AFRL-RZ-WP-TR-2011-2004

ALTERNATIVE FUELS TESTS ON A C-17 AIRCRAFT: EMISSIONS CHARACTERISTICS

Edwin Corporan

Fuels and Energy Branch
Energy/Power/Thermal Division

Matthew J. DeWitt, Christopher D. Klingshirn, and David Anneken

University of Dayton Research Institute

DECEMBER 2010
Interim Report

AIR FORCE RESEARCH LABORATORY
PROPULSION DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the USAF 88th Air Base Wing (88 ABW) Public Affairs (AFRL/PA) Office and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RZ-WP-TR-2011-2004 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH THE ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//

EDWIN CORPORAN
Project Manager
Fuels and Energy Branch
Energy/Power/Thermal Division

//Signature//

JOHN T. DATKO, Acting Chief
Fuels and Energy Branch
Energy/Power/Thermal Division
Propulsion Directorate

//Signature//

RICHARD T. FINGERS
Energy/Power/Thermal Division
Propulsion Directorate

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
December 2010	Interim	17 August 2010 – 17 December 2010

4. TITLE AND SUBTITLE
ALTERNATIVE FUELS TESTS ON A C-17 AIRCRAFT: EMISSIONS CHARACTERISTICS

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62203F

6. AUTHOR(S)
Edwin Corporan (AFRL/RZPF)
Matthew J. DeWitt, Christopher D. Klingshirn, and David Anneken (University of Dayton Research Institute)

5d. PROJECT NUMBER
3048

5e. TASK NUMBER
05

5f. WORK UNIT NUMBER
304805UD

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Fuels and Energy Branch (AFRL/RZPF)
Energy/Power/Thermal Division
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command, United States Air Force

University of Dayton Research Institute
300 College Park Avenue
Dayton, OH 45469-0170

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RZ-WP-TR-2011-2004

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RZPF

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RZ-WP-TR-2011-2004

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Report contains color. PA Case Number: 88ABW-2010-5792; Clearance Date: 29 Oct 2010.

14. ABSTRACT

Emissions evaluations were conducted on a C-17 Globemaster III F117-PW-100 engine operated with alternative fuels blends. These tests support the USAF goal of 50% domestic fuel consumption using alternative (synthetic) fuels with lower or equal carbon footprint than petroleum fuels by 2016. The tests took place at Edwards Air Force Base on the period of August 16 through 27, 2010 as part of the United States Air Force (USAF) Alternative Fuels Certification Office (AFCO) ground and flight tests to certify the C-17 on a 50/50 by volume JP-8/hydroprocessed renewable jet (HRJ) fuel blend. Emissions were collected from engine 3 of the parked aircraft operated on conventional JP-8 and 50/50 blends of JP-8 and a beef tallow-derived HRJ, and a 50/25/25 blend of JP-8, HRJ and a coal-derived Fischer-Tropsch (FT) fuel. Gaseous and particulate matter (PM) emissions were measured. PM measurements included particle number (concentration), mass and size distribution. In addition, hazardous air pollutant (HAPs) emissions, smoke numbers and chemical analysis of soot samples were performed for the engine operated with the three fuels. Emissions were collected for five engine operating conditions ranging from 4% (idle) to ~63% of rated maximum thrust. Test results show that the alternative fuel blends resulted in no operational anomalies or detrimental impacts on the gaseous or PM emissions of the F117 engine for any of the conditions tested. Moderate reductions in carbon monoxide (CO) emissions (~30%) and more significant reductions in sulfur oxides (50%), measured HAPs (>60%) and PM emissions (30-60%) relative to operation with JP-8 were observed. The alternative fuels had negligible impact on nitrogen oxides (NO_x) emissions.

15. SUBJECT TERMS
aircraft emissions, F 117 engine, particulate matter, HAPs, alternative fuels, hydroprocessed renewable jet fuel, C-17

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Edwin Corporan
Unclassified	Unclassified	Unclassified	SAR	36	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

TABLE OF CONTENTS

Section **Page**

List of Figures ii
List of Tables ii
List of Acronyms iii
Acknowledgements iv
1.0 EXECUTIVE SUMMARY 1
2.0 EXPERIMENTAL 2
2.1 Instrumentation 2
2.1.1 Particulate Matter (PM) Emissions 3
2.1.2 Gaseous Emissions 5
2.2 Emissions Sampling System 5
2.3 F117 Engine 9
2.4 Jet Fuel Characteristics 10
2.5 Test Conditions and Procedure 13
2.5.1 Atmospheric Conditions 13
3.0 TEST RESULTS AND DISCUSSION 14
3.1 Particulate Matter (PM) Emissions 14
3.1.1 Particle Number (PN) Emissions 14
3.1.2 Particle Size Distribution 15
3.1.3 Particulate Mass Emissions and Carbon-Burn-off Analysis 18
3.1.4 Smoke Numbers 19
3.2 Gaseous Emissions 20
3.2.1 Carbon Monoxide, Nitrogen Oxides and Sulfur Dioxide 20
3.2.2 Polycyclic Aromatic Hydrocarbons (PAH) and HAPs Analysis 22
4.0 CONCLUSIONS 25
5.0 REFERENCES 26

LIST OF FIGURES

Figure **Page**

1 AFRL TERTEL 2
2 PM and Gaseous Emissions Instrumentation in the TERTEL 3
3 Simplified Emissions Sampling System used in C-17 Emissions Tests 6
4 C-17 Globemaster III and AFRL TERTEL 7
5 Particle and Gas Probes Installation at F117 Engine Exit Plane 8
6 Distillation curves for tested fuels 12
7 Gas Chromatograms of JP-8 and neat HRJ fuels 12
8 Normalized Particle Number EI as a Function of Engine Power for the F117 Operated with Alternative Fuel Blends 15
9 Particle Size Distribution for F117 Engine operated on JP-8 and 50/25/25 Blend of JP-8/ HRJ/FT 16
10 Particle Size Distribution for F117 Engine operated on JP-8 and 50/50 Blend of JP-8/HRJ 17
11 Mean Particle Diameters for F117 Engine operated on JP-8 and Alternative Fuel Blends 18
12 Smoke Numbers of F117 Engine Operating on JP-8 and Alternative Fuel Blends at Several Engine Conditions 19
13 Smoke Samples for F117 Engine Operating on JP-8 and Alternative Fuel Blends 20
14 Comparison of CO and NO_x Emission Indices between the PW2040 (ICAO Engine Emissions Databank Issue 16) and the F117 (these tests) 21
15 Normalized CO and SO_2 Emission Indices for F117 Engine Operated on the JP-8/HRJ and JP-8/HRJ/FT Fuel Blends 22
16 Normalized Formaldehyde and Acetaldehyde Emission Indices Measured using the EPA Compendium Method TO-11A for F117 Engine Operated on the JP-8/HRJ and JP-8/HRJ/FT Fuel Blends 24

LIST OF TABLES

Table **Page**

1 Emissions Instrumentation 3
2 Results of Test Fuel Specification Tests 10
3 Hydrocarbon Fuel Analysis of Neat Fuels 11
4 Test Plan for C-17 Alternative Fuels Emission Tests 13
5 Atmospheric Conditions during Alternative Fuels Testing 13
6 Hazardous Air Pollutants Investigated in F117 Engine Exhaust 23

