Normal Probability Plot of Average Equivalence Ratio Residuals

4.8 Equivalence Ratio at 2350 rpm Regression Analysis

The best model for Equivalence Ratio at 2350 rpm was selected using Backward Elimination with a significance level to stay of 0.05.

Equivalence Ratio at 2350 rpm Model

EqR_{2350}= (AVALK X 1.53638) + (SUALK X 1.2763) +
(tBB X 1.07341) + (mT X 5.8601) + (ETBE X 1.38046) +
(AVALK x TOL X 2.03595) - (AVALK x mT X 8.66098) –
(AVALK x ETBE X 0.28081) + (SUALK x TOL X 2.10244) –
(SUALK x mT X 7.32635) + (TOL x tBB X 1.10499) –
(TOL x mT X 6.91964) + (TOL x ETBE X 1.80136) –
(tBB x mT X 7.1776) + (tBB x ETBE X 1.08439) -
(mT x ETBE X 8.21785) + (AVALK x SUALK x tBB X 2.73699) –
(AVALK x SUALK x mT X 6.13716)

This model has 18 variables and a MSE = 0.000201 with 25 degrees of freedom. This MSE is similar to Pure Error, which is 0.000181. The smallest residual is -2.216 for Blend 7 and the largest residual is 1.842 for Blend 24. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.6738, thus confirming they are from a normal distribution. .

Table 10
Equivalence Ratio at 2350 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	1.41****	1.55****	1.51****	1.53638****
Super Alkylate	x2	1.28****	1.25****	1.21****	1.27630****
Toluene	x3	1.43****	0.39	-0.05	
tert-Butyl Benzene	x4	1.40****	0.79	1.23*	1.07341****
meta-Toluidine	x5	-0.93****	3.69	6.03*	5.8601**
ETBE	x6	1.36****	1.48****	1.45****	1.38046****
	x1*x2		-0.08	0.16	
	x1*x3		1.37	1.81*	2.03595****
	x1*x4		0.51	-0.30	
	x1*x5		-6.67*	-8.27**	-8.66098***
	x1*x6		-0.42	-0.28	-0.28081**
	x2*x3		1.68*	2.10**	2.10244****
	x2*x4		0.89	-0.07	
	x2*x5		-5.87	-6.63*	-7.32635**
	x2*x6		-0.11	0.03	
	x3*x4		0.82	0.66	1.10499**
	x3*x5		-4.02	-6.85	-6.91964**
	x3*x6		1.05	1.72	1.80136***
	x4*x5		-3.26	-8.34	-7.17760**
	x4*x6		0.72	0.63	1.08439***
	x5*x6		-5.29	-9.92**	-8.21785***
	x1*x2*x3			1.30	
	x1*x2*x4			2.88	2.73699***
	x1*x2*x5			-10.12**	-6.13716****
	x1*x2*x6			0.64	

	x1*x3*x4			4.47	
	x2*x3*x4			1.34	
	x3*x4*x5			-12.07	
	x3*x5*x6			5.49	
	x4*x5*x6			8.55	
	# Variables	6	21	30	18
	MSE	0.00038	0.000337	0.000271	0.000201
	Obs/Min Std Res	8/-2.052	2/-1.838	7/-2.166	7/-2.216
	Obs/Max Std Res	30/2.443	24/1.772	17/2.053	24/1.842

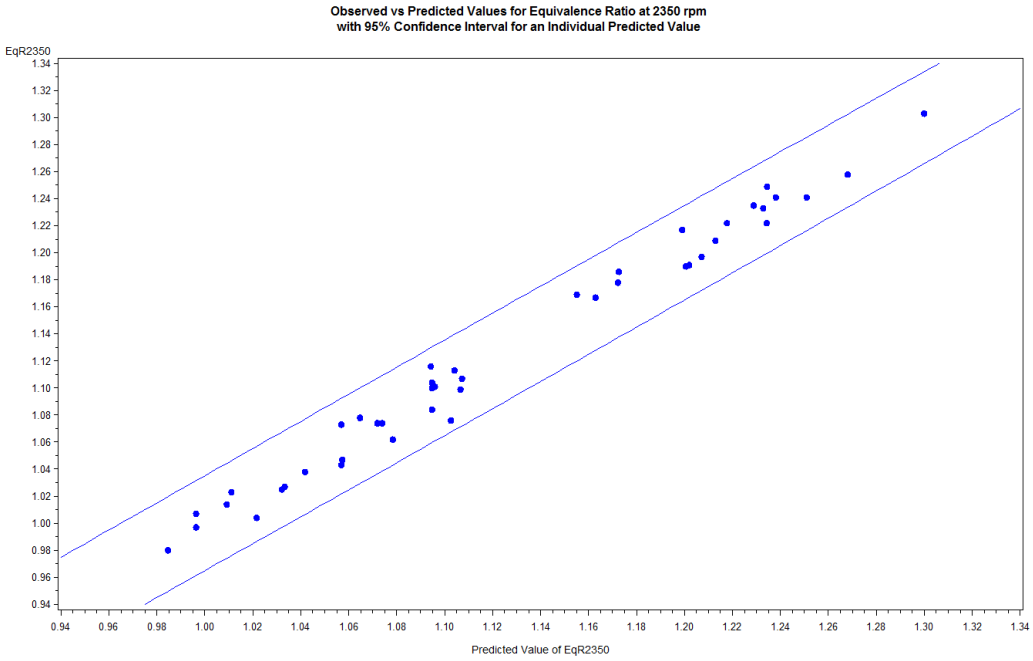

Figure 22 Observed versus Predicted Values for Equivalence Ratio at 2350 rpm with 95% Confidence Interval for an Individual Predicted Value

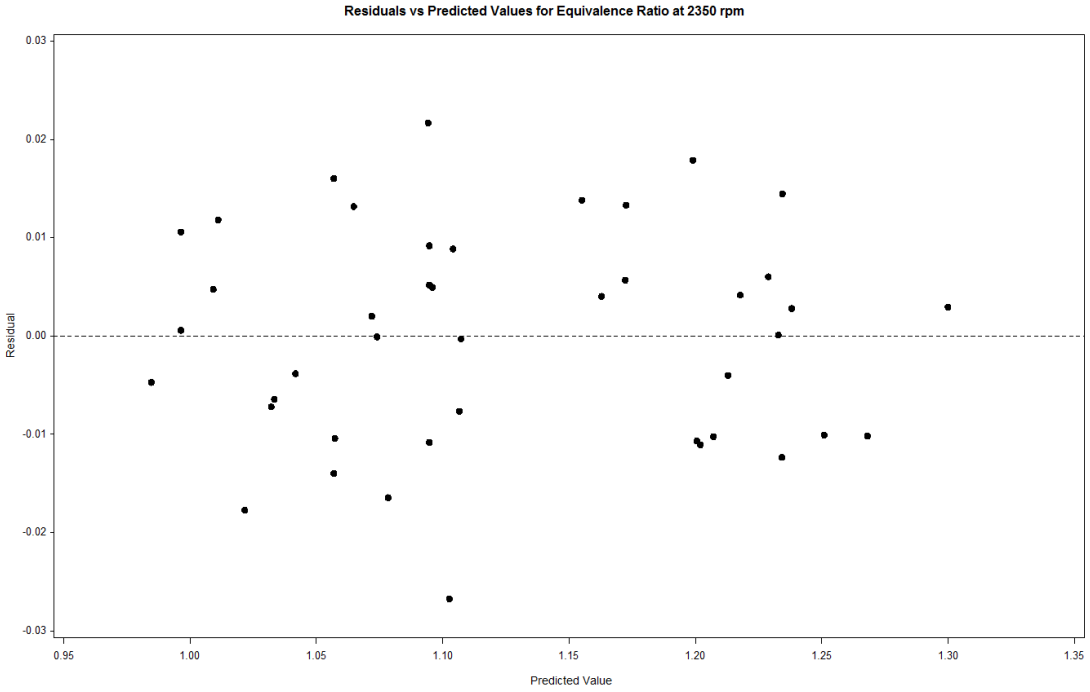

Figure 23 Residual versus Predicted Values for Equivalence Ratio at 2350 rpm

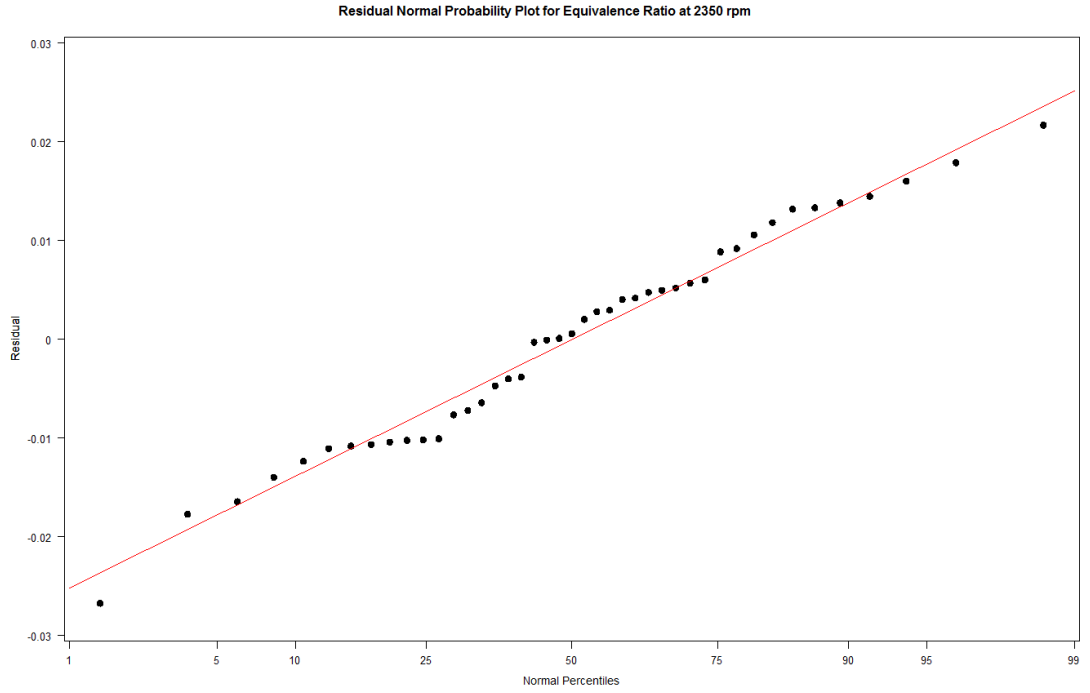

Figure 24 Normal Probability Plot of Equivalence Ratio at 2350 rpm Residuals

4.9 Equivalence Ratio at 2450 rpm Regression Analysis

The best model for Equivalence Ratio at 2450 rpm was selected using Backward Elimination with a significance level to stay of 0.10.

Equivalence Ratio at 2450 rpm Model

EqR_{2450}= (AVALK X 1.43183) + (SUALK X 1.32332) +
(TOL X 1.41061) + (tBB X 1.35499) + (ETBE X 1.40919) -
(TOL x mT X 2.72931) - (tBB x mT X 3.13382) –
(mT x ETBE X 3.76015) - (AVALK x SUALK x mT X 3.85991) +
(TOL x mT x ETBE X 8.50671) + (tBB x mT x ETBE X 17.08459)

This model has 11 variables and a MSE = 0.00042272 with 32 degrees of freedom. This MSE is about five times larger than Pure Error, which is 0.00008650. The smallest residual is -2.402 for Blend 5 and the largest residual is 2.317 for Blend 30. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.6558, thus confirming they are from a normal distribution. .

