U.S. Department of Transportation
Federal Aviation Administration

Evaluation of ARA Catalytic Hydrothermolysis (CH) Fuel

Continuous Lower Energy, Emissions and Noise (CLEEN) Program

Submitted by Pratt & Whitney

DOT/FAA/AEE/2014-08

The Continuous Lower Energy, Emissions and Noise (CLEEN) Program is a Federal Aviation Administration NextGen effort to accelerate development of environmentally promising aircraft technologies and sustainable alternative fuels. The CLEEN Program is managed by the FAA's Office of Environment and Energy.

The report presented herein is a report deliverable submitted by Pratt & Whitney for a project conducted under the CLEEN Program to evaluate the feasibility of selected alternative fuels as viable drop-in replacements to petroleum jet fuel. This project was conducted under FAA other transaction agreement (OTA) DTFAWA-10-C-00041. This is report number DOT/FAA/AEE/2014-08 by the FAA's Office of Environment and Energy.

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In reply please refer to:
SSC:DTFAWA-10-C-00041/15

30 April 2014

FEDERAL AVIATION ADMINISTRATION
Jared Tritle, Contracting Officer
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Room 402
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Subject: FINAL REPORT, PUBLIC RELEASE VERSION, **FR-27652-2a**

Reference: Contract No. DTFAWA-10-C-00041, Item No. 15

In accordance with the applicable requirements under the referenced contract, Pratt & Whitney herewith submits one (1) copy of the Public Release version of the Final Report for the subject contract.

Sincerely,

Sarah S. Christopher

Sarah Christopher
Program Data Manager

<u>With enclosure</u>:
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FR-27652-2 Rev 1
22 April 2014

CONTINUOUS LOWER ENERGY, EMISSIONS, AND NOISE (CLEEN) PROGRAM

APPLIED RESEARCH ASSOCIATES (ARA) CATALYTIC HYDROTHERMOLYSIS (CH)

Prepared for
FAA Office of Environment and Energy

Prepared under
Contract No. DTFAWA-10-C-00041

In Response to
CDRL No. 15

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TABLE OF CONTENTS

LIST OF FIGURES

Figure *Page*

LIST OF TABLES

Table *Page*

ACRONYMS

A

AFRL	Air Force Research Laboratory
APA	Automatic Particle Analyzer
ARA	Applied Research Associates
ASTM	ASTM International (Formally known as American Society for Testing and Materials)
ATP	Acceptance Test Procedure

C

CAAFI	Commercial Aviation Alternative Fuels Initiative
CH	Catalytic Hydrothermolysis
CLEEN	Continuous Lower Energy, Emissions, and Noise
CO	Carbon Monoxide
CO2	Carbon Dioxide

D

DoD	Department of Defense
dP	Pressure Differential

F

FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FMU	Fuel Metering Unit
FN	Flow Number

G

GI	Ground Idle

I

ICAO	International Civil Aviation Organization
ITT	Inter-Turbine Temperature

L

LHV	Lower Heating Value
LII	Laser Induced Incandescence

N

N1	Low Rotor Speed
N2	High Rotor Speed
NRC	National Research Council
NOx	Oxides of Nitrogen

O

OEM	Original Equipment Manufacturers

P

P3	Combustor Inlet Pressure
PM	Particle Matter
pS/m	PicoSeimens per Meter
P&W	Pratt & Whitney
P&WC	Pratt & Whitney Canada

S

SAE	Society of Automotive Engineers
SFC	Specific Fuel Consumption
SGS	SGS Canada Incorporated (Formally known as Société Général de Surveillance)

T

T3	Combustor Inlet Air Temperatures
TTI	Time To Idle
TTL	Time To Light

U

UHC	Unburned Hydrocarbon

COMPANIES AND ORGANIZATIONS

Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, USA

ASTM International (Formally known as American Society for Testing and Materials), PA, USA

Millipore®, also known as Merck Millipore, is a Registered Trademark of Merck KGaA of Darmstadt, Germany

National Research Council (NRC)

SGS Canada Incorporated (Formally known as Société Général de Surveillance) is part of SGS S.A., headquartered in Geneva, Switzerland

Université Laval, Quebec, Canada

Woodward Governor Company, CO, USA

1.0 Executive Summary

This report documents the work performed by Pratt & Whitney (P&W) in evaluating synthetic paraffinic kerosene produced by the Applied Research Associates (ARA) Catalytic Hydrothermolysis (CH) Process. The work was performed under the Continuous Lower Energy, Emissions, and Noise (CLEEN) program, Contract DTFAWA-10-C-00041. P&WC performed a PW615F engine test on a baseline Jet A-1, a 50/50 percent fuel blend of ARA CH/Jet A-1, and 100 percent ARA CH fuel. The objective was to determine the impact of ARA CH on engine performance, operability, and emissions. The PW615F is a 1,460 pound thrust, two-spool turbo fan with a reverse-flow combustor and dual-channel full authority digital engine control (FADEC).

Specific fuel consumption (SFC), gaseous emissions of carbon monoxide (CO), unburned hydrocarbon (UHC), carbon dioxide (CO2), and oxides of nitrogen (NOx), smoke number, and particulate matter (PM) by Laser Induced Incandescence (LII) were measured at six points in engine performance. These points were ground idle (GI), 30 percent power, 50 percent power, 85 percent power, 93 percent power, and 100 percent takeoff power (1,460lbf thrust).

No difference was observed in engine operability for the ARA CH fuel blends compared to the baseline Jet A-1 fuel. No negative impact was observed on SFC, gaseous emissions, smoke number, or PM. Inspection of fuel system components showed no adverse effects from operation on the CH fuel blend. Metallic debris was found during preservation of the fuel metering unit (FMU), following the production Acceptance Test Procedure (ATP) performed at Woodward Governor Company. The source of debris has not been identified, but is not believed to be related to CH fuel.

Under the direction of P&WC, Université Laval performed tests on a single nozzle can combustor test section. Ground starts at 50, 0, -20, -30, and -40 °F and altitude relights at 15, 20, 25, 30, and 35 kft were performed. No starting differences or altitude relight lean boundary differences were observed. The rich limits were not achieved for the relights due to rig constraints.

2.0 Introduction

The objective of the Federal Aviation Administration (FAA) option to Demonstrate Alternate Fuels is to demonstrate feasibility of selected alternative fuels as viable drop-in candidates to petroleum-derived fuels. Depending on the objective and scope of the specific task, alternative fuel feasibility, performance, and operability may be determined through engine, component, or laboratory testing. The alternative fuels being evaluated are selected based on fuel readiness level and FAA approval, with input from the engine and airplane original equipment manufacturers (OEMs), the U.S. Air Force, and the Commercial Aviation Alternative Fuels Initiative (CAAFI).