LIST OF ACRONYMS, ABBREVIATIONS AND SYMBOLS

ACRONYM	DESCRIPTION
AFCO	Alternative Fuels Certification Office
AFRL	Air Force Research Laboratory
ARP	Aerospace Recommended Practice
CPC	Condensation Particle Counter
DC	Dilution Chamber
DMA	Differential Mobility Analyzer
DNPH	Dinitrophenylhydrazine
EC	Elemental Carbon
EI_n	Particle Number Emission Index
EI_m	Particle Mass Emission Index
EPA	Environmental Protection Agency
FT	Fischer-Tropsch
FTIR	Fourier Transform Infrared
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Performance Liquid Chromatography
HRJ	Hydroprocessed Renewable Fuel
MAAP	Multi-Angle Absorption Photometer
NDIR	Non-Dispersive Infrared
OC	Organic Carbon
PM	Particulate Matter
PAH	Polycyclic Aromatic Hydrocarbons
SLPM	Standard Liters per Minute
SMPS	Scanning Particle Mobility Sizer
SN	Smoke Number
TERTEL	Turbine Engine Research Transportable Emissions Laboratory
UDRI	University of Dayton Research Institute

ACKNOWLEDGEMENTS

This work was partially funded by the US Air Force Alternative Fuels Certification Office (AFCO). The work by the University of Dayton Research Institute (UDRI) was supported by the U.S. Air Force Research Laboratory under the cooperative research agreement F33615-03-2-2347. Special thanks to Patrick Terry, James Holther, Sheryl Adamczyk and Fernando Navarro for their logistic and technical support during the tests. The authors are also very grateful to Linda Shafer and Rich Striebich from UDRI for the chemical analysis of the fuels and soot samples, Kim Higgins from UDRI for EC/OC analysis, and Joe Mantz from UDRI and Tom Greene from Phacil Inc. for their technical support during the tests.

1.0 EXECUTIVE SUMMARY

Emissions evaluations were conducted on a C-17 Globemaster III F117-PW-100 engine operated with alternative fuels blends. These tests support the USAF goal of 50% domestic fuel consumption using alternative (synthetic) fuels with lower or equal carbon footprint than petroleum fuels by 2016. The tests took place at Edwards Air Force Base on the period of 16-27 August 2010 as part of the United States Air Force (USAF) Alternative Fuels Certification Office (AFCO) ground and flight tests to certify the C-17 on a 50/50 by volume JP-8/ hydroprocessed renewable jet (HRJ) fuel blend. Emissions were collected from engine #3 of the parked aircraft operated on conventional JP-8 and 50/50 blends of JP-8 and a beef tallow-derived HRJ, and a 50/25/25 blend of JP-8, HRJ and a coal-derived Fischer-Tropsch (FT) fuel. Gaseous and particulate matter (PM) emissions were measured. PM measurements included particle number (concentration), mass and size distribution. In addition, hazardous air pollutant (HAPs) emissions, smoke numbers and chemical analysis of soot samples were performed for the engine operated with the three fuels. Emissions were collected for five engine operating conditions ranging from 4% (idle) to ~63% of rated maximum thrust. Test results show that the alternative fuel blends resulted in no operational anomalies or detrimental impacts on the gaseous or PM emissions of the F117 engine for any of the conditions tested. Moderate reductions in carbon monoxide (CO) emissions (~30%) and more significant reductions in sulfur oxides (50%), measured HAPs (>60%) and PM emissions (30-60%) relative to operation with JP-8 were observed. The alternative fuels had negligible impact on nitrogen oxides (NO_x) emissions. The relative reductions in particle concentrations and smoke were higher at lower power settings and results consistent with previous tests by the Air Force Research Laboratory (AFRL) on TF33, T701C, CFM56 and T63 engines. The lower aromatic content, and hence, lower carbon content in the fuel blend, is the primary cause for the resultant lower PM emissions. Fuel chemical and physical characteristics and details of the test plan and setup are presented.

2.0 EXPERIMENTAL

2.1 Instrumentation

Emissions instrumentation was transported to the test site and housed during testing in the Air Force Research Laboratory - Fuels and Energy Branch Turbine Engine Research Emissions Transportable Emissions Laboratory (TERTEL) (Figure1). The TERTEL is equipped with state-of-the-art instrumentation for the measurement and analysis of turbine engine gaseous and PM emissions. Pictures and a list of the instruments used in this effort are shown in Figure 2 and Table 1 respectively.

Figure 1: AFRL TERTEL

Figure 2: PM and Gaseous Emissions Instrumentation in the TERTEL

Table 1. Emissions Instrumentation

Instrument	Measurement
Condensation Particle Counter (TSI 3022A)	Particle Number
Scanning Mobility Particle Sizer (TSI 3936)	Particle Size Distribution (D=7.0 - 289 nm)
Multi-angle Absorption Photometer	Particle Mass Concentration
FTIR Analyzer (MKS 2030)	CO_2, CO, NO_x, SO_x, HC species
NDIR Analyzer (CA 602P)	Diluted Sample CO_2
Smoke Sampler & Reflectometer (Photovolt Instruments Inc. 577)	Smoke Number
LECO Carbon Analyzer (RC-412)	Elemental/Organic Carbon

2.1.1 PM Emissions

PM2.5 (particulate matter equal or smaller than 2.5 micrometers in diameter) is a criteria pollutant regulated by the Environmental Protection Agency (EPA). Due to the harmful health and environmental impacts of PM2.5 emissions, sources of PM2.5 and resulting EPA PM2.5 non-attainment (i.e., non-compliant) areas have been receiving significant scrutiny in the past decade. The health effects associated with PM2.5 can range from aggravation of respiratory and cardiovascular disease to premature mortality.[1] Most particulate matter from aircraft engines is PM2.5, which make aircraft a relatively large contributor of PM2.5 near airports and military bases. Although a standard methodology for PM measurements from turbine engines is yet to be