Table 11
Equivalence Ratio at 2450 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	1.44****	1.56****	1.37****	1.43183****
Super Alkylate	x2	1.31****	1.39****	1.12****	1.32332****
Toluene	x3	1.39****	1.24	1.33	1.41061****
tert-Butyl Benzene	x4	1.41****	1.04	1.67*	1.35449****
meta-Toluidine	x5	-0.92****	3.12	4.19	
ETBE	x6	1.38****	1.60****	1.83****	1.40919****
	x1*x2		-0.20	0.90	
	x1*x3		0.29	0.54	
	x1*x4		0.12	-0.63	
	x1*x5		-5.29	-4.10	
	x1*x6		-0.62	-0.45	
	x2*x3		0.35	1.03	
	x2*x4		0.21	-0.14	
	x2*x5		-5.00	-2.98	
	x2*x6		-0.52	-0.30	
	x3*x4		-0.56	-4.13	
	x3*x5		-5.33	-11.69*	-2.72931***
	x3*x6		-0.06	-1.27	
	x4*x5		-3.65	-9.45	-3.13382****
	x4*x6		1.01	-0.04	
	x5*x6		-5.30	-10.81*	-3.76015****
	x1*x2*x3			-0.74	
	x1*x2*x4			-0.05	
	x1*x2*x5			-13.45**	-3.85991***
	x1*x2*x6			-0.38	
	x1*x3*x4			9.51	
	x2*x3*x4			2.91	
	x3*x4*x5			11.67	
	x3*x5*x6			25.92	8.50671*

	x4*x5*x6			16.24	17.08459****
	# Variables	6	21	30	11
	MSE	0.00050704	0.00053594	0.00048681	0.00042272
	Obs/Min Std Res	2/-3.061	2/-2.499	2/-2.357	5/-2.402
	Obs/Max Std Res	30/1.735	26/2.226	31/2.385	30/2.317

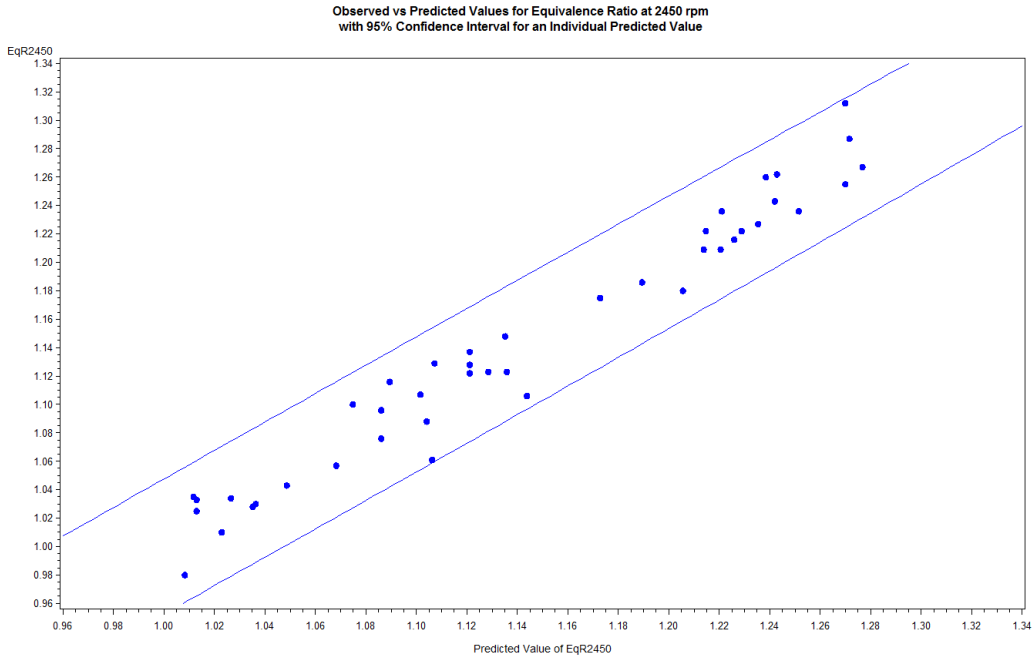

Figure 25 Observed versus Predicted Values for Equivalence Ratio at 2450 rpm with 95% Confidence Interval for an Individual Predicted Value

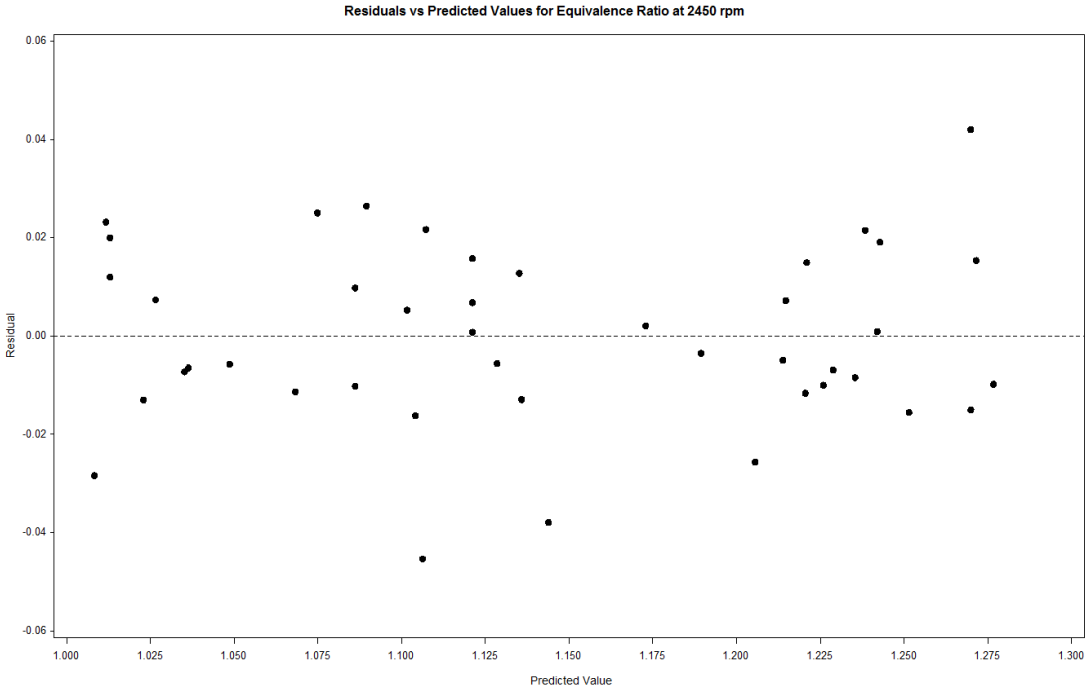

Figure 26 Residual versus Predicted Values for Equivalence Ratio at 2450 rpm

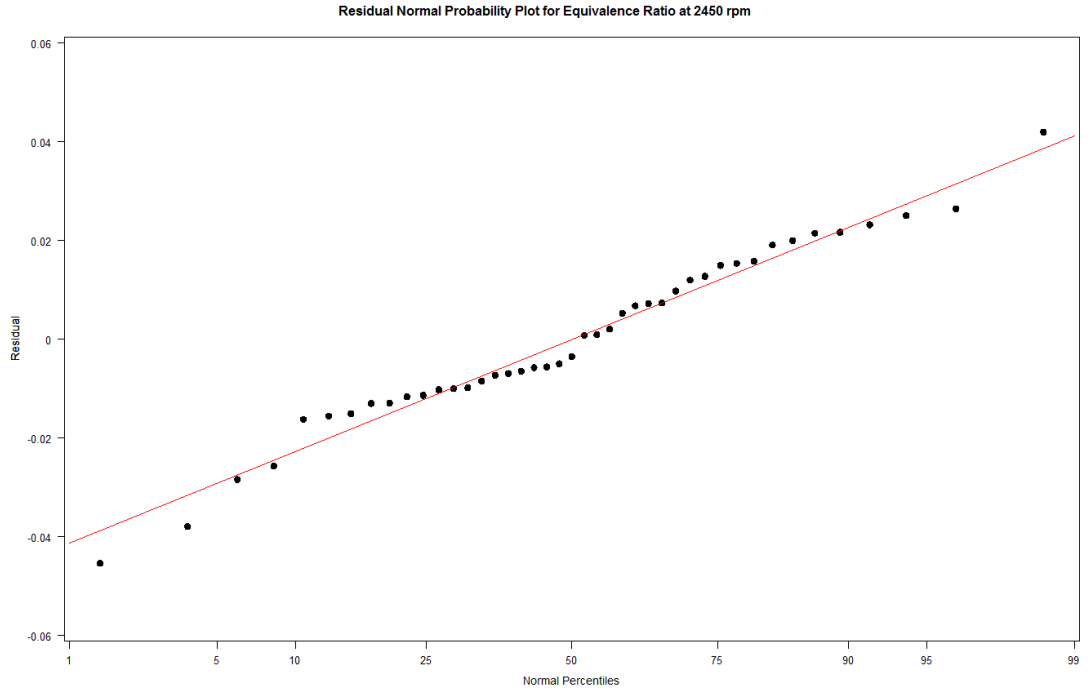

Figure 27 Normal Probability Plot of Equivalence Ratio at 2450 rpm Residuals

4.10 Equivalence Ratio at 2600 rpm Regression Analysis

The best model for Equivalence Ratio at 2600 rpm was selected using Backward Elimination with a significance level to stay of 0.10.

Equivalence Ratio at 2600 rpm Model

EqR_{2600}= (AVALK X 1.50402) + (SUALK X 1.26414) +
(TOL X 1.12423) + (tBB X 2.08692) + (ETBE X 1.39743) +
(AVALK x SUALK X 0.58003) – (AVALK x tBB X 1.64747) –
(AVALK x mT X 0.96996) – (SUALK x tBB X 1.23047) -
(TOL x tBB X 7.00581) + (TOL x ETBE X 1.23804) –
(mT x ETBE X 2.69714) - (AVALK x SUALK x mT X 7.64967) +
(AVALK x TOL x tBB X 15.07) + (SUALK x TOL x tBB X 14.11278)

This model has 15 variables and a MSE = 0.0003092 with 27 degrees of freedom. This MSE is similar to Pure Error, which is 0.00031. The smallest residual is -2.065 for Blend 11 and the largest residual is 2.072 for Blend 9. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.1570, thus confirming they are from a normal distribution. .

Table 12
Equivalence Ratio at 2600 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	1.47****	1.50****	1.49****	1.50402****
Super Alkylate	x2	1.32****	1.29****	1.22****	1.26414****
Toluene	x3	1.45****	0.59	0.70	1.12423****
tert-Butyl Benzene	x4	1.43****	1.48**	1.84**	2.08692****
meta-Toluidine	x5	-0.98****	3.92	4.82	
ETBE	x6	1.38****	1.59****	1.41****	1.39743****
	x1*x2		0.02	0.87	0.58003***
	x1*x3		1.24	0.91	
	x1*x4		-0.14	-1.35	-1.64747***
	x1*x5		-6.24	-6.74	-0.96996***
	x1*x6		-0.17	0.06	
	x2*x3		1.32	1.21	
	x2*x4		0.18	-0.96	-1.23047**
	x2*x5		-5.88	-5.77	
	x2*x6		-0.19	0.20	
	x3*x4		0.57	-4.43	-7.00581***
	x3*x5		-4.55	-6.53	
	x3*x6		0.76	1.05	1.23804**
	x4*x5		-5.68	-5.45	
	x4*x6		-0.32	0.89	
	x5*x6		-6.74	-8.08	-2.69714****
	x1*x2*x3			-1.77	
	x1*x2*x4			1.02	
	x1*x2*x5			-8.50*	-7.64967****
	x1*x2*x6			-1.53	
	x1*x3*x4			13.03*	15.07000***
	x2*x3*x4			10.09	14.11278***

	x3*x4*x5			-5.53	
	x3*x5*x6			4.84	
	x4*x5*x6			-8.82	
	# Variables	6	21	30	15
	MSE	0.00033926	0.00040774	0.00040998	0.0003092
	Obs/Min Std Res	7/-1.929	3/-2.795	3/-2.110	11/-2.065
	Obs/Max Std Res	30/2.044	9/2.909	44/2.331	9/2.072

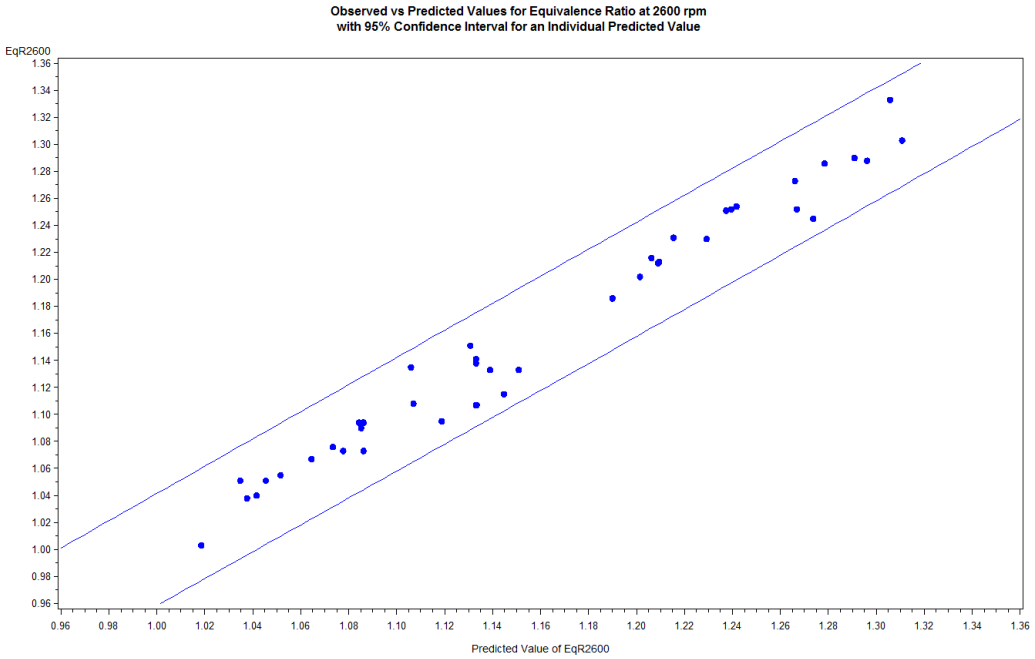

Figure 28 Observed versus Predicted Values for Equivalence Ratio at 2600 rpm with 95% Confidence Interval for an Individual Predicted Value