ASTM International (ASTM) and the Department of Defense (DoD) are currently evaluating a biofuel process known as ARA CH, according to ASTM D4054, *Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives*. Upon approval, it is expected that the CH process will be included as an annex in ASTM D7566, *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*. In August 2013, P&WC tested a PW615F engine at its Longueuil, Canada facility. The objective of this initiative was to determine the impact of CH on the performance properties, operability characteristics, and emissions of a gas turbine engine. In July 2013, Université Laval, under the direction of P&WC, tested a generic can combustor to determine the impact of CH on turbine engine combustor cold starting and altitude relight characteristics.

3.0 Approach

3.1 Test Facility

Engine testing was performed on a PW615F engine, Serial Number 6157 Build 12, at the P&WC engine test facility 1-18 in Longueuil, Canada. Engine installation is shown in ***Figure 1*** and ***Figure 2***.

Figure 1. *Emissions Sampling System*

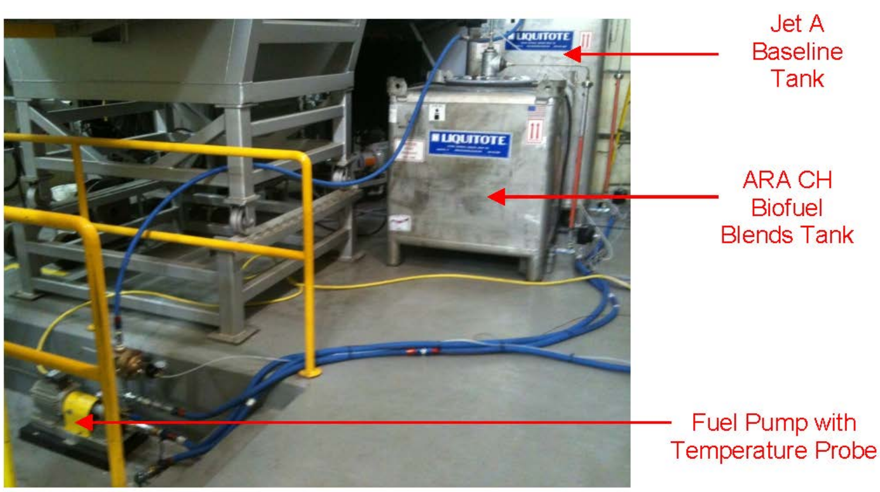

Figure 2. *Fuel Supply System*

3.2 Test Fuels

Test fuels included the following:

- Baseline Jet A-1
- 100 percent ARA CH
- Fuel blend of 50 volume percent ARA CH and 50 volume percent Jet A-1.

The Air Force Research Laboratory (AFRL) supplied all test fuels required for the engine and combustor tests. The same batch of Jet A-1 that was used in the baseline testing was also used to formulate the 50 percent ARA CH/50 percent Jet A-1 blend. Preparation of each fuel blend was conducted at the National Research Council (NRC).

Each test fuel was analyzed to evaluate conformity against the ASTM D1655 "Standard Specification for Aviation Turbine Fuels." The properties evaluation of each fuel sample was performed at SGS Canada Incorporated (SGS) laboratory in Montreal, Canada, which is a P&WC approved laboratory. Results are presented in ***Section 4.1*** of this report.

Test sequence was: baseline Jet A-1, 100 percent ARA CH, 50 percent ARA CH/50 percent Jet A-1, then repeated baseline Jet A-1. This provided the opportunity to document any deterioration in engine performance from the initial baseline. 268 gallons of each fuel blend were supplied for the engine tests. The engine fuel system and the facility fuel system were purged between each test to remove any residual fuel before testing the next fuel. The test sequence was completed in 12.2 hours of engine operation.

3.3 Engine Tests

P&WC performed PW615F engine tests on the baseline Jet A-1 fuel, 100 percent ARA CH fuel, and 50 percent ARA CH/50 percent Jet A-1 fuel to determine the impact of CH fuel on engine performance, operability, and emissions. The PW615F is a 1,460lb thrust, two-spool turbo fan with a reverse-flow combustor and dual-channel FADEC. Prior to each engine test, a new engine fuel filter was installed and a fuel sample was taken. At the conclusion of each engine test, the fuel filters were inspected for indication of contamination and the fuel samples were analyzed to verify that the baseline fuel and the CH fuel blend conformed to ASTM D1655. SFC, gaseous CO, UHC, CO2, and NOx emissions, smoke number, and PM by LII were measured at six engine performance points:

- GI
- 30 percent power
- 50 percent power
- 85 percent power
- 93 percent power
- 100 percent takeoff power (1,460lbf thrust).

The basic criteria used to evaluate successful operation of the PW615F engine during smoke and emissions testing were as follows:

- No visible smoke and no substantial changes in emissions
- Verified repeatability of data measurements
- No hardware deterioration or carbon buildup between the runs, as determined by borescope inspection.

Engine operability for the CH fuel blends was compared to the baseline Jet A-1 fuel test results. Operability metrics included impact on engine start to GI, engine transient times from idle to takeoff power and from takeoff to idle power, flameout margin, and forward and reverse engine bodies between idle and takeoff power.