developed, state-of-the-art instrumentation used in aerosol research applications and accepted by the scientific community for turbine engine measurements, was employed in this effort.[2] Real-time analysis of the mostly non-volatile PM emissions was performed using a TSI Model 3022A Condensation Particle Counter (CPC) to provide a count of the total particles per unit volume (particle number). The CPC uses the principle of condensing supersaturated vapor on sub-micron size particles, which are then counted with an optical detector. Two scanning mobility particle sizers (SMPS) TSI Model 3936 were employed to measure particle size distributions and mean particle diameter according to their mobility through an electric field. The SMPS units consisted of a long differential mobility analyzer (DMA) TSI Model 3081 coupled with either a CPC TSI Model 3776 or Model 3025 for classifying particles in the range of 7 to 289 nanometers (nm) in diameter. One SMPS was used to analyze probe-tip diluted samples, while the second was used to analyze samples diluted in a "dilution chamber" (DC) located at the base of the probe stand. Two identical in-house designed smoke samplers were used for determination of engine smoke numbers following the techniques in the SAE ARP 1179[3] and to collect samples for post-test chemical and carbon type analysis. The soot samples for chemical and carbon-type analysis were collected by passing a predetermined volume (~57 liters) of undiluted exhaust sample through the quartz filters via heated lines (150°C). Soot samples were chemically analyzed to investigate differences in the quantity and type of polycyclic aromatic hydrocarbons (PAH) compounds absorbed onto the particulate samples with the different fuels. The samples were prepared for analysis using ultrasonic extraction with methylene chloride, and analyzed via gas chromatography/mass spectroscopy (GC/MS) to study impacts of the alternative fuels on type and concentration of PAH compounds. A second set of soot samples was analyzed via carbon-burnoff in a LECO RC-612 Multiphase Carbon Analyzer to determine the total mass and the organic and elemental carbon fraction. In the LECO analyzer, the soot sample is oxidized in the presence of excess oxygen as the furnace temperature is increased at a rate of 105°C/min from an initial 325°C (held for 7.5 minutes) to 750°C (held for 10 minutes). Species that oxidize at lower temperatures (< 325°C) are considered volatile organic species (e.g., PAH), while those that oxidize at higher temperatures are assumed to be primarily elemental carbon (EC) (e.g., highly graphitic). The total carbon mass is the sum of the volatile (i.e., organic carbon (OC)) and elemental carbon. Engine PM mass was also measured directly with a Thermo Scientific Model 5012 Multi-angle Absorption Photometer (MAAP). The MAAP measures black (elemental) carbon by simultaneously measuring the optical absorption and light scattering of the particles collected on a glass fiber filter. This technique accounts for the change in light transmission through the filter as well as the effects of reflection and the scattering of light in multiple directions due to particle size and shape. For these tests, most MAAP samples were collected at a flow rate of approximately 10.0 slpm and a nitrogen dilution of 10-80:1 controlled using mass flow controllers. The actual dilution ratios were calculated based on the CO_2 concentration in the diluted sample to the MAAP and the engine raw CO_2 emissions. The CO_2 for the diluted particle sample was measured with a Non-dispersive Infrared (NDIR) analyzer (California Analytical Model 602P).

2.1.2 Gaseous Emissions

Major gaseous species (i.e., CO, SO_2, NO_x) were quantified using an MKS Multi-Gas 2030 Fourier Transform Infrared (FTIR)-based gas analyzer. The analyzer quantifies gas species concentrations by measuring the absorption of an emitted infrared light source through the gas sample. Measurement of aldehydes was accomplished with the FTIR-based analyzer and following the EPA Compendium Method TO-11A.[4] For the latter, engine exhaust flows at 2 SLPM for five minutes through an ozone scrubber and then through a silica gel cartridge treated with 2,4-dinitrophenylhydrazine (DNPH). The ozone scrubber prevents depletion of DNPH. After completion, the cartridges were capped, placed into foil lined bags and stored in a 4°C cooler for transport for post-test analysis. In the laboratory, the cartridges were treated with 5 mL of acetonitrile to extract the derivitized aldehyde, and the extracts were analyzed by High Performance Liquid Chromatography (HPLC). Standard solutions of aldehydes were prepared and analyzed to develop a calibration range between 0 and 15 ug/mL of each derivitized aldehyde.

Volatile organics were collected by flowing engine exhaust at 1 standard liter per minute (SLPM) for 5 minutes through an activated charcoal carbon tube. As with the DNPH cartridges, the tubes were capped and stored in a 4°C cooler for transport to the laboratory for post-test analysis. In the laboratory, the charcoal tube was separated into front and back bed vials, and the organics were extracted from each bed using 1 mL of carbon disulfide spiked with a known quantity of C_{20}, and the solution transferred for quantification in a GC/MS. Standard solutions of most organic compounds were prepared and analyzed to develop a calibration range between 0 and 25 µg/ml. Comparison to the calibration standards was performed to quantify the mass of each HAP per volume of gas.

2.2 Emissions Sampling System

The emissions sampling system consisted primarily of three particle (N_2-diluted) and four gas (undiluted) probes (1.45 mm orifice diameter) connected to heated transfer lines to the instruments. A simplified flow diagram is shown in Figure 3. The probe rake was installed 10 cm off the engine axis (unobstructed by the exhaust nozzle centerbody) and approximately 42 cm from the engine exhaust plane in order to capture the engine core exhaust and avoid diluting with bypass air or contaminating with surrounding air. Special attention was given to align the rake perfectly parallel to the engine axis to prevent any unfavorable loads on the rake side walls, which could create rake instabilities, excessive movement and potential aircraft damage. The rake was mounted on a heavy duty steel structure extending a total height of approximately four meters. The stand was restrained with three tanks of water (~3400 kg total weight) to prevent movement during engine operation (Figure 4). The particle and gas probes had nominal port diameters of 1.6 mm and 1.5 mm, respectively and were separated by 3.18 cm center-to-center (Figure 5). Nitrogen, supplied from liquid dewars, was used to dilute the PM sample at the probe tip to minimize condensation of water and organic species, and particle loss to the wall due to high wall-sample temperature gradients (thermophoresis). Probe-tip dilution is the most widely accepted dilution technique for sampling of turbine engine PM emissions.[2] For engine power

settings above idle, secondary dilution (up to 50% of total) injected into the sample line approximately 2.5 m from the probe tip, was necessary to avoid saturation of the CPC. Although the dilution ratios were set using high precision flow controllers, the reported ratios are based on the ratio of the carbon dioxide (CO_2) concentration of the diluted and undiluted streams. The average of two measurements using different dilution ratios was used for the particle number data reported herein. Dilution ratios were ranged between 4 to 90:1 and varied significantly for each power setting. The sampling system was configured to direct the sample from each probe to different instruments by means of fast-response ball valves. The routing valves were installed in a heated box (150°C) located between the aircraft and the TERTEL. Due to the relatively short run times, each instrument received samples from only one probe for most of the tests. Samples were transported through stainless steel heated lines (150°C – gas, 75°C – diluted PM), 0.77 cm I.D. and approximately 23 m long.

Particulate samples diluted in a "dilution chamber" (DC) were also analyzed. The intent of the chamber (developed under an ongoing environmental (SERDP) program in collaboration with Oak Ridge National Laboratory) is to simulate chemical reactions and physical transformations (e.g., particle formation, condensation and agglomeration) as the engine exhaust mixes, dilutes and cools with the surrounding atmosphere.