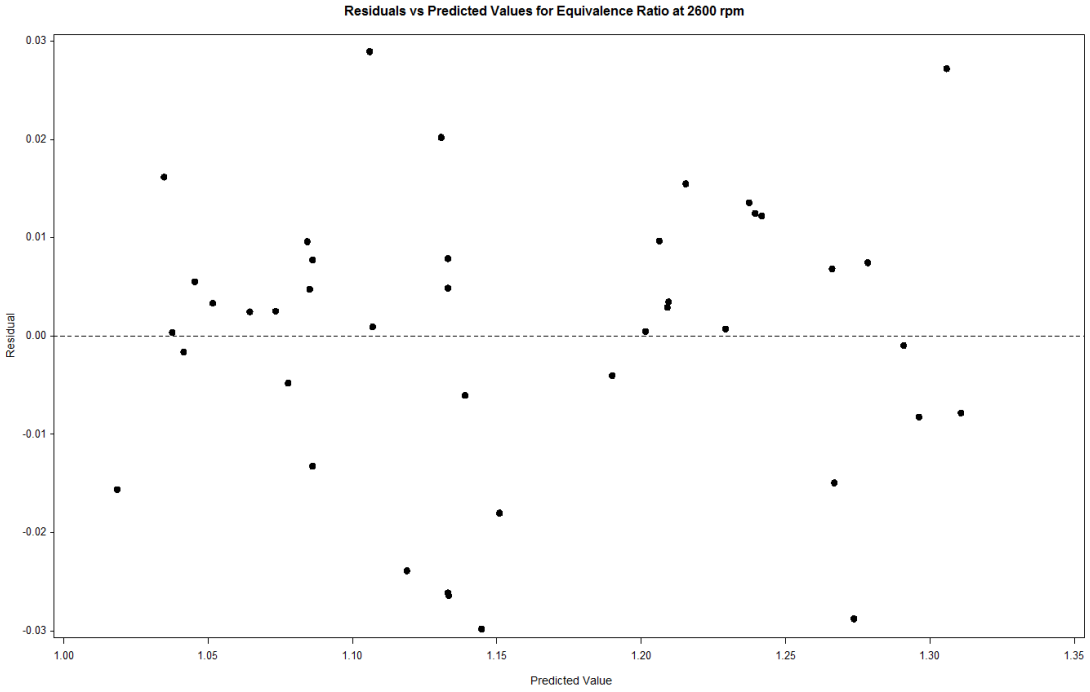

Figure 29 Residual versus Predicted Values for Equivalence Ratio at 2600 rpm

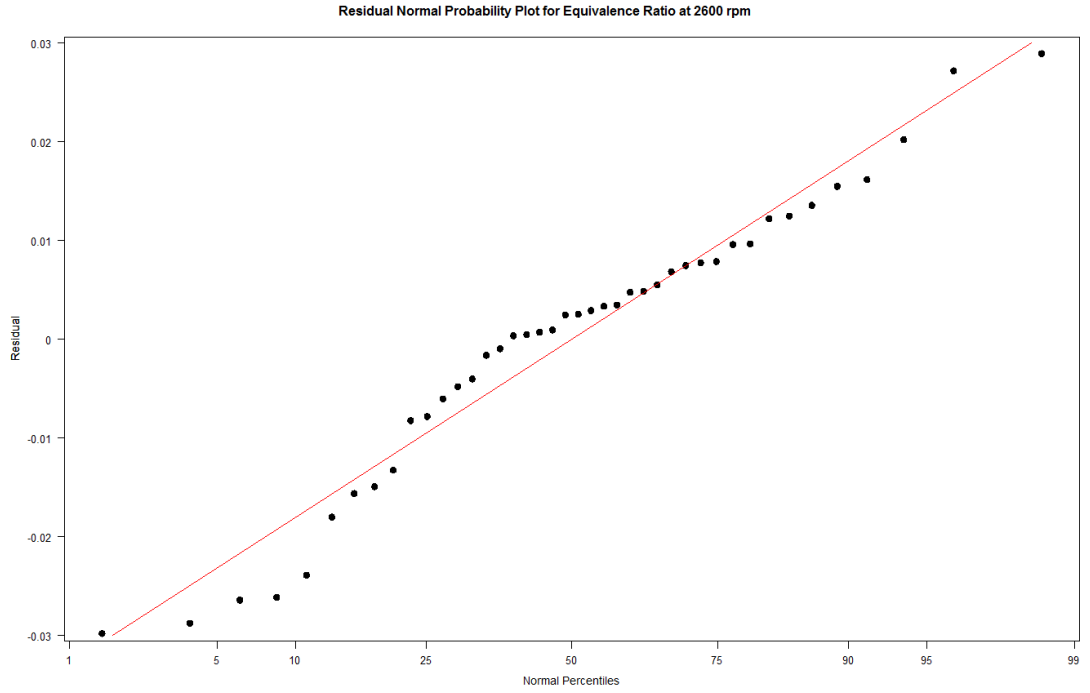

Figure 30 Normal Probability Plot of Equivalence Ratio at 2600 rpm Residuals

4.11 Equivalence Ratio at 2700 rpm Regression Analysis

The best model for Equivalence Ratio at 2700 rpm was selected using Backward Elimination with a significance level to stay of 0.05.

Equivalence Ratio at 2700 rpm Model

EqR_{2700}= (AVALK X 1.66572) + (SUALK X 1.19450) +
(TOL X 1.18903) + (tBB X 1.12886) + (ETBE X 1.57939) -
(AVALK x mT X 1.4255) – (AVALK x ETBE X 0.63865) +
(SUALK x TOL X 0.83362) + (SUALK x tBB X 0.80656) -
(TOL x mT X 3.32546) - (tBB x mT X 3.21774) –
(mT x ETBE X 2.14848) + (TOL x tBB x mT X 32.70286) +
(TOL x mT x ETBE X 16.33154) + (tBB x mT x ETBE X 13.48829)

This model has 15 variables and a MSE = 0.00034742 with 22 degrees of freedom. This MSE is similar to Pure Error, which is 0.000507. The smallest residual is -2.142 for Blend 19 and the largest residual is 1.970 for Blend 32. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.4267, thus confirming they are from a normal distribution. .

Table 13
Equivalence Ratio at 2700 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	1.49****	1.69****	1.56****	1.66572****
Super Alkylate	x2	1.35****	1.30****	1.05***	1.19450****
Toluene	x3	1.51****	0.87	1.42	1.18903****
tert-Butyl Benzene	x4	1.40****	1.57**	1.49	1.12886****
meta-Toluidine	x5	-0.91****	-1.99	2.56	
ETBE	x6	1.43****	1.36****	1.78***	1.57939****
	x1*x2		0.10	0.75	
	x1*x3		0.14	0.58	
	x1*x4		-0.92	-0.14	
	x1*x5		0.34	-3.13	-1.42550***
	x1*x6		-0.50	-0.70	-0.63865***
	x2*x3		0.82	1.07	0.83362***
	x2*x4		-0.29	0.80	0.80656***
	x2*x5		0.64	-0.20	
	x2*x6		0.09	-0.17	
	x3*x4		0.98	-0.51	
	x3*x5		3.81	-12.36	-3.32546**
	x3*x6		0.94	-1.63	
	x4*x5		1.86	-9.56	-3.21774**
	x4*x6		0.30	-0.61	
	x5*x6		2.51	-7.12	-2.14848**
	x1*x2*x3			0.21	
	x1*x2*x4			-1.69	
	x1*x2*x5			-12.27	
	x1*x2*x6			0.13	
	x1*x3*x4			-3.79	
	x2*x3*x4			-1.83	

	x3*x4*x5			58.68	32.70286***
	x3*x5*x6			37.54	16.33154***
	x4*x5*x6			18.56	13.48829**
	# Variables	6	21	30	15
	MSE	0.00048221	0.00043827	0.00057641	0.00034742
	Obs/Min Std Res	7/-1.477	19/-1.942	14/-2.010	19/-2.142
	Obs/Max Std Res	30/2.416	30/1.906	32/1.763	32/1.97

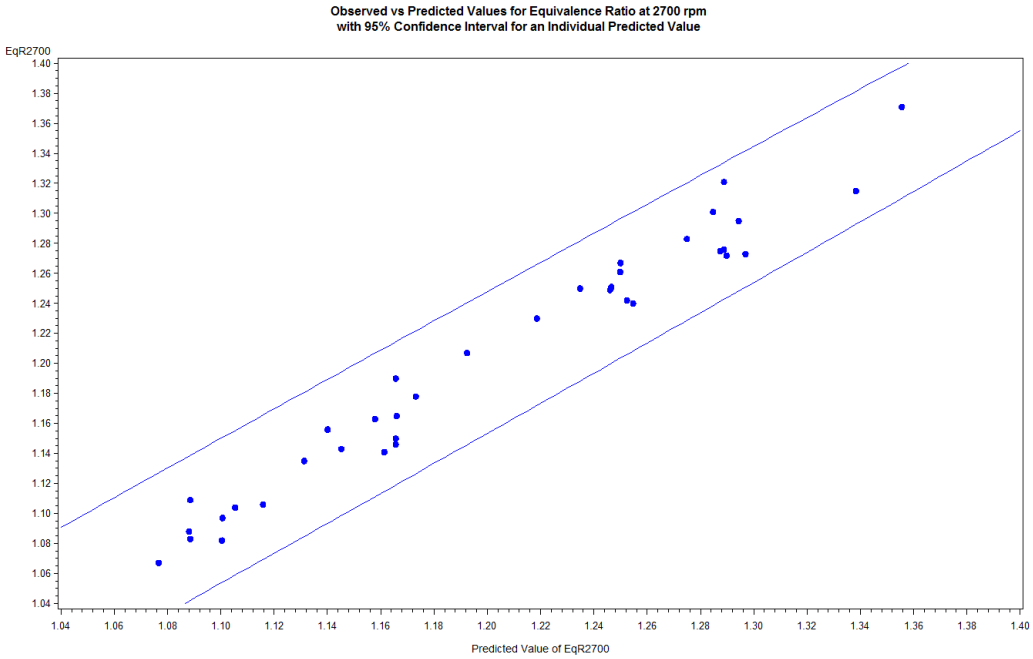

Figure 31 Observed versus Predicted Values for Equivalence Ratio at 2700 rpm with 95% Confidence Interval for an Individual Predicted Value

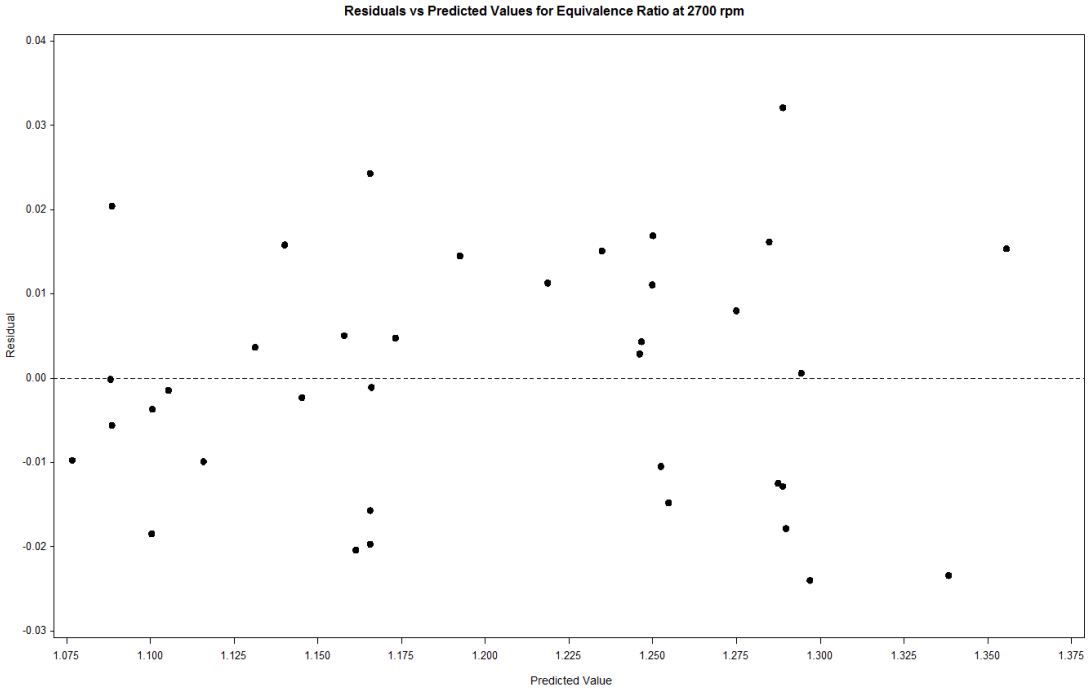

Figure 32 Residual versus Predicted Values for Equivalence Ratio at 2700 rpm

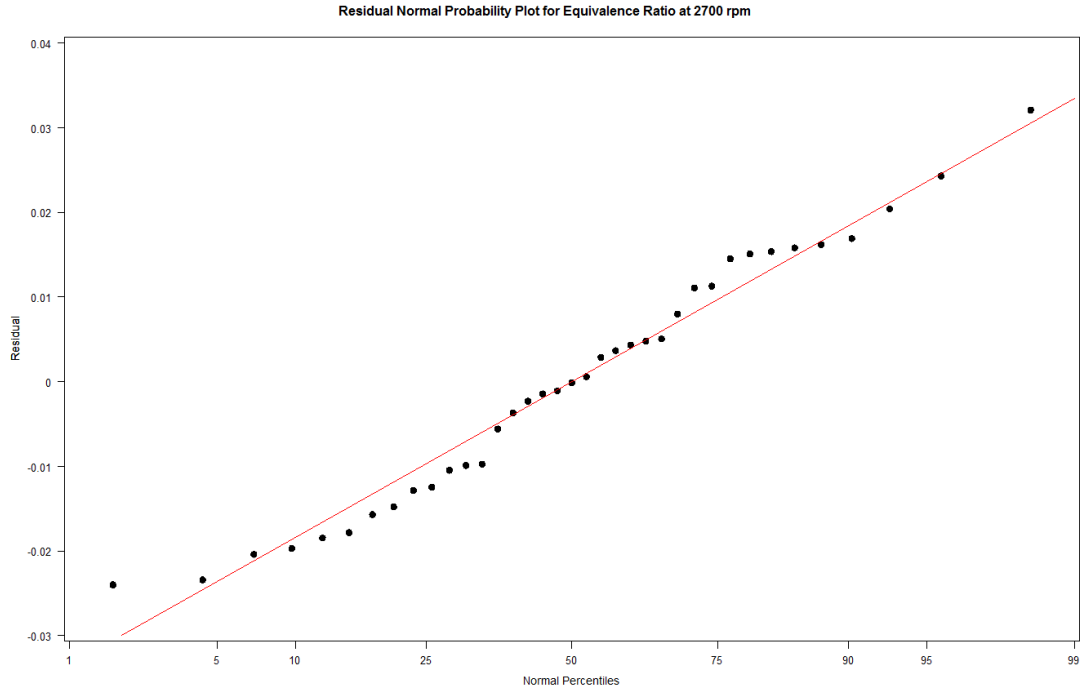

Figure 33 Normal Probability Plot of Equivalence Ratio at 2700 rpm Residuals

4.12 Average BSFC Regression Analysis

The best model for Average BSFC Ratio was selected using Backward Elimination with a significance level to stay of 0.10.