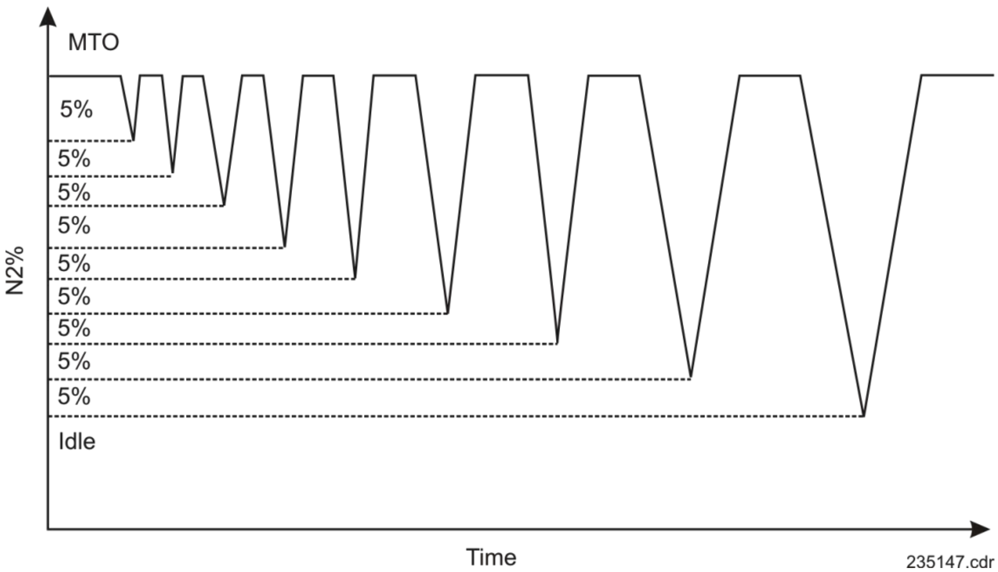

Figure 3. *Forward Bodies Manoeuvre*

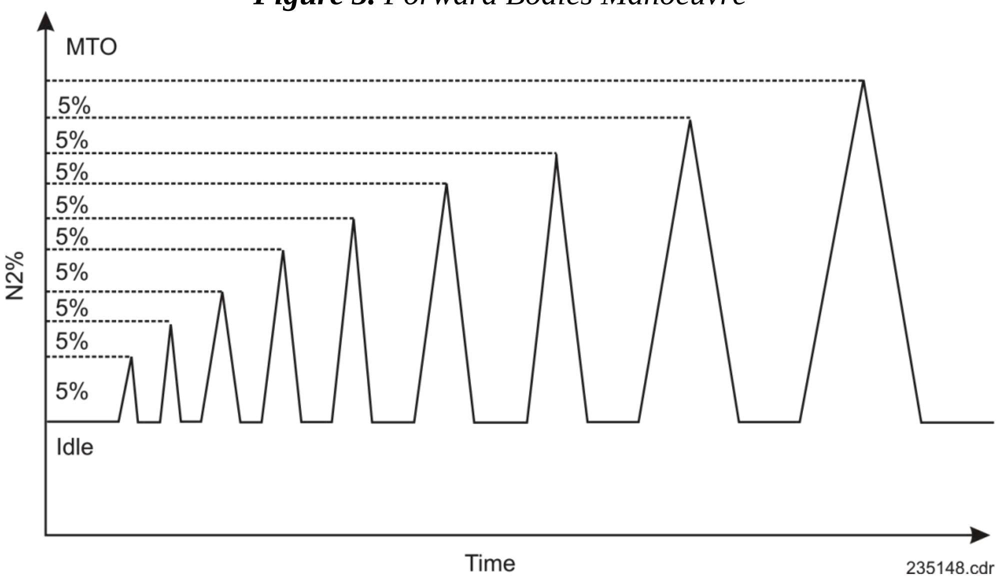

Figure 4. *Reverse Bodies Manoeuvre*

After completion of the test program, before initiating the engine tests, a visual inspection of the combustor fuel nozzles was completed to determine if operation on CH adversely affected these components. The fuel manifold assembly was flow checked and the 14 individual fuel nozzles were tested for spray angle pattern and uniformity coverage at the P&WC Mississauga facility. The FMU was completely characterized using production ATP-178 at the supplier facility, Woodward Governor Company.

3.4 Single Nozzle Can Combustor Rig Tests

Under the direction of P&WC, Université Laval performed rig tests on a single fuel nozzle generic can combustor test section for each of the test fuels. The combustor operability tests included cold starts and altitude relights, as defined below.

Cold Starts: Cold start mapping was performed at sea level with a constant combustor inlet pressure (P3) for each test fuel. Cold start mapping was performed with a pressure differential (dP) across the combustor, ranging from one to ten inches of water at five different combustor inlet air temperatures (T3) of 50, 0, -20, -30, and -40 °F. The objective was to determine the minimum fuel flow rate at which cold start is successful under each of these conditions. With igniter turned on, a successful light-up was defined as lighting within ten seconds of *fuel on*, followed by five seconds of sustained flame. Three successful lights were required at the same fuel flow rate to define the cold start boundary at each T3 and dP condition.

Altitude Relights: Altitude relight tests were performed on each test fuel to determine the maximum and minimum fuel-to-air ratio limits for which relight is successful. Mapping was initiated at 15,000ft, with a dP across the combustor ranging from one to three percent dP/P3. Relights were performed at 15, 20, 25, 30, and 35 kft. At higher altitudes, the maximum combustor pressure drop achieved was lower. Rich limits were not determined, due to rig constraints. With the igniter turned on, a successful light-up was defined as lighting within ten seconds of “fuel on,” followed by five seconds of sustained flame. Three successful lights were required at the same fuel flow rate to define the altitude relight fuel flow rate at each T3 and dP condition.

4.0 Results and Discussion

4.1 Fuel Properties

A fuel sample was taken prior to each engine test. Each of the fuel samples was analyzed according to ASTM D1655 requirements. Hydrogen content, the ratio of hydrogen to carbon, and the lower heating value (LHV) are presented in ***Table 1***. Results from the fuel sample analyses are shown in ***6.0Appendix A***.

The freezing point for 100 percent ARA CH, shown in ***Appendix A***, is -44°C. The 100 percent ARA CH was intentionally cut to meet the ASTM D1655 Jet A -40°C maximum requirement, as opposed to that of Jet A-1 maximum requirement of -47°C. Conductivity is shown as 4 picoSeimens per meter (pS/M), which was expected, since the 100 percent ARA CH is highly hydrotreated and did not contain Static Dissipator Additive.

Table 1. *Test Fuel Properties*

Fuel Property	*Baseline Jet A-1*	*100 Percent ARA CH*	*Fuel Blend 1 (50 percent ARA CH and 50 percent Jet A-1)*
Hydrogen (% weight)	13.80	13.80	13.80
Hydrogen/Carbon	1.850	1.850	1.850
LHV (BTU/lb)	18,594	18,521	18,555

4.2 Fuel System Components

A new engine fuel filter was installed prior to conducting each engine test. The fuel filters were inspected at the conclusion of each engine test for indication of contamination. Each fuel filter patch was rinsed with isopropanol and the residue collected on a 1.2 µm Millipore®[1] filter patch. The residue was evaluated by automatic particle analyzer (APA), followed by a visual examination of each patch. The evaluation did not reveal any indication of adverse effects from operation with the CH fuel blends.

After completion of the test program, before initiating the engine tests, a visual inspection of the combustor and fuel nozzles was completed. No adverse effects from operation with the CH fuel blends were discovered.

Also after completion of the test program, before initiating the engine tests, the fuel manifold assembly was flow checked and the 14 individual fuel nozzles were tested for spray angle pattern and uniformity coverage. The spray test results did not indicate any significant difference in fuel nozzle flow number (FN), spray angle pattern, or uniformity coverage. The FN of each fuel nozzle trended lower than the pre-test FNs after testing with the CH fuel blends, as shown in ***Figure 5***. The FN was above the upper limit by 1.8 percent for Nozzle Position 1 for the pre-test flow check. The FN was under the lower limit by 1.75 percent for Nozzle Position 2 for the post-test flow check. These deviations could be due to measurement variation.

[1] EMD Millipore is a Registered Trademark of Merck KGaA of Darmstaft, Germany.

