EXECUTIVE SUMMARY

CRC RESEARCH RESULTS

UNLEADED HIGH OCTANE AVIATION GASOLINE

A REPORT TO THE CRC UNLEADED AVGAS DEVELOPMENT PANEL

APRIL 24, 2008

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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. Current activities include a formal collaborative industry research program in addition to FAA sponsored research. The industry collaborative research program is currently led by the Coordinating Research Council (CRC) Unleaded AVGAS Development Panel. Working in parallel with this Panel is the CRC Aviation Engine Octane Rating Panel. The FAA William J. Hughes Technical Center has played a pivotal role in providing support and engine test facilities.

The CRC is a non-profit organization that directs, through committee action, engineering and environmental studies on the interaction between transportation equipment and petroleum products. Through CRC, personnel in transportation equipment and petroleum industries can join together, and work with the Government to resolve mutual problems. See www.crcao.org for further information on the CRC organization and background.

The objective of this report is to provide an overview in an executive summary format of CRC UL AVGAS research activities and results to date as related to unleaded high octane aviation gasoline alternatives.

CRC UNLEADED AVGAS DEVELOPMENT PANEL

The industry collaborative initiative is currently led by the CRC Unleaded AVGAS Development Panel that operates under the following Mission Statement.

> *"The Unleaded Aviation Gasoline Development Panel 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 Panel acts as a steering committee, providing oversight and direction for research and testing.*
>
> *The CRC AVGAS Development Panel 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."*

Membership of the CRC Unleaded AVGAS Development Panel currently consists of over 60 individuals representing over 40 different organizations. Working in parallel with this panel, and with mostly a common membership, is the CRC Aviation Engine Octane Rating

Panel 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 have been significant contributors to the overall process and reflect the magnitude and breadth of support for this initiative. The FAA William J. Hughes Technical Center has been instrumental in providing test facilities and funding in support of the CRC objectives. The EPA has continued to monitor the industry program while acknowledging and encouraging industry efforts.

MON SCREENING OF 202 UNLEADED FUEL BLENDS

The operational performance of AVGAS 100LL, manufactured to ASTM D 910 specification, is dependent on many parameters. One of the most significant properties when compared to other gasoline products is the very high octane quality of the fuel, 99.6 motor octane number (MON) minimum. This is necessary as required to meet the octane requirement of the thermally efficient high output aviation engines which comprise a significant portion of the general aviation fleet. Based on broad industry consensus, the CRC UL AVGAS Development Panel sought to investigate this fuel parameter first, while being aware that other critical properties would require assessment at a later stage as the program developed.

During YR2000, the CRC UL AVGAS Development Panel, 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). A research plan was subsequently created and the Development Panel 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 as listed below in Table 1.0. The objective was to discern the MON characteristics of each of the 202 blends.

Table 1.0
CRC UL Fuel Blend Components & Constraints
YR2001 MON Characterization
202 UL Blends

Blend Component	Alkylate Blend Fraction Limits		
	Aviation Alkylate	Motor Alkylate	Super Alkylate
Super Alkylate	0 – 50%	0 – 50%	-
Toluene	0 – 25%	0 – 25%	0 – 25%
ETBE	0 – 30%	0 – 30%	0 – 30%
m-Toluidine	0 – 10%	0 – 10%	0 – 10%
Ethanol	0 – 5%	0 – 5%	0 – 5%
MMT (g Mn/gal)	0 – 0.1	0 – 0.1	0 – 0.1

Notes:
1) Blend fractions are % volume unless shown otherwise

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, 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.

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 and at Cessna Aircraft using a group of 30 unleaded fuel blends developed from the YR2001 MON test program. 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 shown in Table 2.0.

Table 2.0
CRC UL Fuel Blend Constraints
YR2002 Full Scale Engine Tests
30 UL Blends

Blend Component	Blend Fraction Limits
Super Alkylate	0 – 50%
Toluene	0 – 25%
ETBE	0 – 30%
m-Toluidine	0 – 10%
Ethanol	0 – 5%
MMT	0 – 0.1 g/gal Mn

Notes:
2) Blend fractions are % volume unless shown otherwise
3) 8 aviation alkylate blends without MMT
4) 7 aviation alkylate blends with MMT
5) 8 motor alkylate blends without MMT
6) 7 motor alkylate blends with MMT

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 both component properties and a complete D 910 characterization of each blend. Properties identified for each blend include 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 not in agreement with the ASTM D 910 AVGAS Specification. Detail engine test results were published by both the FAA Technical Center and Cessna Aircraft.