Average BSFC Model

AvgBSFC = (AVALK X 0.73093) + (SUALK X 0.52807) + (TOL X 0.55815) +
(tBB X 0.48314) + (mT X 4.25995) + (ETBE X 0.7724) -
(AVALK x mT X 6.37967) – (AVALK x ETBE X 0.24276) +
(SUALK x TOL X 0.37919) + (SUALK x tBB X 0.3599) –
(SUALK x mT X 5.81006) – (TOL x mT X 5.63056) –
(tBB x mT X 5.26634) - (mT x ETBE X 5.75574) +
(AVALK x TOL x tBB X 1.42328) + (tBB x mT x ETBE X 3.95939)

This model has 16 variables and a MSE = 0.00004163 with 21 degrees of freedom. This MSE is similar to Pure Error, which is 0.00004410. The smallest residual is -1.714 for Blend 20 and the largest residual is 1.891 for Blend 9. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.1351, thus confirming they are from a normal distribution. .

Table 14
Average BSFC Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	0.64****	0.73****	0.66****	0.73093****
Super Alkylate	x2	0.56****	0.53****	0.42****	0.52807****
Toluene	x3	0.66****	0.32	0.40	0.55815****
tert-Butyl Benzene	x4	0.64****	0.49*	0.72**	0.48314****
meta-Toluidine	x5	-0.54****	3.98**	5.25**	4.25995****
ETBE	x6	0.69****	0.75****	0.86****	0.77240****
	x1*x2		0.04	0.43	
	x1*x3		0.36	0.50	
	x1*x4		-0.01	-0.18	
	x1*x5		-6.11***	-6.77**	-6.37967****
	x1*x6		-0.23	-0.15	-0.24276****
	x2*x3		0.64	0.87*	0.37919***
	x2*x4		0.28	0.27	0.35990***
	x2*x5		-5.58***	-5.68**	-5.81006****
	x2*x6		-0.01	0.08	
	x3*x4		0.67	-1.03	
	x3*x5		-5.03**	-9.04**	-5.63056****
	x3*x6		0.33	-0.11	
	x4*x5		-4.44**	-8.08**	-5.26634***
	x4*x6		0.16	-0.48	
	x5*x6		-5.12***	-8.34***	-5.75574****
	x1*x2*x3			-0.38	
	x1*x2*x4			-0.18	
	x1*x2*x5			-4.39	
	x1*x2*x6			-0.57	
	x1*x3*x4			2.90	1.42328**
	x2*x3*x4			0.79	

	x3*x4*x5			11.80	
	x3*x5*x6			8.99	
	x4*x5*x6			8.76	3.95939**
	# Variables	6	21	30	16
	MSE	0.000087	0.00005873	0.00005301	0.00004163
	Obs/Min Std Res	7/-2.393	10/-1.896	7/-1.977	20/-1.714
	Obs/Max Std Res	30/2.622	9/2.380	25/1.876	9/1.891

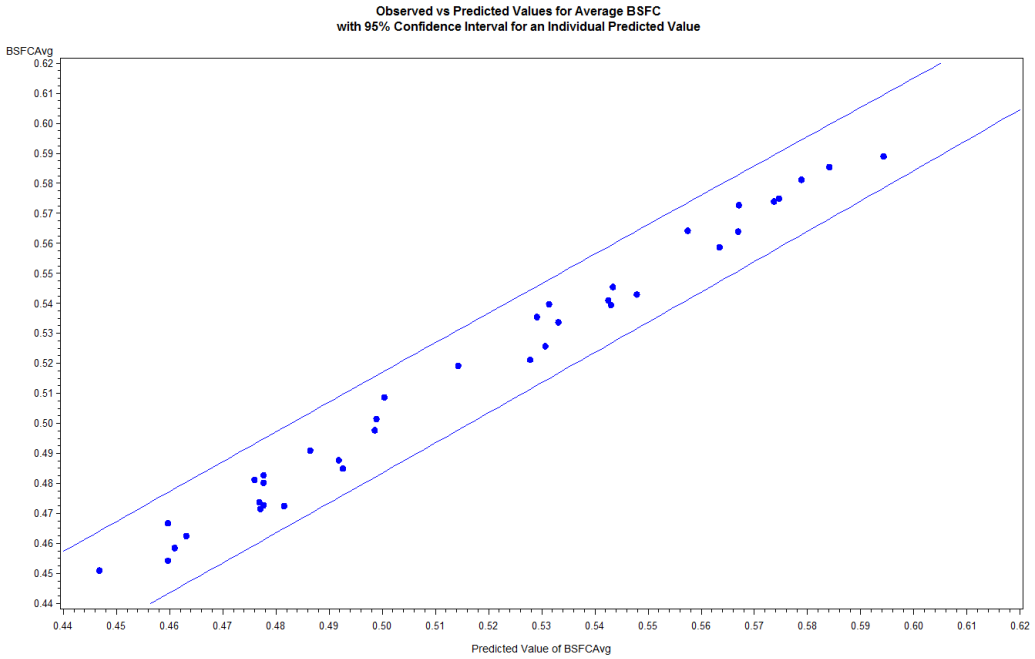

Figure 34 Observed versus Predicted Values for Average BSFC with 95% Confidence Interval for an Individual Predicted Value

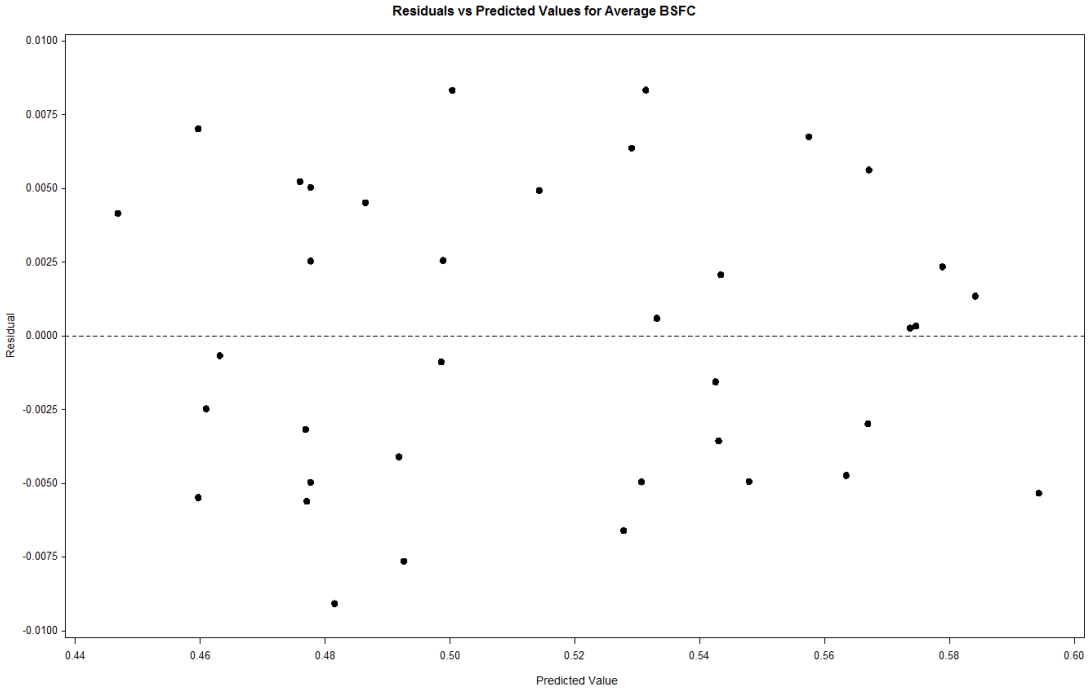

Figure 35 Residual versus Predicted Values for Average BSFC

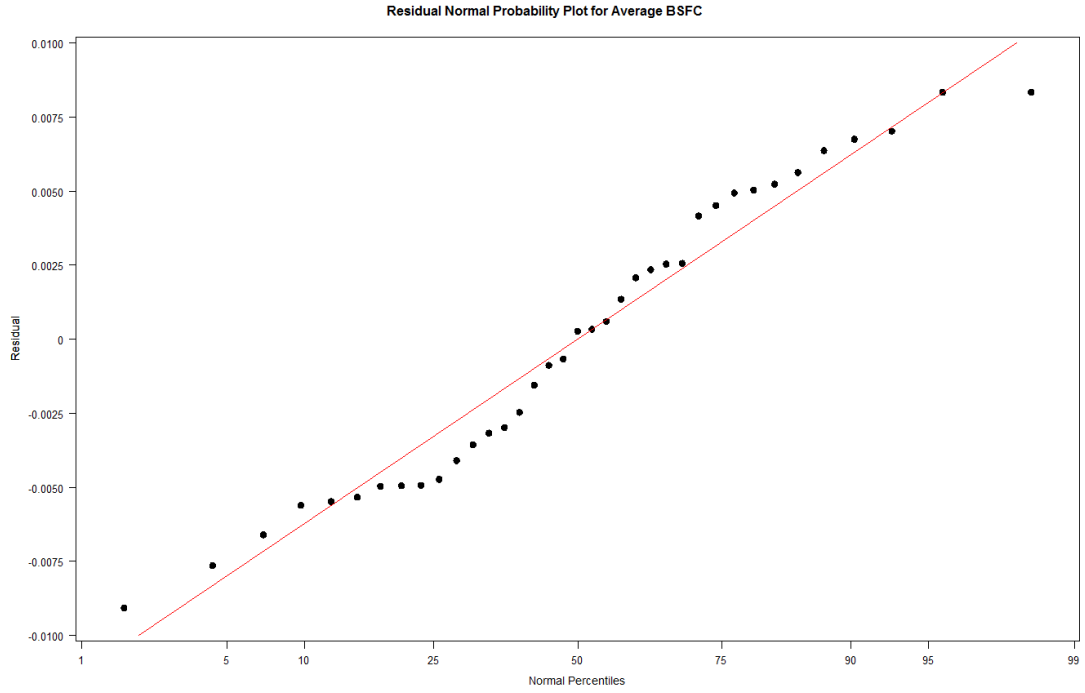

Figure 36 Normal Probability Plot of Average BSFC Residuals

4.13 BSFC at 2350 rpm Regression Analysis

The best model for BSFC at 2350 rpm was selected using Backward Elimination with a significance level to stay of 0.05 and the additional requirement that all linear terms remain in the model.

BSFC at 2350 rpm Model

$BSFC_{2350}$ = (AVALK X 0.62012) + (SUALK X 0.42309) + (TOL X 0.22438) +
(tBB X 0.68264) + (mT X 5.11987) + (ETBE X 0.91618) +
(AVALK x SUALK X 0.2866) + (AVALK x TOL X 0.70722) -
(AVALK x mT X 6.42829) – (AVALK x ETBE X 0.1608) +
(SUALK x TOL X 1.04282) + (SUALK x tBB X 0.34703) –
(SUALK x mT X 5.55709) – (TOL x mT X 8.04396) –
(tBB x mT X 8.23241) – (tBB x ETBE X 0.9494) –
(mT x ETBE X 8.66071) – (AVALK x SUALK x mT X 3.6949) +
(AVALK x TOL x tBB X 2.60091) + (TOL x mT x ETBE X 7.86298) +
(tBB x mT x ETBE X 13.58904)

This model has 21 variables and a MSE = 0.0000379 with 22 degrees of freedom. This MSE is similar to Pure Error, which is 0.0000398. The smallest residual is -2.171 for Blend 4 and the largest residual is 1.92 for Blend 24. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.7830, thus confirming they are from a normal distribution. .