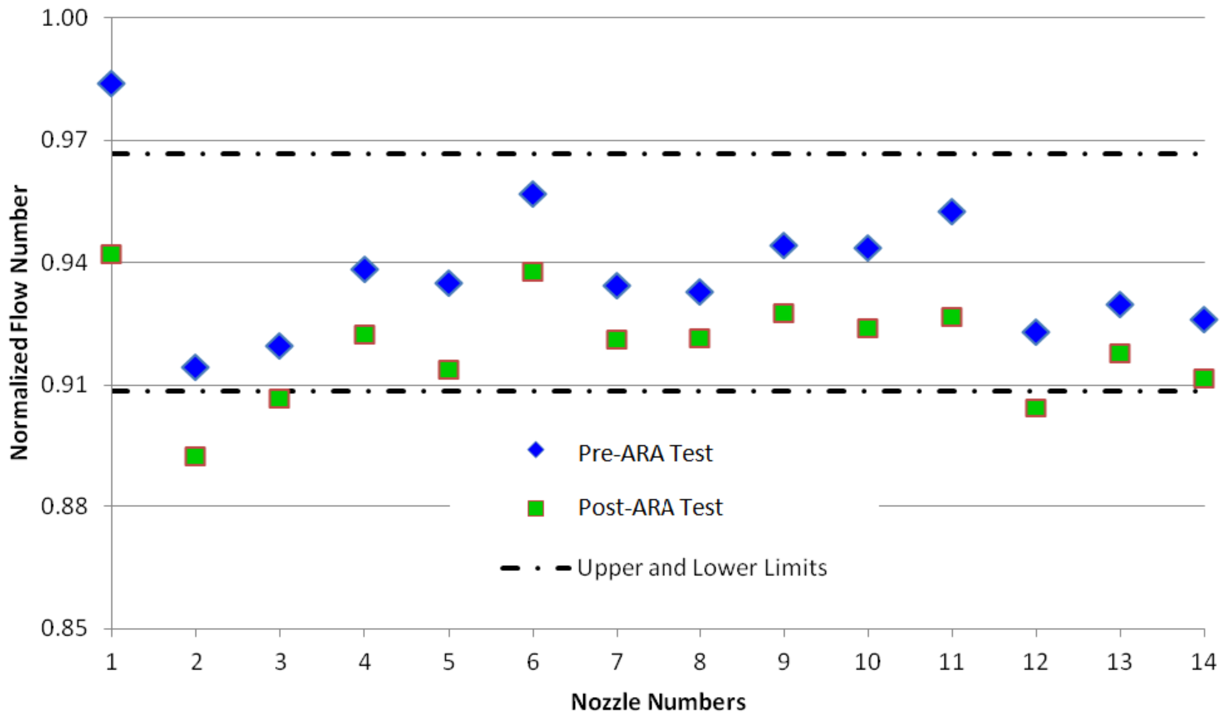

Figure 5. *Flow Number for Each Fuel Nozzle Before and After the Engine Tests*

The FMU was completely characterized using production ATP-178 at the supplier facility, Woodward Governor Company. The FMU S/N 18128932 was tested before and after the PW615F engine testing and found to meet all ATP-178 requirements. Following the ATP, during preservation of the unit, metallic debris was found in the preservation fluid. However, the debris is not determined to be fuel-related.

4.3 Engine Operability

Engine operability was evaluated during a series of maneuvers performed while the test engine was operating on the baseline Jet A-1 fuel. The maneuvers were then repeated for the 100 percent ARA CH fuel and for the 50 percent ARA CH/50 percent Jet A-1 fuel. The engine operability demonstrated while the engine was powered by the two biofuel blends was compared to the operability demonstrated with the baseline Jet A-1, to determine if any differences could be observed. No significant differences in engine operability were observed that could be attributed to the change in fuel.

The parameters time to light (TTL) and time to idle (TTI), as well as the peak inter-turbine temperature (ITT) can be used to evaluate the quality of the engine start with both the baseline Jet A-1 and ARA CH fuel blends. While differences within the measured values can be observed, no discernable trend between fuels can be seen. These differences are within the observed and expected scatter for these types of measurements. This data was demonstrates that all three fuels demonstrated equivalent engine start characteristics.

Slam accelerations and decelerations between GI and takeoff power were performed with all three fuels. As defined by P&WC test procedures and control system requirements, representative acceleration and deceleration times were used in this comparison. The differences observed were not considered large enough to have a significant impact on the operability of the engine. The acceleration and deceleration capability demonstrated during the slam maneuvers were considered equivalent.

Negative fuel spiking tests were conducted with all three fuels to assess the flameout margin that exists within the test engine. For all fuels, a series of negative fuel spikes were repeated at least once until a flameout was observed; the spike prior to flameout was identified as the limiting spike. These spikes were evaluated by comparing the ratio unit measured during the limiting spike. The ratio unit is defined as the measured fuel flow normalized by the compressor exit pressure. The biofuels flamed out with a fuel spike different than the baseline fuel. Differences observed within the ratio units of the limiting spike were typically within the scatter observed for these maneuvers, and therefore determined to be negligible. It is concluded that there are no significant differences in the operability of the engine while operating on these three fuels, because the only differences observed were small enough to fall within the natural variations of the test.

Engine operability is further quantified between fuels when observing forward and reverse body performances for any differences. Despite maneuvers representing the most aggressive operability testing, none of the fuels produced an engine surge or flameout. Similar trends with the ITT and the ratio unit were observed. These results were taken to further indicate that the operability of the engine was maintained, despite the change in fuel.

4.4 Engine Performance

Engine performance was evaluated by taking steady state measurements at six representative power settings: GI, 30 percent, 50 percent, 85 percent, 93 percent and 100 percent of rated takeoff thrust. A five minute stabilization time was used prior to taking any performance measurements. The results show that the biofuel blends had no significant impact on SFC, low rotor speed (N1) or high rotor speed (N2).

The pre to post-test comparison with the Jet A-1 baseline fuel revealed a small decrease in fuel consumption, but it was determined to be a result of a small error on fuel flow measurement. The biofuel results are compared with the repeat Jet A-1 fuel and presented in ***Table 2.***

Table 2. *Performance Test Main Parameters at Takeoff Thrust of 1,460lbf*

Engine/Build		6157B12	6157B12	6157B12	6157B12
Description		Baseline Jet A-1	50% ARA CH /50% Jet A-1	100% ARA CH	Repeat Jet A-1
Test Date		8 May 2013	8 May 2013	8 June 2013	8 June 2013
Parameters	***Units***				
SFC	-	1,000	0,994	0,992	0,994
WF	-	1,000	0,995	0,992	0,996
N1	-	1,000	0,999	1,000	1,000
N2	-	1,000	1,000	1,000	1,000

Measured SFC for the biofuel blends is 0.1 to 0.8 percent lower than the baseline Jet A-1. These variations are attributed to a fluctuation in fuel flow measurements. A review of the data indicates the fuel flow variations are consistent with observed combustion efficiency fluctuations. Adjusting the data for constant combustion efficiency, the SFC of the two biofuel blends is within 0.2 percent of the Jet A-1 baseline, which is within the accuracy of the measurement.