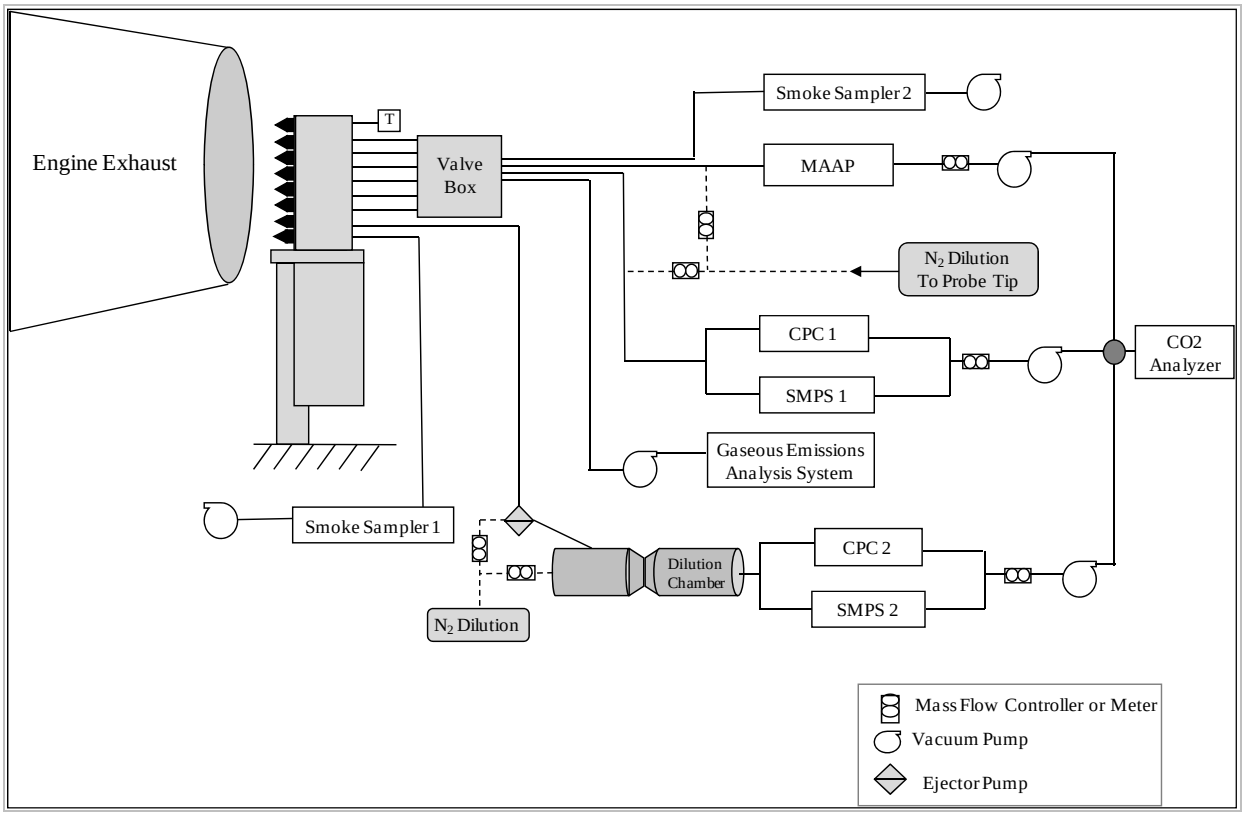

Figure 3: Simplified Emissions Sampling System used in C-17 Emissions Tests

Figure 4: C-17 Globemaster III and AFRL TERTEL

Figure 5: Particle and Gas Probes Installation at F117 Engine Exit Plane

These transformations will affect the physical properties and subsequent environmental and health impacts of the PM emissions. The DC consisted of a cylindrical design (21 cm I.D.) with three basic regions: a sample/diluent introduction zone (80 cm long), a turbulent mixing zone comprised of a converging/diverging section and a homogeneous sampling zone (sample extraction point located approximately 1.10 m downstream of divergence). The raw engine exhaust sample was drawn into the DC using a nitrogen-driven (motive flow) ejector pump via a 2.4 m long, 0.77 cm diameter heated line (150°C). The sample was diluted with additional nitrogen (secondary flow) to obtain the desired overall dilution. Since ambient air was not used as a diluent in this effort (for simplicity), minimal physical/chemical transformations of the PM emissions were expected. The motive and secondary dilution flows were maintained constant at approximately 76 and 350 SLPM, respectively, and sample flow varied from 10-16 SLPM depending on exhaust pressure, resulting in dilution ratios of 19 to 50:1. The diluted sample was transported to dedicated SMPS and CPC instruments in the TERTEL via unheated 23 m long, 0.77 cm I.D. stainless steel tubing.

2.3 F-117 Engine

The F117-PW-100 engine is the military variant of Pratt & Whitney's PW2000 commercial engine, which powers the Boeing 757-200 aircraft. The F117 engine has a maximum thrust rating of 40,400 lb, an overall pressure ratio of 30.8:1 and bypass ratio of 5.9:1.[5] For these evaluations, emissions were measured at engine powers ranging from 4 to ~63% of max thrust.

2.4 Jet Fuel Characteristics

The fuels used during this evaluation were analyzed using ASTM specification conformance tests to verify fuel compliance with all JP-8 specifications (MIL-DTL-83133G).[6] Results are shown in Table 2. Note that two JP-8 fuels were used either as a blend stock or neat during the tests. The JP-8b fuel was not used for ground or flight tests because it did not pass the specification tests for thermal stability (JFTOT) and water separation. Also, although within specification values, a significantly higher gum content was observed in the off-spec JP-8 compared to the baseline JP-8 (JP-8a) and the alternative fuels. Large gum content is indicative of fuel contamination by higher boiling oils or particulate matter. Despite not complying with the JP-8 specifications, a 50/50 blend of the off-spec JP-8 with the HRJ passed all the specification tests, and was therefore considered adequate for used in the C-17 evaluations. This is an important finding as off-spec JP-8, which would have otherwise been discarded, can be blended with an SPK-type fuel resulting in a fuel which complies with the JP-8 requirements. The second JP-8 (JP-8a) complied with all specification tests and was blended with the HRJ and FT in a 50/25/25 by volume ratio. Results of the hydrocarbon type analysis of the neat HRJ, FT and two JP-8 fuels are shown in Table 3. As listed, the JP-8 fuels were very similar in composition and distribution of paraffins and aromatics. The Sasol FT was comprised of primarily highly branched *iso*-paraffins (91%) with the balance in cycloparaffins, while the HRJ also consisted of only paraffinic compounds: ~10% normal, 2% cyclic and 88% branched. Both alternative fuels complied with the ASTM 7566-09 requirements for synthetic hydrocarbons for jet fuel.[7]

Table 2. Results of Test Fuel Specification Tests

ASTM Tests	Standard	JP-8a (POSF-6372)	JP-8b (POSF-6365)	JP-8b/HRJ (POSF-6366)	JP-8a/HRJ/FT (POSF-6374)
Total Acid Number, mg KOH/g (D3242)	Max 0.015	0.006	0.005	0.006	0.004
Aromatics, % vol (D1319)	Max 25.0	19.1	19.0	9.5	10.6
Total Sulfur, % wt (D4294)	Max 0.30	0.08	0.08	0.05	0.05
Distillation, Initial Boiling Point (IBP), °C (D86)	Report	152	146	152	151
10% Recovered, °C (D86)	Max. 205	176	177	171	168
20% Recovered, °C (D86)	Report	186	186	182	176
50% Recovered, °C (D86)	Report	210	212	211	200
90% Recovered, °C (D86)	Report	251	254	251	248
Final Boiling Point, °C (D86)	Max 300	274	276	269	270
Distillation-Residue, % vol (D86)	Max 1.5	0.90	1.2	1.3	1.2
Loss, %vol (D86)	Max 1.5	0.10	0.4	0.20	0.90
Freeze Point, °C (D5972)	Max -47	-48	-49	-52	-56
Existent Gum, mg/100mL (D381)	Max 7.0	<1.0	**5.4**	1.2	<1.0
Viscosity @ -20°C, cSt (D445)	Max 8.0	5.2	4.9	4.8	4.5
Density@15°C, kg/L (D4052)	0.775	0.813	0.813	0.786	0.786
Naphthalenes, vol% (D1840)	Max 3.0	1.5	1.4	0.70[a]	0.75[a]
Thermal Stability (D3241) Tube Deposit Rating, Visual	<3 Max	1	**2A**	1	1
FSII (DiEGME), % vol (D5006)	0.10-0.15	0.12	0.11	0.10	0.10
Smoke Point, mm (D1322)	Min 19.0	21.0	22.0	32.0	30.0
Flash Point °C (D93)	38	44	40	46	44
Heat of Combustion, BTU/lb (D3338)	18400	18529	18529	18744	18700
Hydrogen content, % mass (D3343)	13.4	13.9	13.6	14.4	14.4

[a]Estimated based on JP-8 values

Distillation curves for the neat JP-8 fuels and the blends are shown in Figure 6. The distillation temperatures are similar for the four fuels with the largest (although fairly small) difference with the JP-8/HRJ/FT fuel blend. This is the result of the lower distillation temperatures of the coal-derived FT fuel relative to the HRJ and JP-8s.

