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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

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CRC Aviation Committee  
of the  
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## 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 blend 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.<sup>(1)</sup> 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.<sup>(1)</sup> 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.<sup>(2)</sup> 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.<sup>(3)</sup> 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.<sup>(2)</sup>

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://rql.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.<sup>(2)</sup>



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/Supercharged 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](http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgMakeModel.nsf/MainFrame)
- 4.11. 14 CFR Part 33, FAA Certification Requirements for Reciprocating Aircraft Engines

## About CRC

The Coordinating Research Council (CRC) is a non-profit organization that directs, through committee action, engineering and environmental studies on the interaction between automotive/other mobility equipment and petroleum products. The Sustaining Members of CRC are the American Petroleum Institute (API), the Society of Automotive Engineers (SAE) and a group of automobile manufacturers (Chrysler, Ford, General Motors, Honda, Mitsubishi, Nissan, Toyota, and Volkswagen). CRC research programs are managed by five technical committees (Advanced/Vehicle/Fuel/Lubricants, Atmospheric Impacts, Emissions, Performance, and Aviation.)

Through CRC, personnel in the automotive equipment and other related mobility industries and in the energy industries can join together, and can join with Government, to work on mutual problems. CRC has no facilities for conducting direct research. There are two basic approaches to accomplishing the research objectives. One approach involves a pooling of efforts carried out in the laboratories of cooperating companies. The result is a large-scale research program that no one company would be willing to undertake.

The second approach involves supporting research under contract to universities, industrial laboratories, and private research organizations. In this case, a small committee of technical experts develops the program, selects the research organization, and monitors the research to its conclusion. Funding for the contract research is largely provided by the American Petroleum Institute, the automobile manufacturers, the Government, and others.

CRC is not involved in any way in regulation, which remains a governmental responsibility; nor is CRC involved in the development of hardware or petroleum products, which remains the responsibility of private industry. The formal objective of CRC is to encourage and promote the arts and sciences by directing scientific cooperative research to develop the best possible combinations of fuels, lubricants, and the equipment in which they are used, and to afford a means of cooperation with the Government on matters of national or international interest within this field.