In addition, the remaining performance parameters, N1 and N2, also show negligible deltas with regards to the baseline fuel at constant thrust.

4.5 Smoke and Emissions

Engine exhaust emissions were measured and processed in accordance with International Civil Aviation Organization (ICAO) regulations [1]. The smoke analyzer and reflectometer were used together to calculate the smoke number at each condition point. An LII system was used to measure the PM mass and number count.

As expected, smoke number did not significantly change between the various fuels, due to the similar aromatic content. All other engine emissions for the baseline Jet A-1, the 100 percent ARA CH and the 50 percent ARA CH/50 percent Jet A-1 blends were within experimental scatter of those obtained with Jet A-1. Engine emission measurements for each fuel type are summarized in ***Figure 6***. Emissions meter readings for each pollutant are plotted against thrust. All shown results have been normalized.

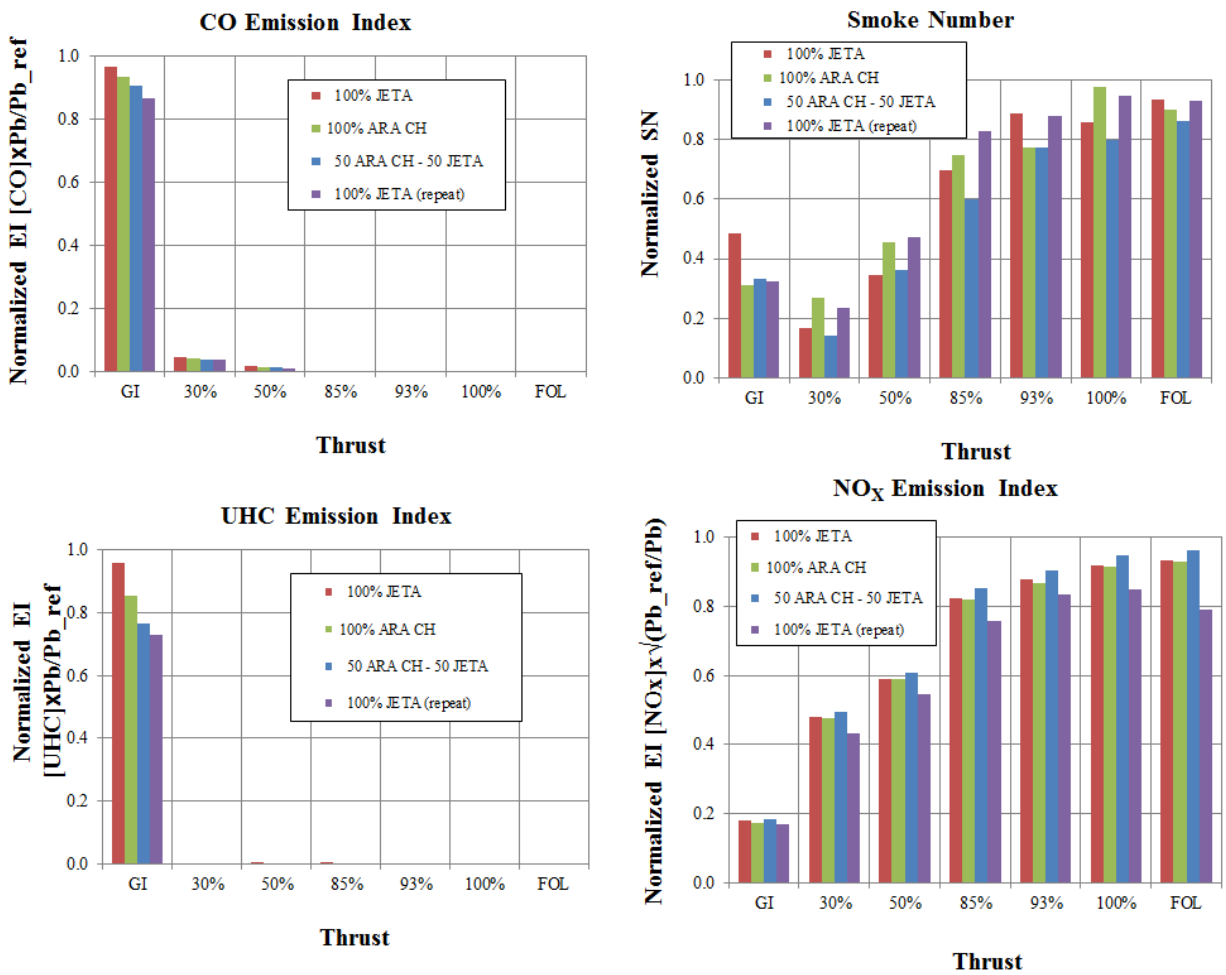

Figure 6. *Engine Emissions Comparison of Jet A-1 and ARA CH Biofuel Blends*

As is evident in the plots, the ARA CH blends had no impact on UHC, CO, or NOx emissions. Any variation shown is within expected test scatter. Jet A-1 and ARA CH have similar aromatic content, so it is understandable that Society of Automotive Engineers (SAE) smoke numbers are similar.

A LII 200 system was used as part of the test setup and measurement was taken at each of the power settings. The purpose of the LII 200 measurements was to identify the soot mass concentration and validate the correlation with smoke number.

The soot average mass concentrations and particle count number for ARA CH fuel blends and baseline Jet A-1 are presented in ***Table 3.*** Smoke densities were calculated based on the smoke number collected from the smoke analyzer and reflectometer, then measured as PM concentrations by the LII machine, as shown in ***Figure 7***. Smoke density measured by the LII under-predicts the SAE smoke number at high power conditions, as calculated by the smoke analyzer and reflectometer, by up to 41 percent. This amount of deviation is expected, due to the use of very distinct sampling methods and analysis tools.

Table 3. *Summary of Mass Concentration and Particle Count Number by LII Equipment*

	100% JET-A		*50% ARA CH /50% JET-A*		*100% ARA CH*		*100% JET-A (repeat)*	
Condition	***mass_con (mg/m3)***	***Count Number***	***mass_con (mg/m3)***	***Count Number***	***mass_con (mg/m3)***	***Count Number***	***mass_con (mg/m3)***	***Count Number***
GI	0,117	0,892	0,097	0,974	0,123	0,900	0,129	0,883
438lb	0,147	0,982	0,113	0,983	0,131	0,978	0,139	0,984
730lb	0,287	0,986	0,238	0,982	0,295	0,983	0,301	0,990
1,241lb	0,752	0,983	0,782	0,978	0,758	0,996	0,802	1,000
1,358lb	0,820	0,983	0,794	0,982	0,832	0,975	0,842	0,984
1,460lb	0,915	0,979	0,853	0,983	0,937	0,983	0,921	0,981
1,500lb	0,980	0,982	0,927	0,986	0,970	0,975	1,000	0,986
GI			0,109	0,982	0,129	0,983	0,125	0,987
	Avg=	0,970	Avg=	0,981	Avg=	0,972	Avg=	0,974
	Stdev=	0,034	Stdev=	0,004	Stdev=	0,032	Stdev=	0,040