Table 15
BSFC at 2350 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	0.62****	0.69****	0.65****	0.62012****
Super Alkylate	x2	0.55****	0.51****	0.45****	0.42309****
Toluene	x3	0.65****	0.15	0.10	0.22438*
tert-Butyl Benzene	x4	0.64****	0.28	0.60**	0.68264****
meta-Toluidine	x5	-0.45****	4.66***	4.78***	5.11987****
ETBE	x6	0.67****	0.74****	0.86****	0.91618****
	x1*x2		0.02	0.24	0.28660***
	x1*x3		0.75*	0.75*	0.70722***
	x1*x4		0.39	-0.09	
	x1*x5		-6.79****	-6.25***	-6.42829****
	x1*x6		-0.14	-0.17	-0.16080***
	x2*x3		0.91**	1.22***	1.04282****
	x2*x4		0.58	0.27	0.34703***
	x2*x5		-6.10***	-5.48***	-5.55709****
	x2*x6		0.01	-0.003	
	x3*x4		0.82	0.10	
	x3*x5		-6.24***	-6.55***	-8.04396****
	x3*x6		0.57	0.28	
	x4*x5		-5.16***	-6.74***	-8.23241****
	x4*x6		0.30	-0.52	-0.94940***
	x5*x6		-6.00***	-7.90****	-8.66071****
	x1*x2*x3			-0.84	
	x1*x2*x4			0.59	
	x1*x2*x5			-3.04*	-3.69490***

	x1*x2*x6			0.15	
	x1*x3*x4			3.85	2.60091***
	x2*x3*x4			0.63	
	x3*x4*x5			-7.90	
	x3*x5*x6			5.60	7.86298***
	x4*x5*x6			10.90**	13.58904****
	# Variables	6	21	30	21
	MSE	0.0001145	0.0000755	0.0000443	0.0000379
	Obs/Min Std Res	7/-2.471	10/-1.855	7/-2.447	4/-2.171
	Obs/Max Std Res	30/2.417	24/2.038	17/2.409	24/1.92

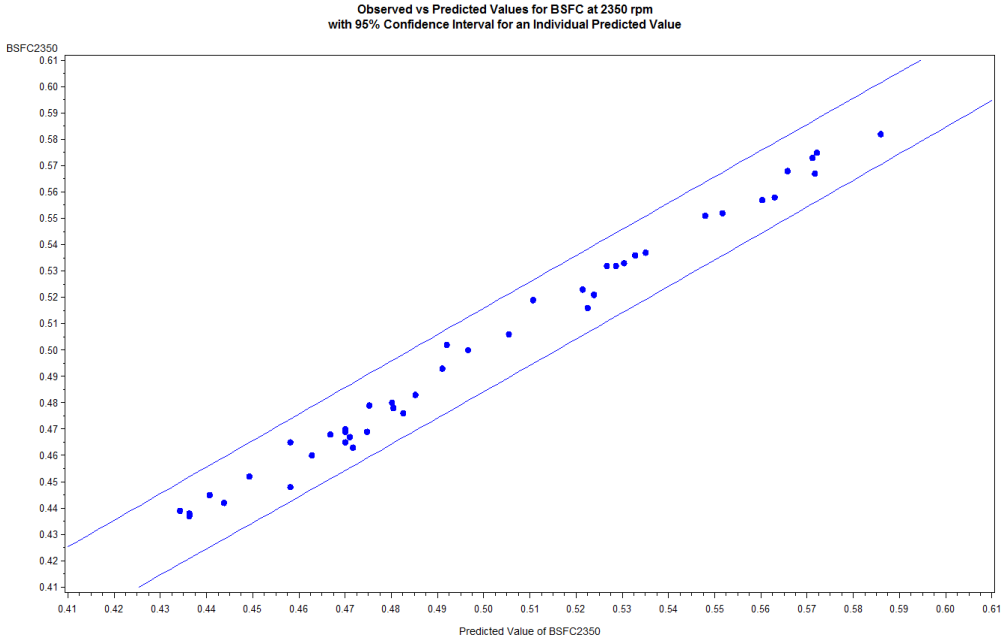

Figure 37 Observed versus Predicted Values for BSFC at 2350 rpm with 95% Confidence Interval for an Individual Predicted Value

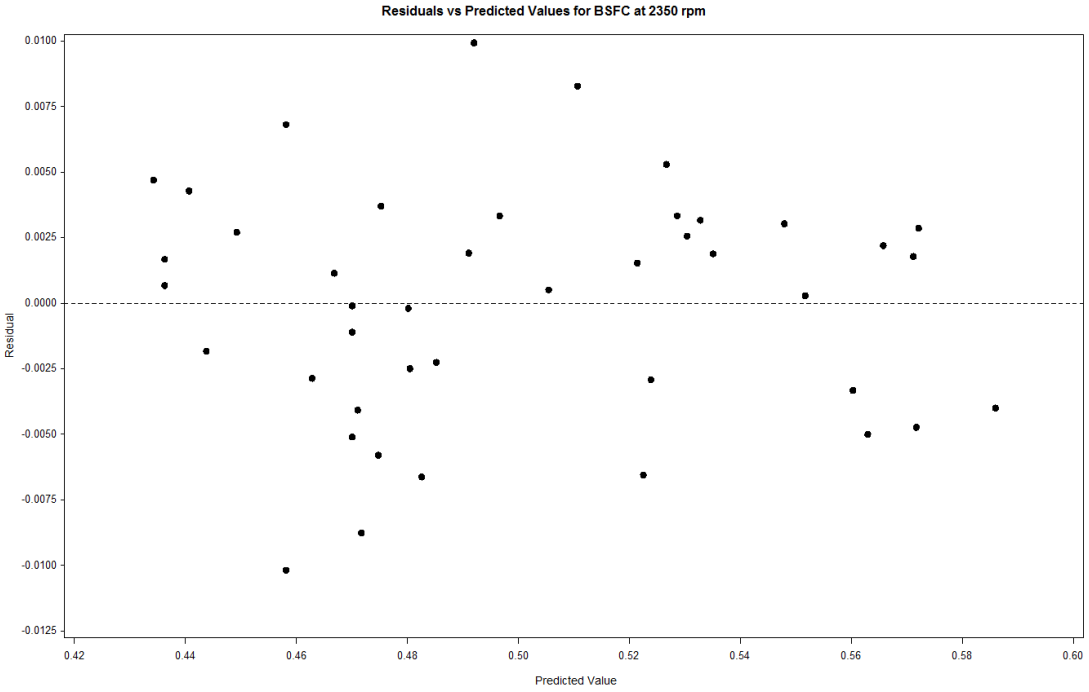

Figure 38 Residual versus Predicted Values for BSFC at 2350 rpm

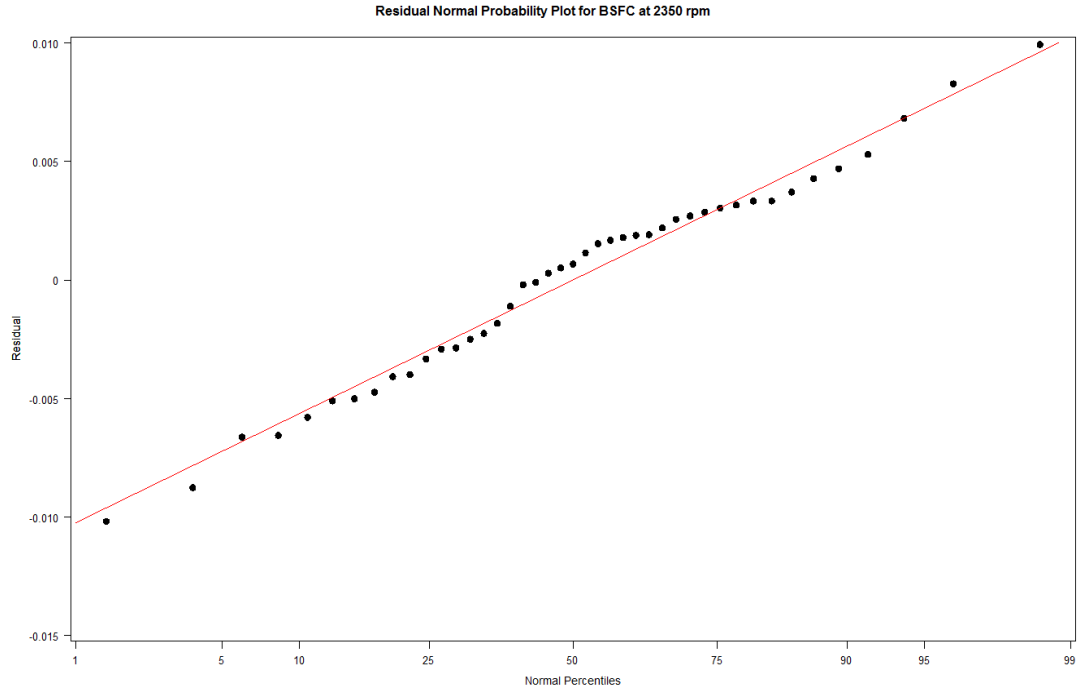

Figure 39 Normal Probability Plot of BSFC at 2350 rpm Residuals

4.14 BSFC at 2450 rpm Regression Analysis

The best model for BSFC at 2450 rpm was selected using Backward Elimination with a significance level to stay of 0.10.

BSFC at 2450 rpm Model

$BSFC_{2450}$ = (AVALK X 0.66071) + (SUALK X 0.49242) + (TOL X 0.60314) +
(tBB X 0.75555) + (mT X 4.13666) + (ETBE X 0.77406) +
(AVALK x SUALK X 0.23307) - (AVALK x tBB X 0.36267) -
(AVALK x mT X 5.59687) – (AVALK x ETBE X 0.13487) +
(SUALK x TOL X 0.40447) - (SUALK x mT X 5.02789) – (TOL x tBB X 1.42896) –
(TOL x mT X 6.05028) – (tBB x mT X 5.75529) –
(mT x ETBE X 6.28398) – (AVALK x SUALK x mT X 3.14568) +
(AVALK x TOL x tBB X 4.08594) + (tBB x mT x ETBE X 3.4229)

This model has 19 variables and a MSE = 0.00004516 with 24 degrees of freedom. This MSE is about eight times larger than Pure Error, which is 0.00000567. The smallest residual is -1.815 for Blend 22 and the largest residual is 2.128 for Blend 25. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.3825, thus confirming they are from a normal distribution.

Table 16
BSFC at 2450 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	0.62****	0.67****	0.63****	0.66071****
Super Alkylate	x2	0.55****	0.54****	0.47****	0.49242****
Toluene	x3	0.64****	0.35	0.37	0.60314****
tert-Butyl Benzene	x4	0.65****	0.46	081***	0.75555****
meta-Toluidine	x5	-0.51****	3.90**	4.47***	4.13666****
ETBE	x6	0.68****	0.79****	0.88****	0.77406****
	x1*x2		-0.01	0.31	0.23307**
	x1*x3		0.54	0.45	
	x1*x4		0.16	-0.35	-0.36267***
	x1*x5		-5.67***	-5.54***	-5.59687****
	x1*x6		-0.18	-0.20	-0.13487**
	x2*x3		0.64	0.83*	0.40447****
	x2*x4		0.26	-0.02	
	x2*x5		-5.31***	-4.92***	-5.02789****
	x2*x6		-0.10	-0.09	
	x3*x4		0.09	-2.50	-1.42896****
	x3*x5		-5.56***	-7.55***	-6.05028****
	x3*x6		0.20	0.12	
	x4*x5		-4.62**	-7.29***	-5.75529****
	x4*x6		0.29	-0.27	
	x5*x6		-5.52***	-7.71**	-6.28398****
	x1*x2*x3			-0.20	
	x1*x2*x4			0.17	
	x1*x2*x5			-4.23**	-3.14568***
	x1*x2*x6			-0.15	

	x1*x3*x4			6.11**	4.08594****
	x2*x3*x4			2.04	
	x3*x4*x5			8.16	
	x3*x5*x6			5.78	
	x4*x5*x6			8.04	3.42290**
	# Variables	6	21	30	19
	MSE	0.00009624	0.00008218	0.00005842	0.00004516
	Obs/Min Std Res	7/-2.206	14/-1.622	35/-2.376	22/-1.815
	Obs/Max Std Res	30/2.23	9/2.234	31/2.205	25/2.128

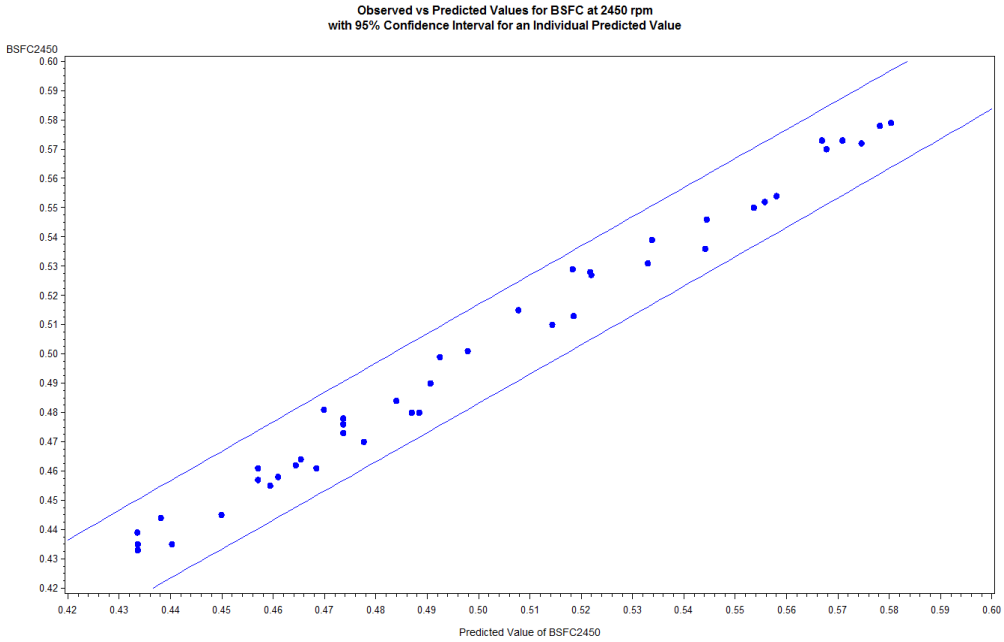

Figure 40 Observed versus Predicted Values for BSFC at 2450 rpm with 95% Confidence Interval for an Individual Predicted Value