Table 3. Hydrocarbon Fuel Analysis of Neat Fuels

Summarized D2425 (mass%)	**JP-8a (POSF-6372)**	**JP-8b (POSF-6365)**	**HRJ (POSF-6361)**	**FT Sasol (POSF-5642)**
Paraffins	46	46	98	91
Cycloparaffins (noncondensed)	22	23	2	5
Dicycloparaffins (condensed)	10	9	<1	4
Tricycloparaffins (condensed)	2	2	<1	<1
Alkylbenzenes	10.6	10.3	<0.3	0.4
Indan and Tetralins	7.0	6.8	<0.3	<0.3
Indenes C_nH_{2n-10}	0.5	0.5	<0.3	<0.3
Naphthalene	<0.3	<0.3	<0.3	<0.3
Naphthalenes	1.9	1.9	<0.3	<0.3
Acenaphthenes	0.3	0.3	<0.3	<0.3
Acenaphthylenes	<0.3	<0.3	<0.3	<0.3
Tricyclic Aromatics	<0.3	<0.3	<0.3	<0.3
Total	100	100	100	100
D6379 (volume%)				
Monoaromatics	16.5	16.0	<0.2	0.4
Diaromatics	1.9	1.9	<0.1	<0.1
Total Aromatics	18.4	17.9	<0.2	0.4
Total Saturates	81.6	82.1	99.8	99.6
n-Paraffins (weight %)				
n-Heptane	0.14	0.14	<0.001	<0.001
n-Octane	0.34	0.33	1.75	<0.01
n-Nonane	0.95	0.89	1.78	<0.05
n-Decane	1.97	1.93	1.37	<0.03
n-Undecane	2.44	2.46	1.10	<0.02
n-Dodecane	2.36	2.34	0.94	<0.01
n-Tridecane	1.97	1.91	1.23	<0.01
n-Tetradecane	1.48	1.41	0.73	<0.01
n-Pentadecane	1.08	1.02	1.06	<0.005
n-Hexadecane	0.51	0.50	0.003	<0.003
n-Heptadecane	0.20	0.20	<0.001	<0.001
n-Octadecane	0.050	0.052	<0.001	<0.001
n-Nonadecane	0.010	0.012	<0.001	<0.001
Total n-Paraffins	**13.5**	**13.2**	**9.9**	**<0.2**

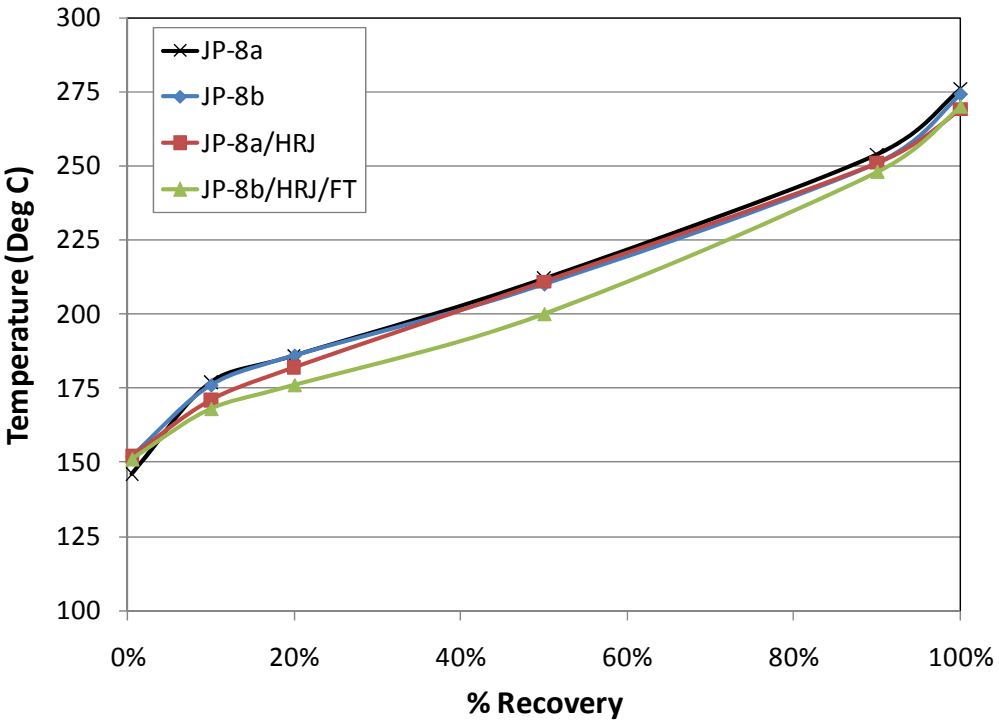

Figure 6: Distillation Curves for Tested Fuels

In this report, the emissions of the two alternative fuel blends are compared against those of the compliant JP-8 (JP-8a) with the understanding that it may not be a valid comparison for the JP-8b/HRJ fuel due to the sensitivity of the PM emissions to the chemical composition of the fuel. Potential impacts of the chemical speciation on emissions are discussed in the results section.

Gas chromatograms of a typical JP-8, the tallow-derived HRJ and coal-derived FT fuels are depicted in Figure 7. As shown, the HRJ and JP-8 have a similar range of carbon number compounds (~C_8-C_{18}), and thus very similar boiling point distributions. The coal FT has a relatively narrow component distribution of lower molecular weight compounds (~C_8-C_{12}), which inherently lowers the average fuel carbon number, fuel end point and flash point.