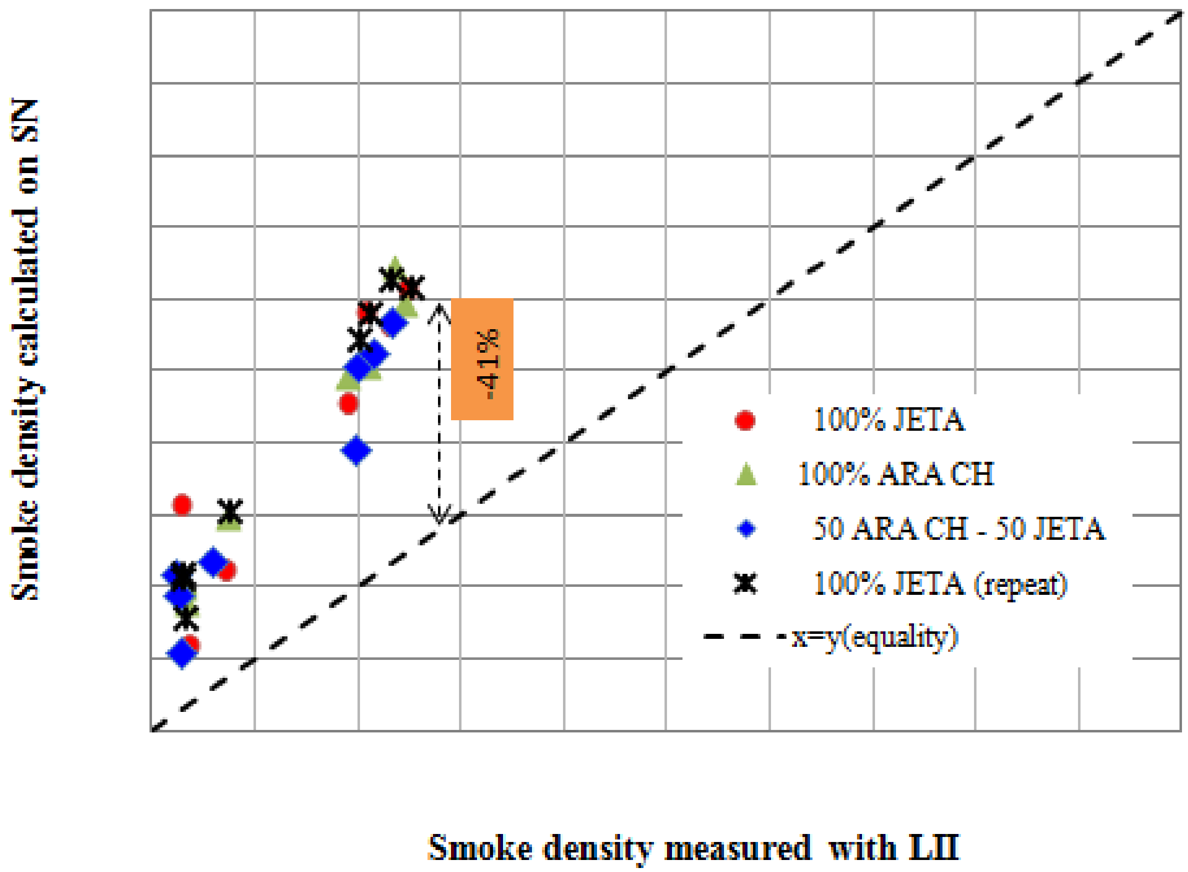

Figure 7. *Smoke Density Comparison Between Smoke Analyzer and LII Equipment*

4.6 Can Combustor Cold Start

Figure 8 and ***Figure 9*** display the lean ignition boundary at 0°F and -40°F for a combustor pressure differential ranging from one to ten inches H_2O. Cold start mapping was performed at combustor inlet temperatures of 50, -20, and -30 °F. The results of these tests showed a similar response. The start characteristics at the two temperatures for 100 percent ARA CH and 50 percent ARA CH/50 percent Jet A-1 behave similarly to the baseline Jet A-1 fuel.