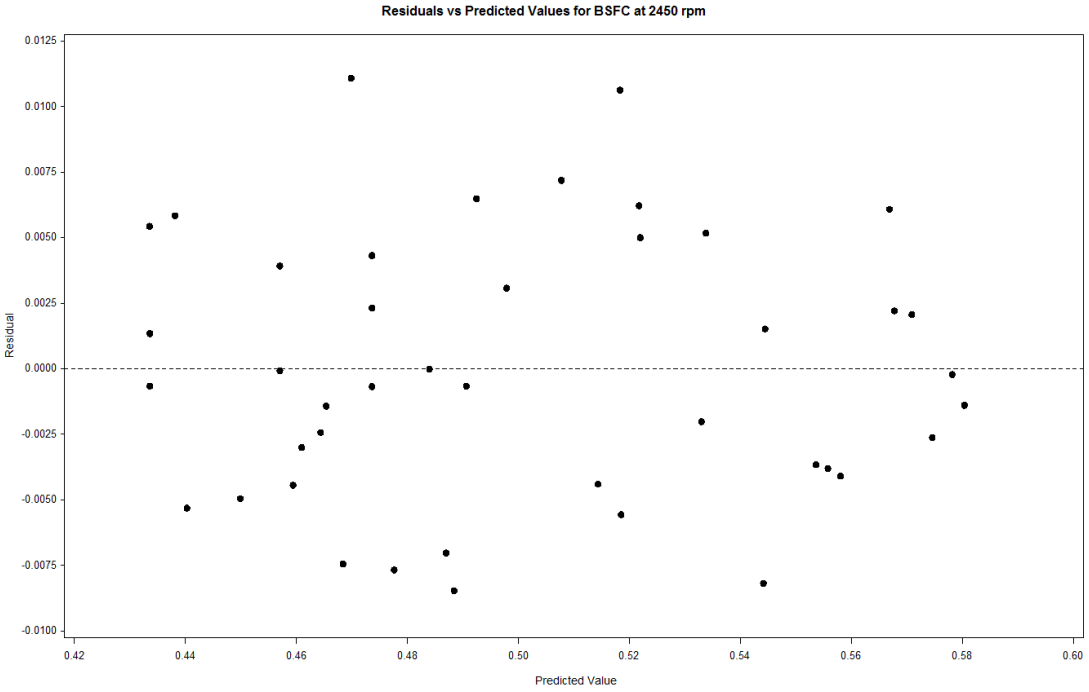

Figure 41 Residual versus Predicted Values for BSFC at 2450 rpm

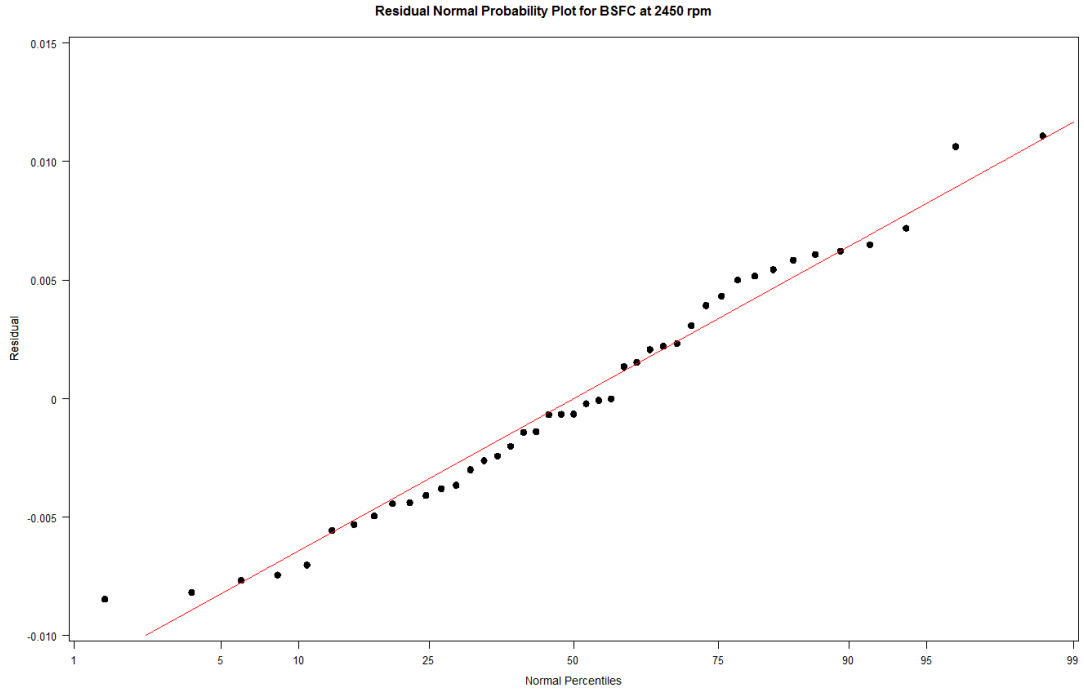

Figure 42 Normal Probability Plot of BSFC at 2450 rpm Residuals

4.15 BSFC at 2600 rpm Regression Analysis

The best model for BSFC at 2600 rpm was selected using Backward Elimination with a significance level to stay of 0.05.

BSFC at 2600 rpm Model

$BSFC_{2600}$ = (AVALK X 0.68261) + (SUALK X 0.5821) + (TOL X 0.69495) + (tBB X 0.66055) + (mT X 4.83373) + (ETBE X 0.70353) - (AVALK x mT X 6.88976) – (SUALK x mT X 6.50155) – (TOL x mT X 6.83777) – (tBB x mT X 6.56438) - (mT x ETBE X 6.48778)

This model has 11 variables and a MSE = 0.00008068 with 31 degrees of freedom. This MSE is similar to Pure Error, which is 0.000010772. The smallest residual is -2.11 for Blend 3 and the largest residual is 2.533 for Blend 9. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.6246, thus confirming they are from a normal distribution. .

Table 17
BSFC at 2600 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	0.64****	0.68****	0.66****	0.68261****
Super Alkylate	x2	0.56****	0.55****	0.47****	0.58210****
Toluene	x3	0.66****	0.42	0.45	0.69495****
tert-Butyl Benzene	x4	0.65****	0.66**	0.89**	0.66055****
meta-Toluidine	x5	-0.55****	4.39***	5.05***	4.83373****
ETBE	x6	0.69****	0.82****	0.76****	0.70353****
	x1*x2		0.01	0.57*	
	x1*x3		0.37	0.17	
	x1*x4		-0.06	-0.63	
	x1*x5		-6.30***	-6.73***	-6.88976****
	x1*x6		-0.15	0.02	
	x2*x3		0.51	0.56	
	x2*x4		0.15	-0.24	
	x2*x5		-5.95***	-6.07***	-6.50155****
	x2*x6		-0.13	0.15	
	x3*x4		0.40	-1.64	
	x3*x5		-6.10***	-6.63**	-6.83777****
	x3*x6		0.10	0.31	
	x4*x5		-5.98***	-6.55**	-6.56438****
	x4*x6		-0.27	-0.15	
	x5*x6		-6.08***	-7.31***	-6.48778****
	x1*x2*x3			-1.03	
	x1*x2*x4			0.05	
	x1*x2*x5			-4.64**	
	x1*x2*x6			1.12	
	x1*x3*x4			6.50*	
	x2*x3*x4			3.27	
	x3*x4*x5			-6.29	
	x3*x5*x6			-0.09	

	x4*x5*x6			0.42	
	# Variables	6	21	30	11
	MSE	0.00010782	0.00009325	0.00007361	0.00008068
	Obs/Min Std Res	7/-2.178	3/-2.783	3/-1.938	3/-2.110
	Obs/Max Std Res	30/2.271	9/3.071	8/2.301	9/2.533

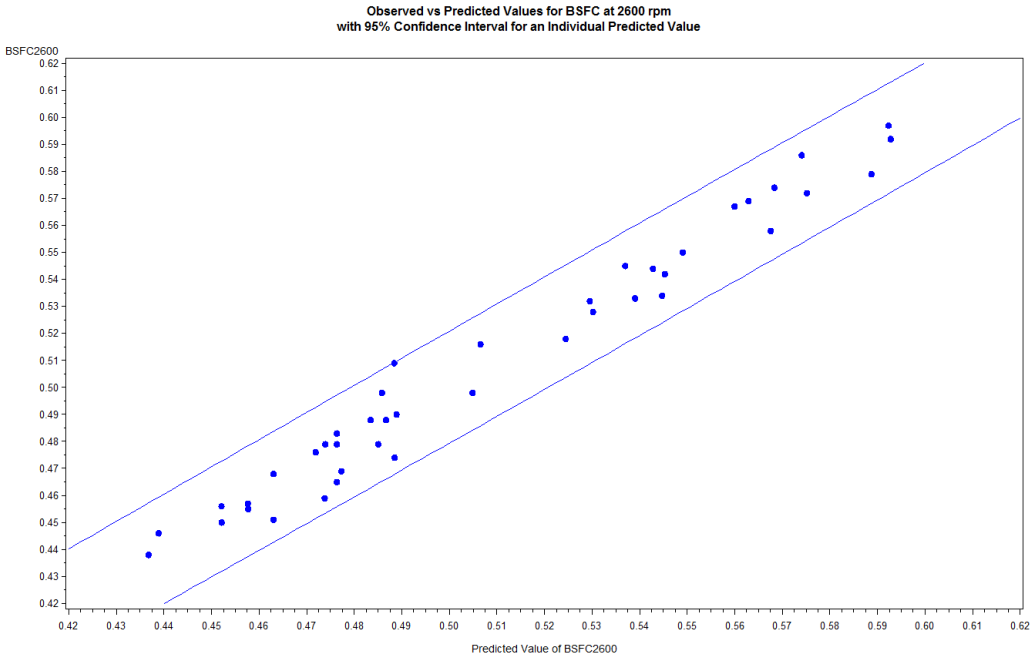

Figure 43 Observed versus Predicted Values for BSFC at 2600 rpm with 95% Confidence Interval for an Individual Predicted Value