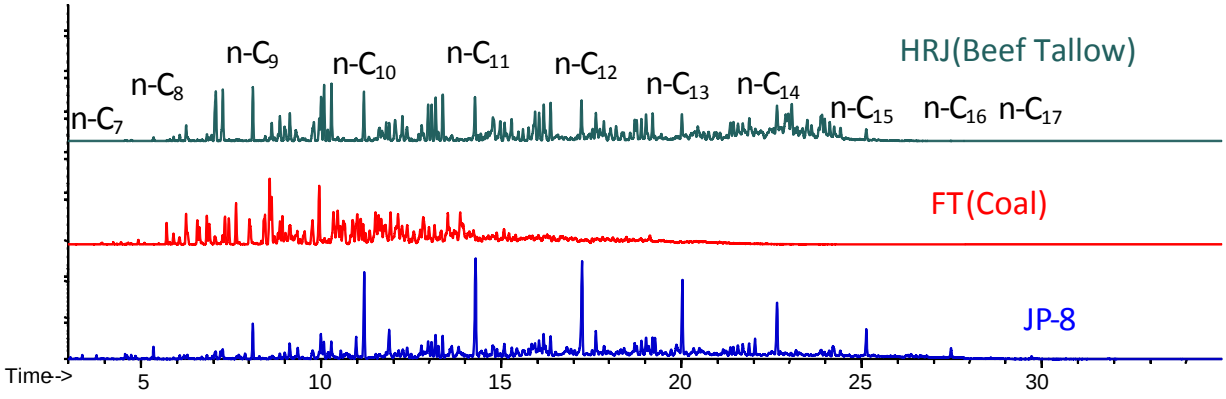

Figure 7. Gas Chromatograms of JP-8 and Neat HRJ and FT fuels

2.5 Test Conditions and Procedure

The test plan for this effort is shown in Table 4. The intent was to measure the C-17 emissions from engine #3 at a wide range of conditions within the limitations of available test fuel and ground test time. Tests were conducted from low-to-high engine power, and each condition was run for approximately 15 minutes. This time period was usually sufficient to acquire steady state particle number data, two particle size distributions (for probe-tip and DC dilution) and particle mass measurements at two different dilution ratios. Also, five smoke number measurements, three soot samples on quartz filters, gaseous emissions and adequate sampling of volatile organics were accomplished.

Table 4. Test Plan for C-17 Alternative Fuels Emission Tests

Fuel	***Engine Power (% Max Thrust)***
JP-8a *(baseline)*	4%, 33%, 45%, 54%, 63%
50/50 Blend *JP-8b/HRJ (tallow)*	4%, 33%, 45%, 54%, 63%
50/25/25 Blend *JP-8a/HRJ (tallow)/FT (coal)*	4%, 33%, 45%, 54%, 63%

2.5.1 Atmospheric Conditions

Atmospheric conditions for each test day were recorded to assess any impact on emissions if conditions were significantly different. Average dry bulb temperature, relative humidity and atmospheric pressure for each test day are listed in Table 5. All three test days were very similar with clear sunny skies, high temperatures and low relative humidity. The similarity in weather conditions suggests that these had minimal impact on the relative emissions measured.

Table 5. Atmospheric Conditions During Alternative Fuels Testing on the C-17

Test Date	Temp (°C)	Relative Humidity (%)	Pressure (atm)
17-Aug-10	36.4	11	0.91
18-Aug-10	36.7	13	0.91
25-Aug-10	37.8	13	0.91

3.0 TEST RESULTS AND DISCUSSION

3.1 PM Emissions

3.1.1 Particle Number (PN) Emissions

Engine PN emissions (probe-tip dilution) ranged from 1.0E+07 – 2.5E+07 particles per cubic centimeter (#/cm^3) for operation on JP-8 and 0.33E+07 – 1.5E+07 #/cm^3 for the alternative fuel blends over the range of conditions tested. (Note: PN data were not corrected for particles losses in the sample lines.) For most test runs, the PN random uncertainties were $< \pm 5\%$, reflecting the steadiness of the engine operation and robustness of the sampling system. Generally, the PN increased directly with engine power. The PN emission index (EI_n), defined as the number of particles per kg-fuel burned [mainly a function of the particle number and CO_2 (i.e., fuel/air ratio)], ranged between 7.6E+14 – 13.0E+14 #/kg-fuel for JP-8 combustion, and from 2.1E+14 – 12.6E+14 #/kg-fuel for the alternative fuel blends with consistently lower values for the JP-8/HRJ/FT blend. Samples diluted in the DC yielded very consistent/reproducible particle numbers at each condition with very low relative uncertainty ($< \pm 3\%$). EI_n trends and magnitudes were very similar to the probe-tip dilution data with values ranging from 6.0E+14 – 14.0E+14 #/kg-fuel for JP-8 and 2.0 E+14 – 6.0 E+14 for the JP-8/HRJ/FT blend (data for JP-8/HRJ testing was limited due to high winds causing air entrainment in the DC). Displayed in Figure 8 are the EI_n for each alternative fuel blend normalized to the JP-8 EI_n for each condition (except for 45% max thrust due to issues with the dilution system). As shown, significantly lower particle concentrations were generated for the alternative fuel blends relative to JP-8, especially for the idle condition (4%) which shows ~63% and ~73% lower particle concentrations for the JP-8/HRJ and JP-8/HRJ/FT fuels respectively. Likewise, the DC diluted samples show reduced EI_n of ~52% and ~68% for the JP-8/HRJ and JP-8/HRJ/FT fuels respectively. The consistency in the particle number data with these two dilution methods is very encouraging as it demonstrates the validity of dilution chamber approach, and provides a second data set to further demonstrate the reduced PM emissions with the alternative fuel blends. The lower PM emissions with the SPK fuel blends are primarily due to their aromatic-free nature. Aromatics are known soot precursors which form PAH, which subsequently nucleate into soot particles. The propensity of aromatics to produce soot has consistently been demonstrated in large scale combustors and laboratory flames.[8] It is observed that an increase in engine power decreased the net effect of the alternative fuel on particulate emissions, but was still significant at ~37% lower for the JP-8/HRJ/FT blend at 63% max rated thrust. The larger impact on particulate emissions at lower engine power with SPK fuels has been observed previously.[9,10] It has been postulated that at lower combustion temperatures, the rate of particle formation with low or zero aromatic fuels is lower compared to fuels with higher aromatics. As combustion temperatures increase, the relative role of aromatics on soot formation is reduced due to the increase in the chemical rates of soot production from the paraffinic compounds via fragmentation and polymerization reactions. Lower EI_n at low engine power with the alternative fuel may also be the result of reductions in unburned hydrocarbons (UHC), as these may condense to form nuclei size particles in sample lines. The JP-8/HRJ blend, which as mentioned previously did NOT contain the baseline JP-8, showed very similar EI_n compared to operation with JP-8 for engine power $\geq 54\%$ max thrust and significantly higher values relative to the JP-8/HRJ/FT blend. This suggests that the off-spec JP-8 (JP-8b) used in the HRJ/JP-8

blend had a higher propensity for PM formation than the baseline JP-8. This was unexpected considering that the composition (including aromatic content and type) of both JP-8s was similar. The main difference between the JP-8s is the poorer thermal stability and higher (5X) gum content in the off-spec JP-8. Previous studies have shown that fuel thermal stability additives have negligible impact on PM emissions.[11] It is plausible that higher fuel gum content contributed to the relatively high PM emissions with the JP-8/HRJ blend; however, further research is warranted.