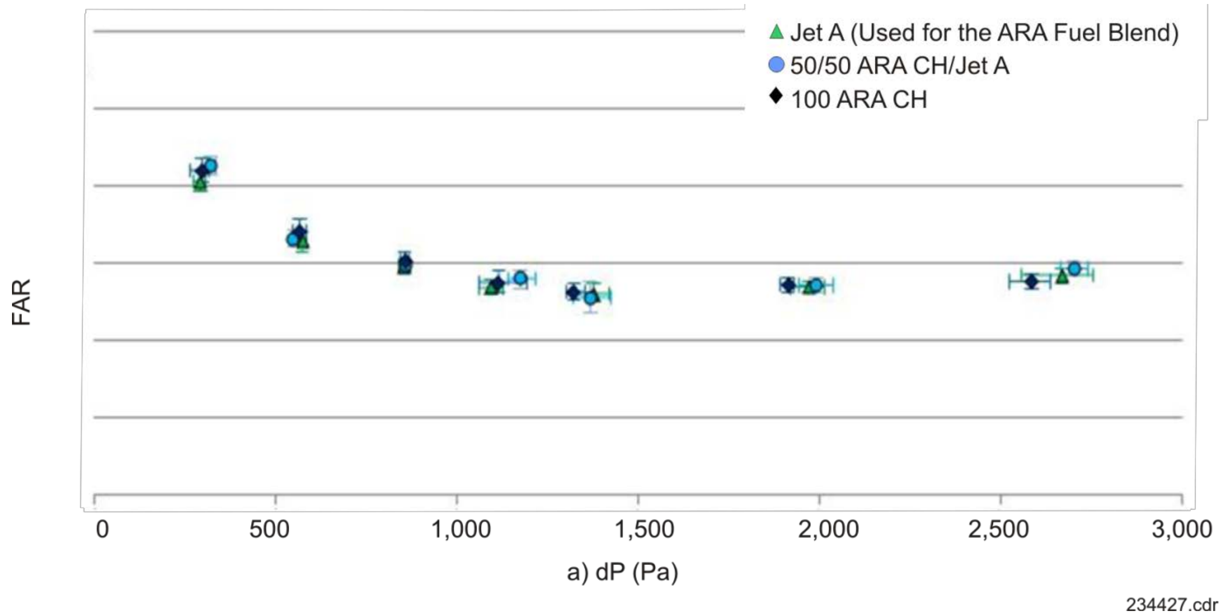

Figure 8. *ARA CH Cold Start at 0°F*

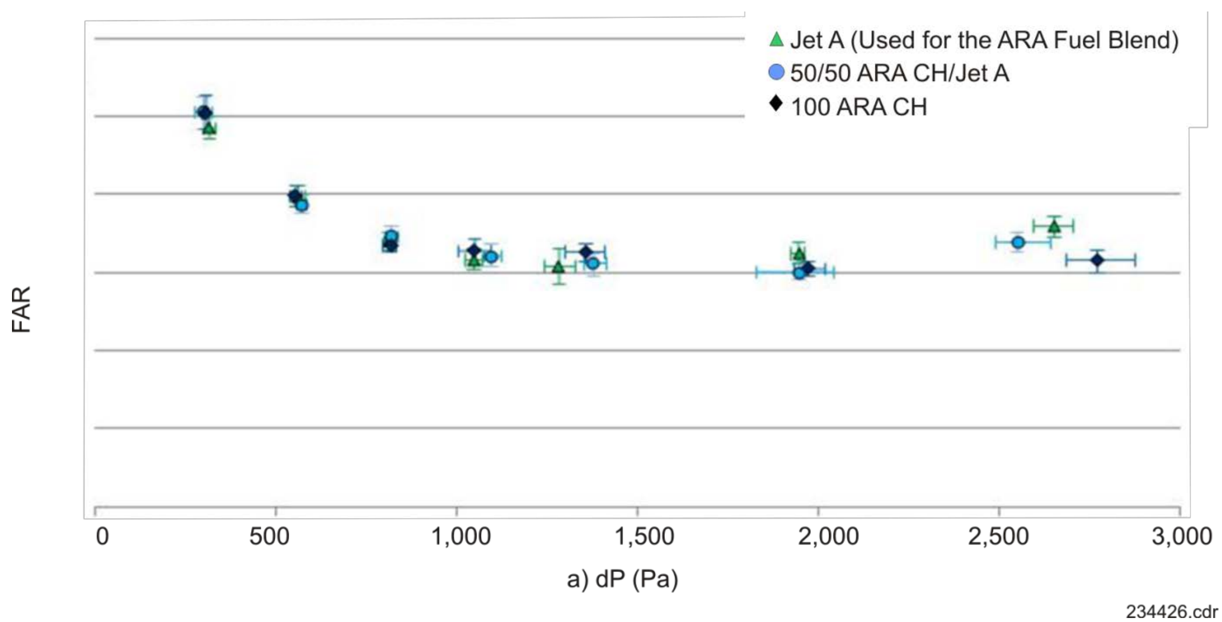

Figure 9. *ARA CH Cold Start at -40°F*

4.7 Can Combustor Altitude Relights

Altitude relights were performed at 15, 20, 25, 30, and 35 kft. The lean ignition boundary was determined, but the rich ignition boundary was not determined, due to rig limitations. The lean ignition boundary for successful starts at 15 and 30 kft is shown in ***Figure 10*** and ***Figure 11***. For altitudes up to 25kft, the relight response was similar for the 100 percent ARA CH and 50 percent ARA CH/50 percent Jet A-1 biofuel blend to the Jet A-1 baseline. At altitudes of 30 and 35 kft, the biofuels showed minor improvement in relight capability, as shown in ***Figure 11***.