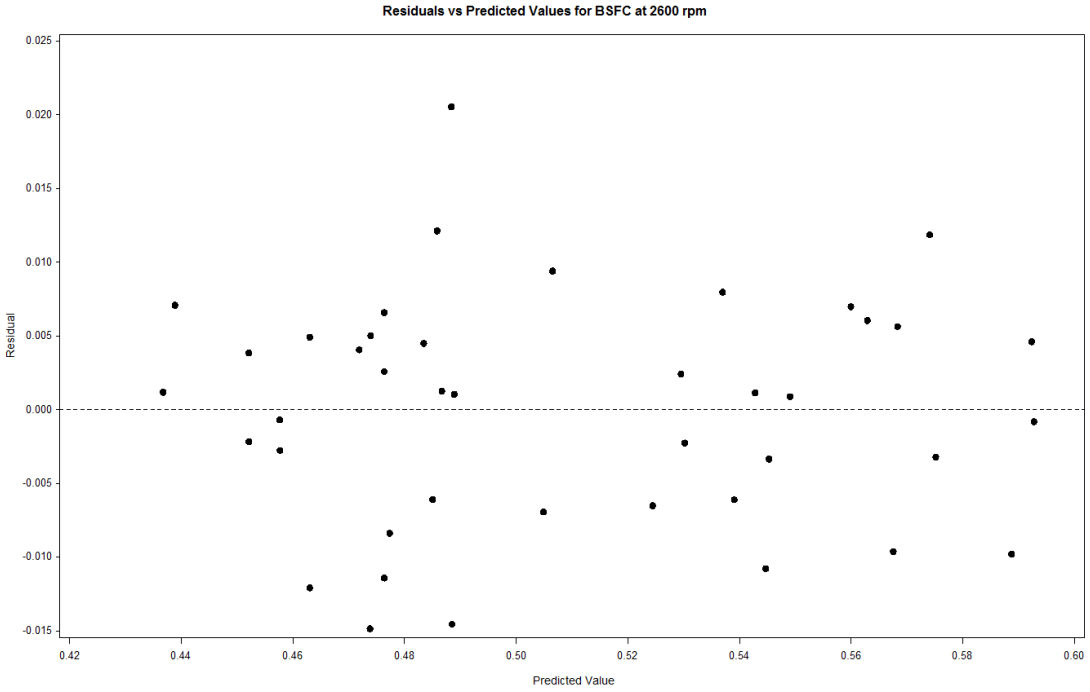

Figure 44 Residual versus Predicted Values for BSFC at 2600 rpm

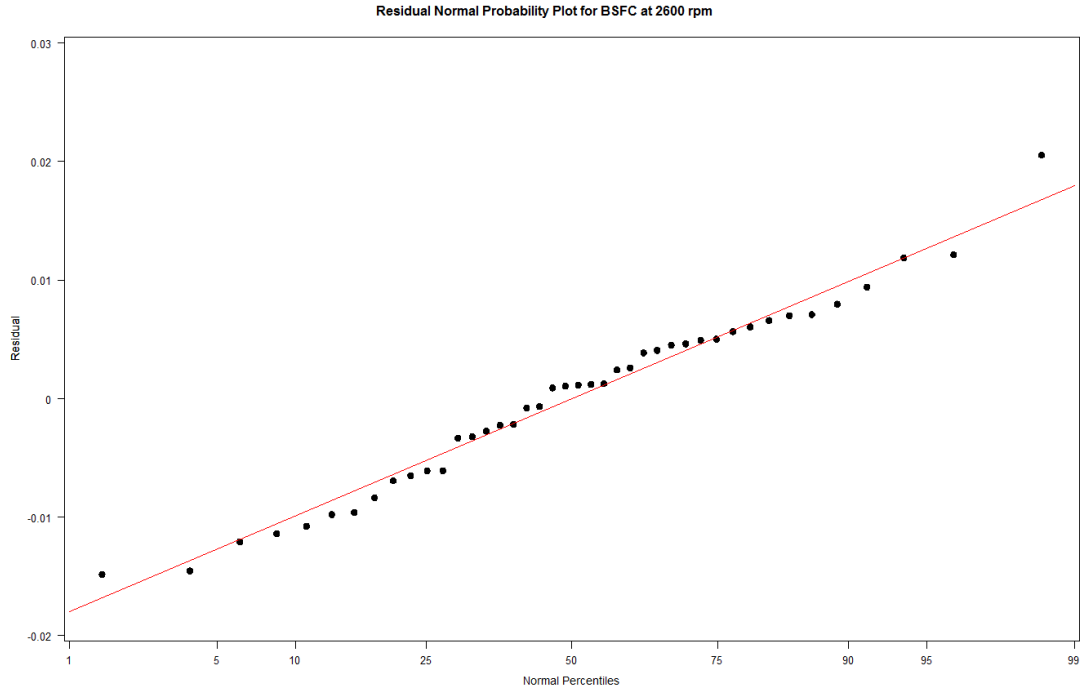

Figure 45 Normal Probability Plot of BSFC at 2600 rpm Residuals

4.16 BSFC at 2700 rpm Regression Analysis

The best model for BSFC at 2700 rpm was selected using Backward Elimination with a significance level to stay of 0.05.

BSFC at 2700 rpm Model

$BSFC_{2700}$ = (AVALK X 0.78679) + (SUALK X 0.54331) + (TOL X 0.58248) + (tBB X 0.71321) + (mT X 3.34016) + (ETBE X 0.72664) - (AVALK x tBB X 0.41454) – (AVALK x mT X 5.61087) - (AVALK x ETBE X 0.31975) + (SUALK x TOL X 0.36344) – (SUALK x mT X 4.73814) – (TOL x mT X 4.33809) – (tBB x mT X 3.91132) - (mT x ETBE X 3.85731)

This model has 14 variables and a MSE = 0.00006478 with 23 degrees of freedom. This MSE is similar to Pure Error, which is 0.00011933. The smallest residual is -1.801 for Blend 4 and the largest residual is 1.672 for Blend 8. The residuals exhibit a random pattern when plotted against the predicted values, thus meeting the condition of a homogeneous variance. The points in the normal probability plot of the residuals tend to follow a straight line and the p-value for the Shapiro-Wilk test of normality is 0.3452, thus confirming they are from a normal distribution. .

Table 18
BSFC at 2700 rpm Models

Composition Variable	Model Description	Linear	Quadratic	Special Cubic	Final Model
Aviation Alkylate	x1	0.65****	0.78****	0.72****	0.78679****
Super Alkylate	x2	0.58****	0.54****	0.43***	0.54331****
Toluene	x3	0.70****	0.47	0.63	0.58248****
tert-Butyl Benzene	x4	0.64****	0.70**	0.81	0.71321****
meta-Toluidine	x5	-0.54****	2.88	4.26	3.34016**
ETBE	x6	0.70****	0.70****	0.85***	0.72664****
	x1*x2		0.08	0.44	
	x1*x3		0.02	0.16	
	x1*x4		-0.42	-0.32	-0.41454****
	x1*x5		-5.00**	-5.90	-5.61087***
	x1*x6		-0.29	-0.30	-0.31975****
	x2*x3		0.46	0.63	0.36344***
	x2*x4		-0.02	0.24	
	x2*x5		-4.38**	-4.55	-4.73814***
	x2*x6		0.06	0.06	
	x3*x4		0.46	-0.84	
	x3*x5		-3.31	-8.06	-4.33809**
	x3*x6		0.24	-0.45	
	x4*x5		-3.36	-7.34	-3.91132**
	x4*x6		0.05	-0.60	
	x5*x6		-3.32	-6.57	-3.85731**
	x1*x2*x3			-0.47	
	x1*x2*x4			-0.77	
	x1*x2*x5			-4.10	
	x1*x2*x6			-0.39	
	x1*x3*x4			0.58	
	x2*x3*x4			0.05	
	x3*x4*x5			19.15	

	x3*x5*x6			10.06	
	x4*x5*x6			8.88	
	# Variables	6	21	30	14
	MSE	0.00013127	0.00007678	0.00011697	0.00006478
	Obs/Min Std Res	7/-2.251	38/-1.673	20/-1.895	4/-1.801
	Obs/Max Std Res	30/2.754	9/1.611	8/1.588	8/1.672

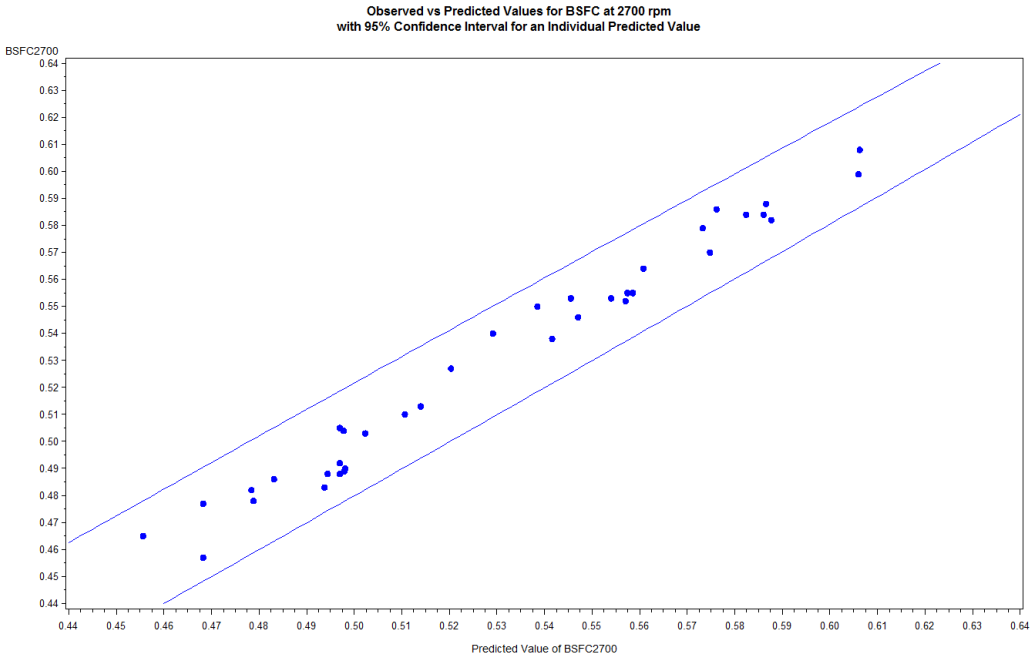

Figure 46 Observed versus Predicted Values for BSFC at 2700 rpm with 95% Confidence Interval for an Individual Predicted Value

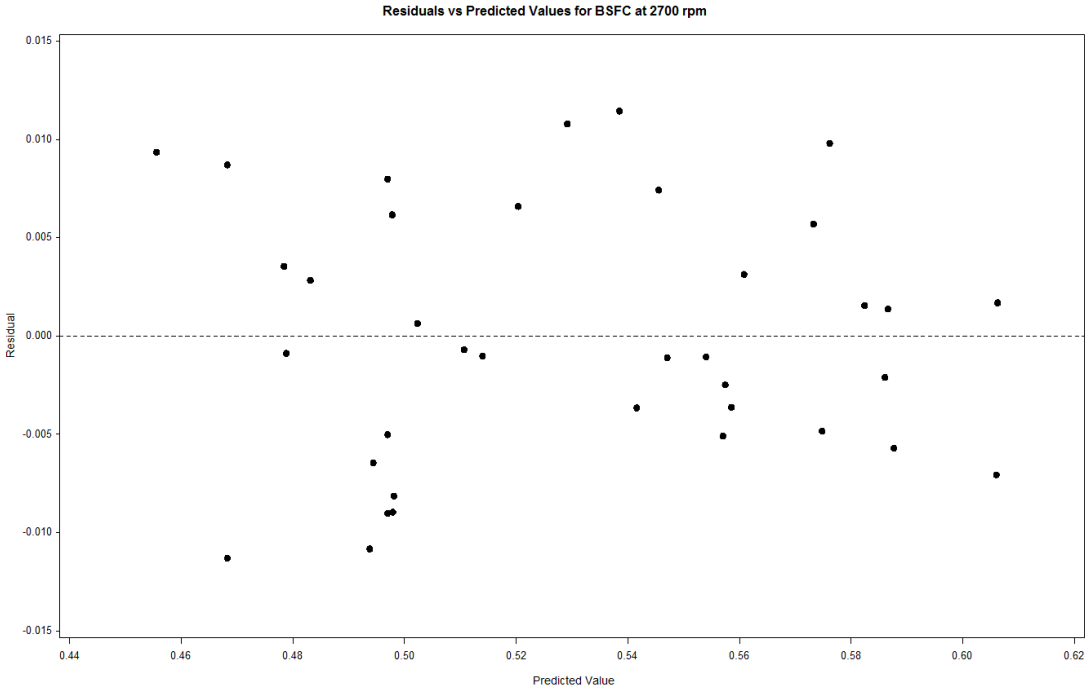

Figure 47 Residual versus Predicted Values for BSFC at 2700 rpm

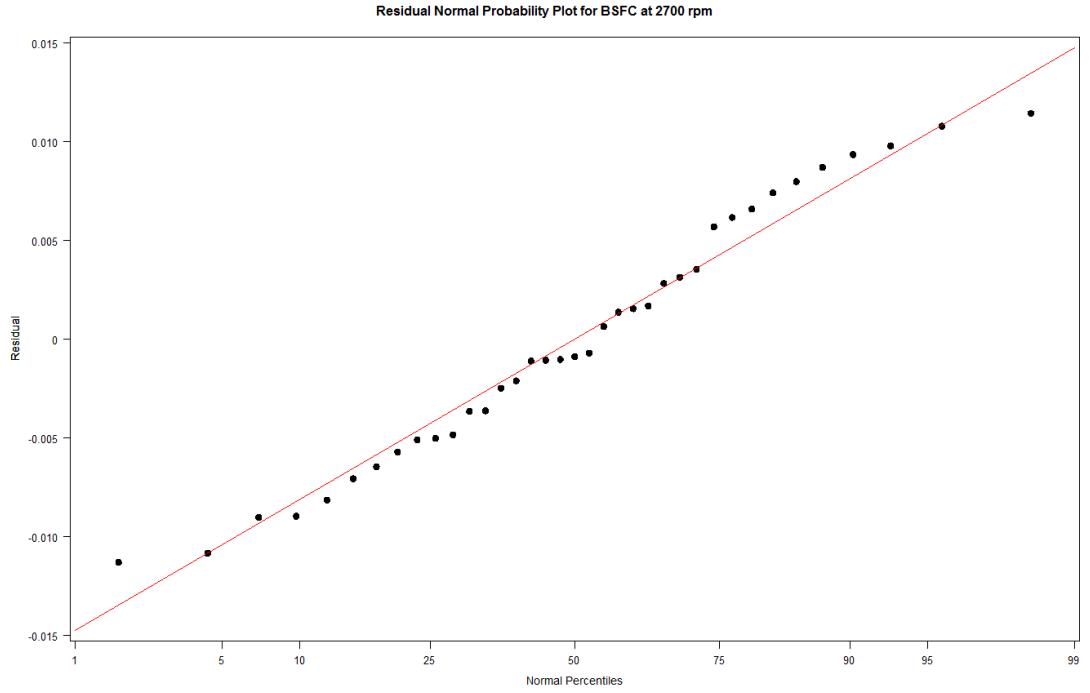

Figure 48 Normal Probability Plot of BSFC at 2700 rpm Residuals

5.0 AN EVALUATION OF REGRESSION MODELS

5.1 Comparison of Response Variance to MSE

When evaluating models based on mixture data, a meaningful comparison is the ratio of MSE to the variance of the response. The following table gives the variance of observed values, MSE, and ratio of MSE to Variance for each response. The smallest ratio is 0.015 for MON and the largest is 0.054 for Equivalence Ratio at 2450 rpm. Thus, MSE ranges from 1.5% to 5.4% of response variances and all of these models do an excellent job of explaining observed variation.