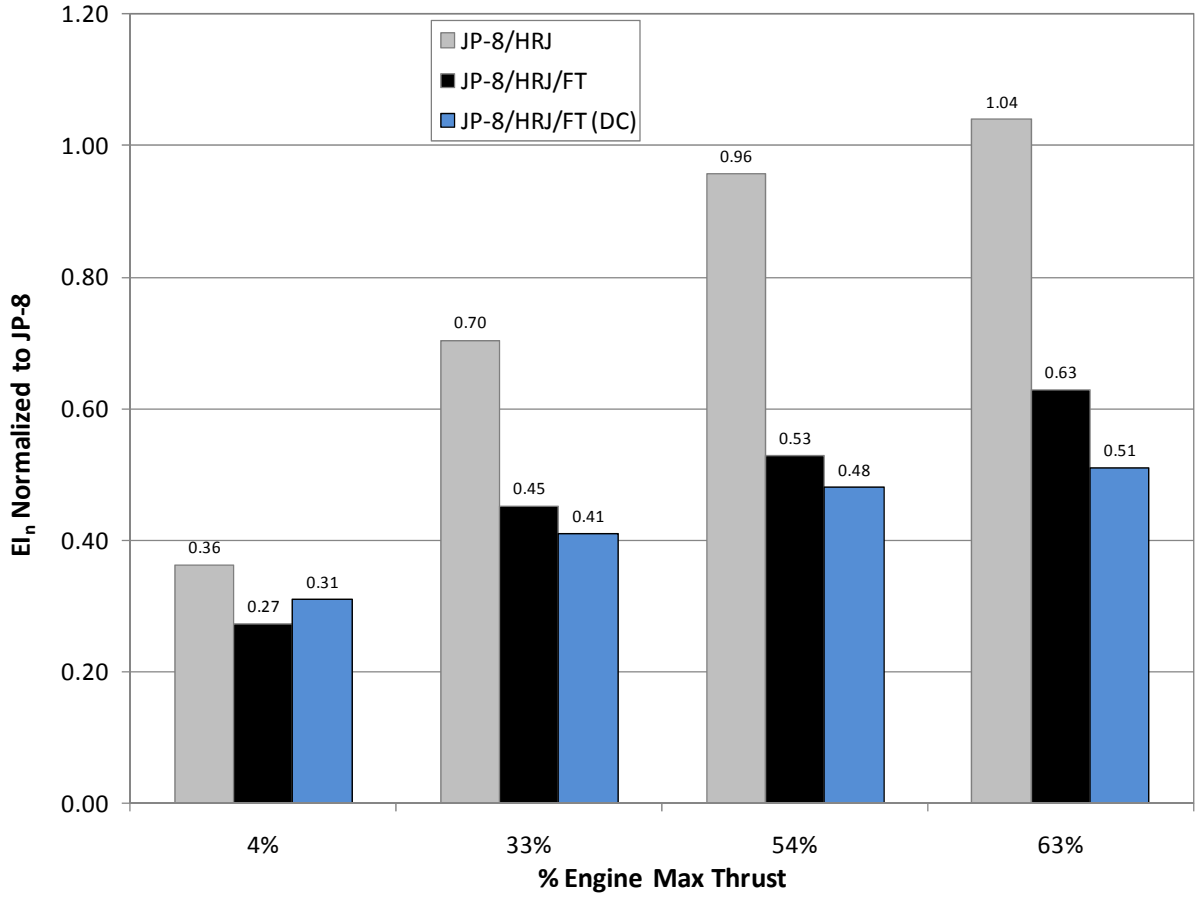

Figure 8: Normalized Particle Number EI as a Function of Engine Power for the F117 Operated with Alternative Fuel Blends

3.1.2 Particle Size Distribution

Particle size distributions for each power setting for JP-8 and the alternative fuel blends are shown in Figures 9 and 10. Each distribution is an average of a minimum of four distributions at two different dilution ratios. The size distributions follow typical turbine engine PM lognormal profiles with particle numbers (peaks) increasing as a function of engine power up to

54% max thrust after which they decreased. As expected, the particle size increased for all fuels as a function of engine power due to the increased formation, growth, coagulation and agglomeration of soot nuclei. Similar size distributions profiles and trends were observed for the PM samples diluted in the DC. Notably, no nucleation mode (which indicates formation of particles via condensation of volatile components) was observed in the DC samples.

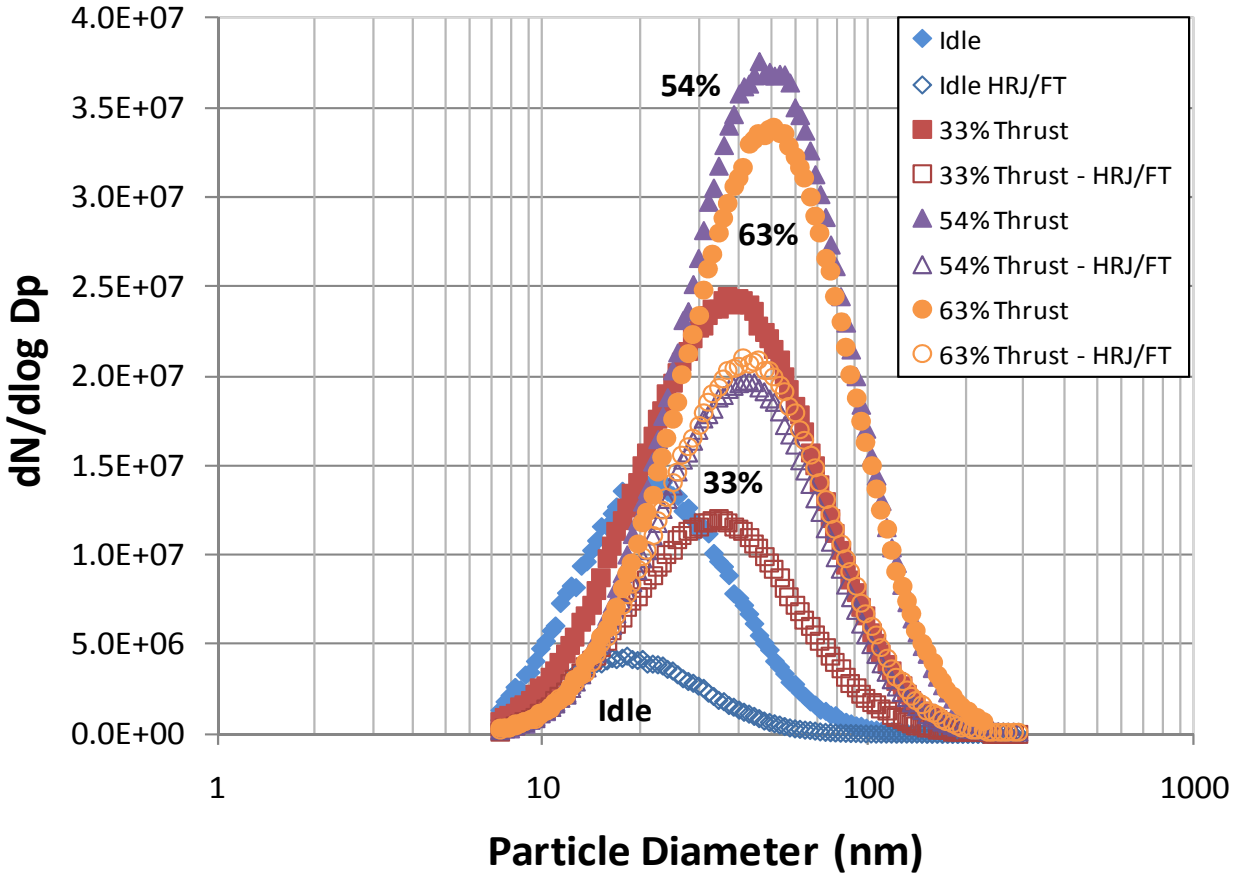

Figure 9: Particle Size Distribution for F117 Engine operated on JP-8 and 50/25/25 Blend of JP-8/HRJ/FT