FULL SCALE ENGINE TESTING OF 45 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 45 unleaded fuel blends derived from the prior research results. Full scale engine testing was resumed and completed in 2007 at the FAA William J. Hughes Technical Center using this group of 45 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 45 UL blends were furnished as anonymous blends, identified only by a blend number and were formulated to meet the requirements listed in Table 3.0. A final test report for the 45 UL blends is being prepared for publication.

Table 3.0
CRC UL Fuel Blend Constraints
YR2007 Full Scale Engine Tests
45 UL Blends

Blend Component	Blend 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 + isopentane	75% Max
*Av alkylate + isopentane	65% Max

Notes:
1) Blend fractions are % volume
2) *Add isopentane into alkylate totals to set the limits shown

ENGINE TESTS OF LEADED VS UNLEADED FUELS OF SIMILAR MON

Under the guidance of the CRC Octane Rating Panel, full scale engine testing was performed at the FAA Technical Center 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 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 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.

FACILITATING PROGRESS

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

- Air BP
- Cessna Aircraft
- Chevron
- ConocoPhillips
- Dixie Services
- Ethyl Corporation
- ExxonMobil
- FAA Technical Center
- Lyondell Chemical

CRC AVIATION ENGINE OCTANE RATING PANEL

The Octane Rating Panel works closely in parallel with the CRC UL AVGAS Development Panel. It also functions as a collaborative industry effort wherein testing is performed at the FAA Technical Center using engines furnished by the engine manufacturers with fuels furnished by the petroleum companies. The objective of the Octane Rating Panel was to develop a method to consistently octane rate aircraft engine octane requirements under repeatable conditions of a harsh but representative operational environment and to use this data to determine the unleaded fuel octane requirement of the general aviation fleet. It should be noted that an industry standard for octane rating aircraft engines did not previously exist; furthermore, the aviation method is significantly different as compared to automotive practice and requires specialist facilities and expertise.

Two ASTM standard practices, ASTM D 6424 and ASTM D 6812 were developed and implemented as a result of the work of the CRC Octane Rating Panel. 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 observed difference between leaded and unleaded fuels to achieve octane satisfaction in full size engines as observed by other CRC test work.

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

INDUSTRY PARTICIPATION

With as many as 200,000 general aviation engines operating worldwide, industry estimates have indicated that as much as half of the fleet may require a high octane AVGAS; however, industry experts believe it is this segment which accounts for most of the flying time today. Therefore, the continued availability of an appropriate high-octane aviation gasoline is viewed as a high priority by the general aviation industry. Active participation of industry stakeholders has played a major role in the progress of the CRC Unleaded AVGAS Development Panel. Stakeholders include airframe and engine manufacturers, fuel producers, the FAA, representatives of the major trade organizations (AOPA, EAA, and GAMA) and other interested parties. The large and diverse membership of the CRC Unleaded AVGAS Development Panel reflects the interest and commitment of the industry stakeholders. In a broad sense, the interests of the regulatory, user, and manufacturing communities are represented by the membership of the CRC UL AVGAS Development Panel.

CRC UL AVGAS RESEARCH MILESTONES

Significant CRC milestones relating to UL AVGAS research activities are summarized in the following Table 4.0. A summary CRC report documenting the CRC Unleaded AVGAS research results is being prepared for release in the near future.

Table 4.0
Significant Research Milestones
CRC UL AVGAS Development Panel & Octane Rating Panel

✓	1999	White 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, 45 UL Blends
✓	2005	Test Plan Finalized, Full Scale Engine Tests, 45 UL Blends
✓	2006	Full Scale Engine Tests Completed of Leaded & Unleaded Fuels of Similar MON & Performance Number
✓	2007	Full Scale Engine Tests Completed, 45 UL Blends
✓	2007	Consideration Given to Expansion of CRC Research to Include Test of Engine Modifications
✓	2008	Work Initiated On Summary CRC Research Report

CONCLUSIONS

CRC research into unleaded aviation gasoline alternatives has focused on meeting engine octane requirements. Research results to date reflecting the unleaded fuel blends identified above have not identified 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 require further evaluation with respect to environmental impact. Economic viability of the blends tested is not the jurisdiction of CRC and will also need to be evaluated 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 specialist components may achieve or 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 specifications. Depending upon engine power output and configuration, high performance aviation engines can require unleaded fuels in excess of 100 MON to achieve octane satisfaction. 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.

– END –