Table 19
Comparison of MSE to Response Variance

Response	**MON**	**Avg FF**	**FF2350**	**FF2450**	**FF2600**	**FF2700**
Variance	5.33222	91.67613	75.38494	99.49959	124.84531	132.17836
MSE	0.08185	2.32925	1.60656	3.86202	3.76114	6.07291
MSE ÷ Variance	0.015	0.025	0.021	0.039	0.030	0.046
Response	**Avg EqR**	**EqR2350**	**EqR2450**	**EqR2600**	**EqR2700**	
Variance	0.006668	0.007702	0.007877	0.007935	0.006701	
MSE	0.000195	0.000201	0.000423	0.000309	0.000347	
MSE ÷ Variance	0.029	0.026	0.054	0.039	0.052	
Response	**Avg BSFC**	**BSFC2350**	**BSFC2450**	**BSFC2600**	**BSFC2700**	
Variance	0.00182876	0.00194396	0.00210352	0.00218793	0.00186507	
MSE	0.00004163	0.0000379	0.00004516	0.00008068	0.00006478	
MSE ÷ Variance	0.023	0.019	0.021	0.037	0.035	

5.2 Affect of Missing Data

The pattern of missing data for this data set exhibits the trend that as rpms increase, the number of missing values increases. At 2300 rpms and 2450 rpms, there are two missing values corresponding to Blends 15 and 21. At 2600 rpms, there are three missing values corresponding to Blends 15, 21 and 6. However, Blend 6 and Blend 28 are duplicates, so the additional loss of Blend 6 primarily impacts Pure Error variance with the loss of one degree of freedom. At 2700 rpms, there are eight missing values corresponding to Blends 2, 3, 5, 6, 15, 21, 28, and 31. This many missing values affects the symmetry of the designed experiment, affects the precision with which coefficients are estimated, and could potentially affect the variation of prediction errors. However, by selecting parsimonious final models, this additional increase in missing values minimally affects the analysis.

Attachment I
Design Points and Responses

Blend	AvAlky	SupAlky	Toluene	t-Bt_Bnz	m-Tol	ETBE	i-Pen
1	0.4224	0	0	0.1995	0.0308	0.2973	0.0501
2	0.2689	0.2702	0.1016	0.1912	0.118	0	0.0501
3	0	0.2299	0.164	0.1359	0.1205	0.2997	0.05
4	0.5998	0.0171	0.013	0.1998	0.1201	0	0.0501
5	0	0.4998	0.0841	0.1569	0.0832	0.126	0.0501
6	0.1298	0.5001	0	0.1998	0.1201	0	0.0502
7	0.1672	0.4997	0.0107	0.1002	0.0657	0.1063	0.0501
8	0.4162	0.2837	0	0.036	0.1201	0.0939	0.0501
9	0	0.3969	0.1689	0	0.0838	0.3002	0.0501
10	0.2487	0.235	0.0588	0	0.1073	0.3001	0.0501
11	0.172	0.2198	0.1979	0.0298	0.0302	0.3002	0.0501
12	0.001	0.4999	0.1071	0.0742	0.0309	0.2369	0.0501
13	0.6	0.0438	0.0107	0.1041	0.0651	0.1261	0.0502
14	0.3291	0	0.2	0	0.1199	0.2998	0.0511
15	0.1029	0.5001	0.091	0.0069	0.1202	0.1288	0.0502
16	0.2949	0.3949	0.1482	0.0321	0.0798	0	0.0501
17	0.0903	0.4997	0	0	0.0597	0.3002	0.0501
18	0.5468	0	0.1001	0.1997	0.0389	0.0643	0.0501
19	0.5998	0	0.0321	0	0.0302	0.2878	0.0501
20	0.3929	0	0	0.1369	0.12	0.3001	0.0501
21	0	0.429	0	0.1009	0.12	0.3	0.0501
22	0.1009	0.4997	0.2003	0	0.0302	0.1188	0.0501
23	0.5997	0	0	0	0.108	0.2422	0.0501
24	0.1893	0.2294	0.0206	0.1997	0.0892	0.2216	0.0501
25	0.1671	0.4995	0.0802	0.1728	0.0302	0	0.0501
26	0.4509	0.0152	0.1178	0.0911	0.1201	0.1547	0.0501
27	0.2949	0.3949	0.1482	0.0321	0.0798	0	0.0501
28	0.1298	0.5001	0	0.1998	0.1201	0	0.0502
29	0.4392	0.2609	0.0031	0.1967	0.0349	0.0152	0.0501
30	0.596	0.1038	0.1369	0.0811	0.0302	0.0018	0.0501
31	0.0298	0.4996	0.2002	0.1002	0.12	0	0.0501
32	0.3797	0.3199	0.0673	0	0.0302	0.1528	0.0501
33	0.5299	0.0219	0.1901	0	0.059	0.1491	0.0501
34	0.3489	0	0.195	0.1049	0.0302	0.2709	0.0501
35	0.5997	0.1	0.1239	0	0.1201	0.0063	0.0501
36	0.2949	0.3949	0.1482	0.0321	0.0798	0	0.0501
37	0.5998	0.0171	0.013	0.1998	0.1201	0	0.0501
38	0	0.3198	0.1001	0.1997	0.0302	0.3002	0.0501
39	0.2439	0.2588	0.016	0.1009	0.0302	0.3001	0.0501
40	0	0.5	0	0.1998	0.0302	0.2199	0.0501
41	0.1901	0.2853	0.2001	0.0321	0.12	0.1223	0.0501
42	0.4026	0	0.0978	0.078	0.0711	0.3003	0.0501
43	0.5539	0	0.2001	0.1001	0.0958	0	0.0501
44	0.2701	0	0.1002	0.1998	0.0919	0.2879	0.0501
45	0.2141	0.2987	0.191	0.1086	0.0483	0.0893	0.0501

Blend	MON	AvgFF	FF2350	FF2450	FF2600	FF2700
1	99.7	127.775	100.7	119.9	135.8	154.7
2	104.8	.	76.9	85.7	107.7	.
3	105.3	.	83.7	94	102.2	.
4	103.9	101.175	80.2	96.7	106.6	121.2
5	104.1	.	84.4	96.1	112.1	.
6	106	.	75.1	88.9	.	.
7	103.4	106.4	83.5	99.2	112.3	130.6
8	105	99.225	75.6	92	105.6	123.7
9	102.5	114.5	90.3	104.1	120.4	143.2
10	103.9	104.275	81.2	94.3	109	132.6
11	99.8	128.025	101.8	118.4	133.7	158.2
12	101.1	122	97	112.4	127.9	150.7
13	101.2	117.875	94.3	106.8	122.8	147.6
14	104	105.55	82	93	111.8	135.4
15	106.3	.	.	.	.	.
16	102.8	107.425	84.7	99.7	110.6	134.7
17	102.7	112.75	89	102.8	117.4	141.8
18	99.6	125.1	100.3	114.9	131.4	153.8
19	97.6	131.025	104.2	119.8	139.1	161
20	104.2	107.675	86.2	99.4	113.9	131.2
21	106.2	.	.	.	.	.
22	100.5	121.65	96.6	112.1	126.7	151.2
23	103	110.85	86	101.5	118.3	137.6
24	103.3	112.45	90.9	104.8	115.6	138.5
25	101	121.45	96.7	110.7	129.3	149.1
26	104	108.275	86.3	100.9	113.4	132.5
27	102.7	110	85.3	101.1	114.8	138.8
28	106	.	75.9	89.3	101.9	.
29	100.2	123.25	97.5	111.9	130.2	153.4
30	97.6	130.575	103.7	118.6	136.8	163.2
31	105.6	.	76.7	90.4	104.6	.
32	98.8	127.075	100	115.6	133.6	159.1
33	101.1	120.85	94.7	110.3	126.9	151.5
34	98.8	129.55	102.5	119	138.5	158.2
35	103.8	103.975	82.9	95.6	108.2	129.2
36	103	109	85.6	100.3	115.2	134.9
37	104.1	105.4	84.2	95.8	110.4	131.2
38	100.6	127	99.3	115.9	133.8	159
39	100.4	127.9	102	118.3	135.4	155.9
40	102	121.25	93.4	113.9	128.6	149.1
41	104.8	100.925	79.4	90	104.8	129.5
42	101.5	120.275	95.6	109.6	125.6	150.3
43	102.6	110.275	86.6	101.1	115.8	137.6
44	102.9	117.075	90.8	107.9	121.9	147.7
45	101.1	118.625	93.3	107.8	125.2	148.2

A decimal point "." represents a missing value.

Blend	AvgEqR	EqR2350	EqR2450	EqR2600	EqR2700
1	1.27975	1.241	1.287	1.29	1.301
2	.	1.004	0.98	1.076	.
3	.	1.038	1.028	1.003	.
4	1.07375	1.043	1.096	1.073	1.083
5	.	1.062	1.061	1.095	.
6	.	0.997	1.025	.	.
7	1.1095	1.076	1.106	1.115	1.141
8	1.039	0.98	1.043	1.051	1.082
9	1.1325	1.101	1.116	1.135	1.178
10	1.0545	1.025	1.034	1.055	1.104
11	1.2455	1.222	1.243	1.245	1.272
12	1.21425	1.19	1.209	1.216	1.242
13	1.202	1.186	1.18	1.202	1.24
14	1.05675	1.027	1.03	1.073	1.097
15	.	.	.	.	.
16	1.11575	1.084	1.122	1.107	1.15
17	1.133	1.113	1.123	1.133	1.163
18	1.2485	1.233	1.236	1.252	1.273
19	1.28575	1.258	1.267	1.303	1.315
20	1.0595	1.047	1.057	1.067	1.067
21	.	.	.	.	.
22	1.2185	1.197	1.216	1.212	1.249
23	1.11125	1.074	1.107	1.108	1.156
24	1.12375	1.116	1.129	1.107	1.143
25	1.2395	1.217	1.222	1.252	1.267
26	1.0945	1.078	1.1	1.094	1.106
27	1.14225	1.104	1.137	1.138	1.19
28	.	1.007	1.033	1.04	.
29	1.24325	1.222	1.222	1.254	1.275
30	1.32975	1.303	1.312	1.333	1.371
31	.	1.014	1.035	1.051	.
32	1.28	1.249	1.262	1.288	1.321
33	1.22275	1.191	1.209	1.23	1.261
34	1.26925	1.241	1.255	1.286	1.295
35	1.09675	1.074	1.088	1.09	1.135
36	1.12875	1.1	1.128	1.141	1.146
37	1.088	1.073	1.076	1.094	1.109
38	1.24075	1.209	1.227	1.251	1.276
39	1.26275	1.235	1.26	1.273	1.283
40	1.22375	1.178	1.236	1.231	1.25
41	1.03975	1.023	1.01	1.038	1.088
42	1.19	1.169	1.175	1.186	1.23
43	1.13	1.099	1.123	1.133	1.165
44	1.15325	1.107	1.148	1.151	1.207
45	1.20425	1.167	1.186	1.213	1.251

A decimal point "." represents a missing value.

Blend	AvgBSFC	BSFC2350	BSFC2450	BSFC2600	BSFC2700
1	0.575	0.558	0.579	0.579	0.584
2	.	0.442	0.435	0.456	.
3	.	0.476	0.464	0.459	.
4	0.45425	0.448	0.461	0.451	0.457
5	.	0.469	0.461	0.476	.
6	.	0.438	0.433	.	.
7	0.4725	0.463	0.47	0.474	0.483
8	0.451	0.445	0.444	0.45	0.465
9	0.50875	0.5	0.499	0.509	0.527
10	0.4715	0.467	0.462	0.469	0.488
11	0.574	0.567	0.573	0.572	0.584
12	0.543	0.536	0.539	0.542	0.555
13	0.52125	0.519	0.51	0.518	0.538
14	0.47375	0.468	0.458	0.479	0.49
15	.	.	.	.	.
16	0.47275	0.465	0.473	0.465	0.488
17	0.49775	0.493	0.49	0.498	0.51
18	0.55875	0.557	0.55	0.558	0.57
19	0.589	0.582	0.578	0.597	0.599
20	0.485	0.483	0.48	0.488	0.489
21	.	.	.	.	.
22	0.5395	0.533	0.536	0.534	0.555
23	0.491	0.478	0.484	0.498	0.504
24	0.5015	0.502	0.501	0.49	0.513
25	0.53975	0.532	0.529	0.545	0.553
26	0.48125	0.479	0.481	0.479	0.486
27	0.48275	0.469	0.478	0.479	0.505
28	.	0.437	0.435	0.438	.
29	0.5455	0.537	0.531	0.55	0.564
30	0.5855	0.575	0.573	0.586	0.608
31	.	0.439	0.439	0.446	.
32	0.56425	0.552	0.552	0.567	0.586
33	0.53375	0.523	0.527	0.533	0.552
34	0.58125	0.573	0.572	0.592	0.588
35	0.4625	0.46	0.455	0.457	0.478
36	0.48025	0.47	0.476	0.483	0.492
37	0.46675	0.465	0.457	0.468	0.477
38	0.564	0.551	0.554	0.569	0.582
39	0.57275	0.568	0.57	0.574	0.579
40	0.541	0.521	0.546	0.544	0.553
41	0.4585	0.452	0.445	0.455	0.482
42	0.5355	0.532	0.528	0.532	0.55
43	0.48775	0.48	0.48	0.488	0.503
44	0.51925	0.506	0.515	0.516	0.54
45	0.52575	0.516	0.513	0.528	0.546

A decimal point "." represents a missing value.

– End of Report –