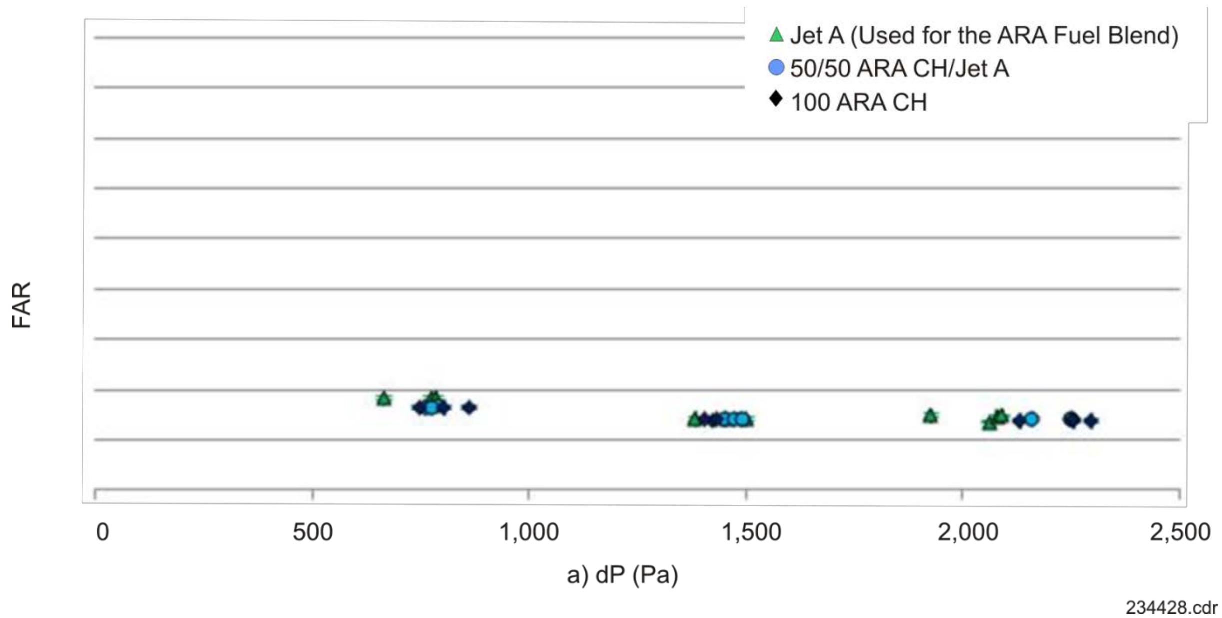

Figure 10. *ARA CH Altitude Relight at 15kft*

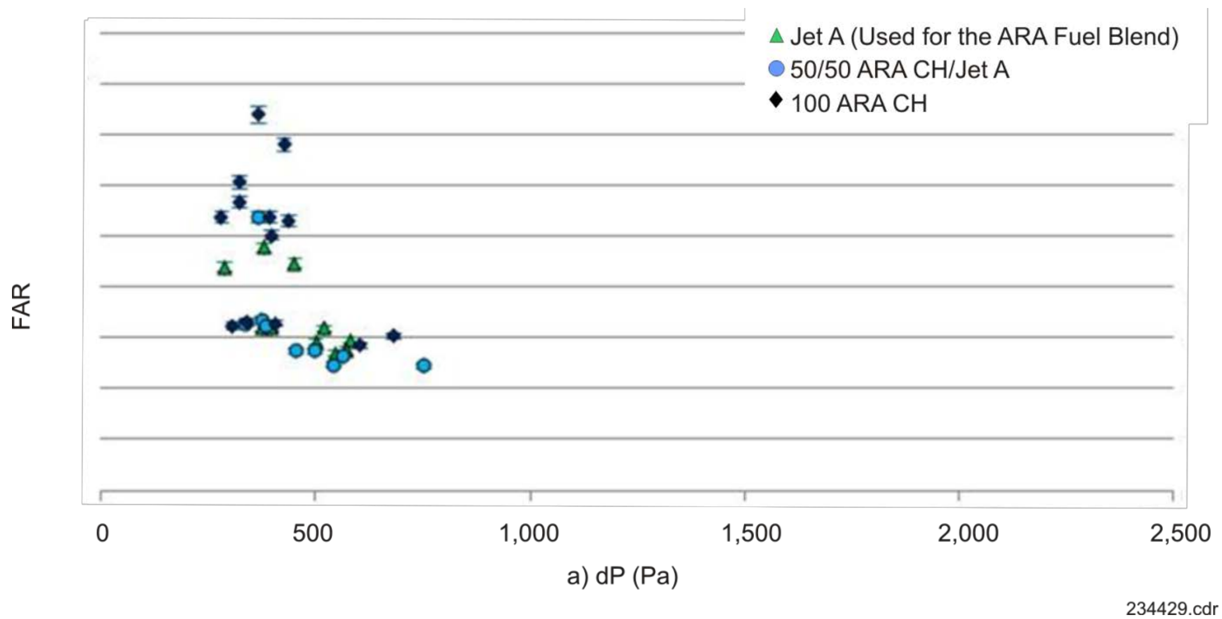

Figure 11. *ARA CH Altitude Relight at 30kft*

5.0 Conclusions

No difference was observed in PW615F engine operability for the 50 percent ARA CH/50 percent Jet A-1 or the 100 percent ARA CH biofuel blends compared to the baseline Jet A-1 fuel. No negative impact was observed on SFC, gaseous emissions, smoke number, or PM. Inspection of fuel system components showed no adverse effects from operation on the CH fuel blend. Metallic debris was found during preservation of the FMU, following the ATP. The source of debris has not been identified, but it is not believed to be CH fuel related.

Single nozzle can combustor tests were conducted at Université Laval, under the direction of P&WC. Ground starts at 50, 0, -20, -30, and -40 °F and altitude relights at 15, 20, 25, 30, and 35 kft were performed. No starting differences or altitude relight lean boundary differences were observed. The rich limits were not achieved for the relights, due to rig constraints.

Successful completion of the PW615F engine test performed on a CH fuel is a significant milestone in the approval process defined by ASTM-D4054, *Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives*. The results of this engine test will be included in an ASTM research report, along with results from specification tests, fit-for-purpose tests, component tests, and a possible engine endurance test. The ASTM research report will be used by the engine and airplane manufacturers, the DoD, FAA, and ASTM to approve CH blends for use in military and commercial aircraft.

6.0 References

[1] International Civil Aviation Organization Environmental Protection Annex 16, Volume II Aircraft Engine Emissions, Second Edition – 1993.

Appendix A – Fuel Properties Analysis

Table 4.*Fuel Properties Analysis*

					100% ARA CH	50%/50% ARA CH/Jet A-1
	ASTM	ASTM D1655	ASTM D7566 (table 1)	Jet A-1 Fuel CPMC 79024	Biofuel LCPMC 77004	CPS 7793
S.G.S certificate of Analysis	N/A	N/A	N/A	MT13-00103.001	MT13-00103.003	MT13-00103.002
Free water and particulate contamination	D4176 (procedure 1)	------------------------	------------------------	Pass	Pass	Pass
Acid number	D3242	0.10 mg KOH/g, max	0.10 mg KOH/g, max	0.01 mg KOH/g	0.01 mg KOH/g	0.01 mg KOH/g
Aromatics content	D1319	25% vol, max	25% vol, max	18% vol	17% vol	18% vol
Olefins content	D1319	------------------------		0.8% vol	0.9% vol	0.8% vol
Total sulfur content	D4294	0.30 % mass, max	0.30 % mass, max	0.05 % mass	<0.03%	0.03% mass
Distillation	D86					
- Initial boiling point				145°C	150°C	148°C
- 10% recovery		205 °C, max	205 °C, max	168°C	165°C	166°C
- 20% recovery				176°C	172°C	173°C
- 50% recovery				199°C	200°C	200°C
- 90% recovery				243°C	249°C	246°C
- Final boiling point		300 °C, max	300 °C, max	267°C	268°C	266°C
% residue		1.5%, max	1.5%, max	1.3%	1.2%	1.2%
% loss		1.5%, max	1.5%, max	0.9%	0.9%	1.0%
Mercaptan sulfur	D3227	0.003% mass, max	0.003% mass, max	<0.003% mass	<0.003% mass	<0.003% mass
TAG flash point	D56	38°C, min	38°C, min	37°C	45°C	42°C
Density at 15°C	D4052	775 to 840 kg/m^3	775 to 840 kg/m^3	801 kg/m^3	804 kg/m^3	802 kg/m^3
Freezing point	D5972	-47 °C, max	-47 °C, max	-51°C	** -44°C	-47 °C
Kinematic viscosity at -20°C	D445	8.0 mm^2/sec , max	8.0 mm^2/sec , max	4.0 mm^2/sec	4.0 mm^2/sec	4.0 mm^2/sec
* Smoke point	D1322	18 mm, min	18 mm, min	23 mm	24 mm	23 mm
* Naphtalene content	D1840 (procedure B)	3.0% vol, max	3.0% vol, max	1.1% vol	0.3% vol	0.7% vol
Net heat of combustion * corrected for sulfur	D3338	42.8 MJ/kg, min	42.8 MJ/kg, min	43.2 MJ/kg	43.3 MJ/kg	43.3 MJ/kg
Copper strip corrosion (2h/100°C)	D130	No. 1 max	No. 1 max	1a	1b	1b
Heater tube control temperature	D3241	260°C min	260°C min	260°C	260°C	260°C
Maximum pressure drop	D3241	25 mm Hg, max	25 mm Hg, max	2 mm Hg	1 mm Hg	0 mm Hg
Heat tube deposit rating	D3241	< 3 max	< 3 max	1	<2	1
Peacock	D3241	------------------------	------------------------	No	No	No
Abnormal	D3241	------------------------		No	No	No
Existent gum	IP 540	7 mg/100 ml, max	7 mg/100 ml, max	< 1mg/100 ml	1mg/100 ml	< 1mg/100 ml
Particulate contamination (4L of volume filtrated)	D5452	------------------------	------------------------	0.40 mg/L	0.20 mg/L	0.38 mg/L
MSEP-A	D3948	70 min	70 min	86	91	86
Conductivity	D2624	50 to 600 pS/m	50 to 600 pS/m	296 pS/m	*** 4	115 pS/m

* Smoke point and Naphthalene limits must both be met at the same time

** 100% ARA CH was intentionally cut to meet ASTM D1655 Jet A -40C maximum requirement

*** Low conductivity was expected since 100% ARA is highly hydrotreated and did not contain Static Dissipator Additive

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