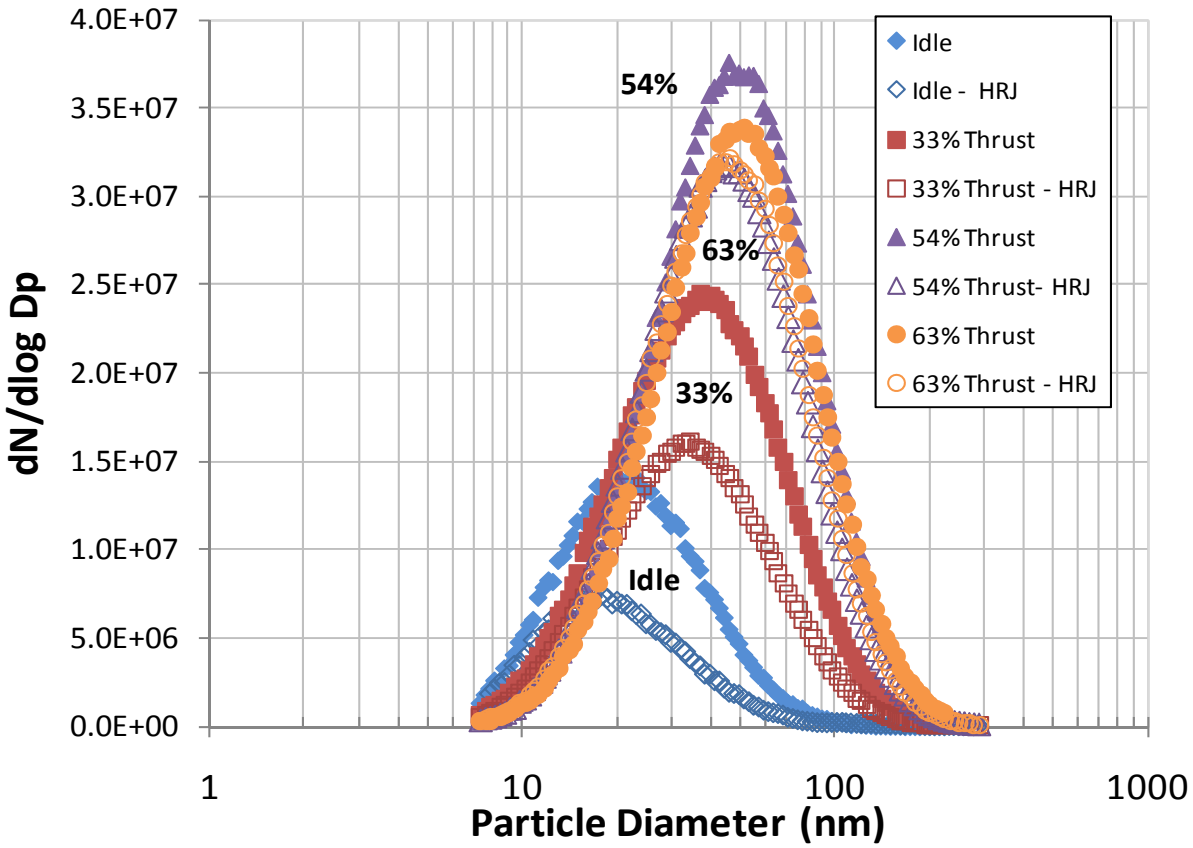

Figure 10: Particle Size Distribution for F117 Engine operated on JP-8 and 50/50 Blend of JP-8/HRJ

Consistent with the particle number data, significantly lower particle concentrations were measured with the SMPS for the engine operating with the JP-8/HRJ/FT blend than for the baseline JP-8 and the JP-8/HRJ blend. Distribution curves for the alternative fuel blends at each power setting decreased in amplitude and shifted left compared to JP-8 operation reflecting the reduced concentration and particle size. Engine particle mean diameters, shown as a function of engine power in Figure 11, ranged from 27 - 55 nm for operation on JP-8, 21 – 51 nm for JP-8/HRJ and 21 – 49 nm for the JP-8/HRJ/FT blend. These ranges of mean diameters are similar to those previously measured on CFM56, T700 and T701C engines on JP-8.[9,11] On average, the fuel blends produced particles with mean diameters 10-15% lower than the baseline JP-8, which agree with trends observed on TF33, CFM56 and T63 engines using 50/50 JP-8/FT blends.[10,12,13] Similar particle diameters and reduction trends were observed with the samples diluted in the DC.

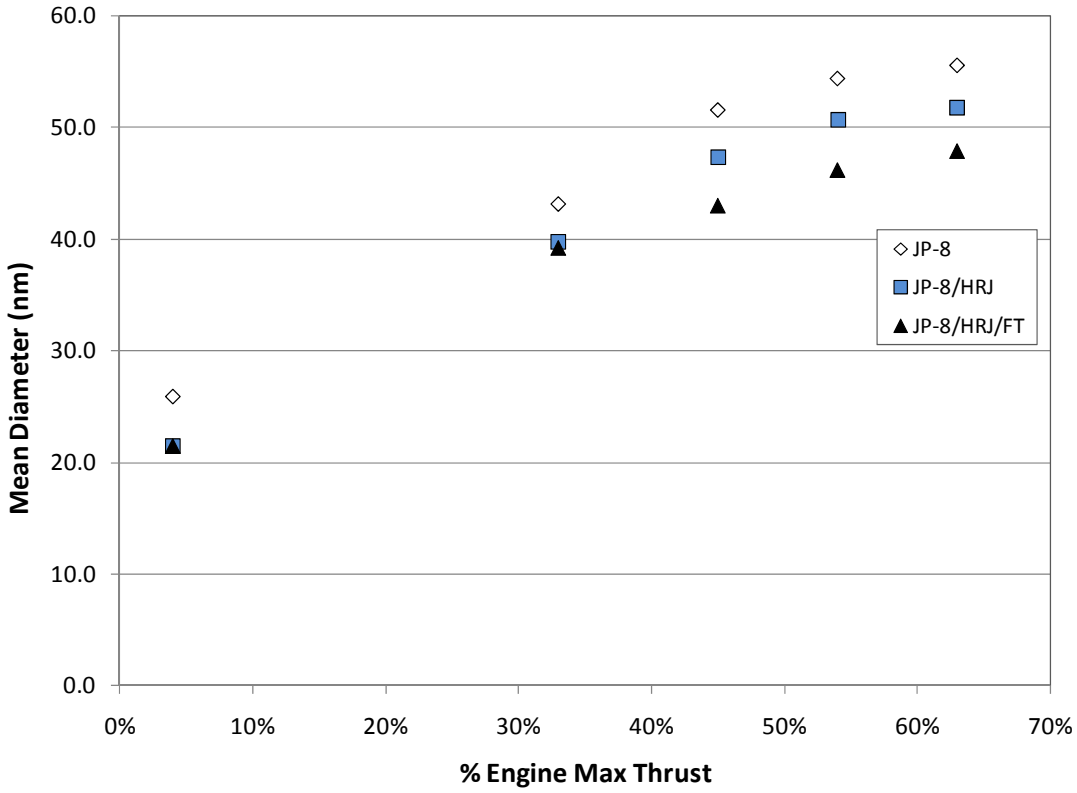

Figure 11: Mean Particle Diameters for F117 Engine operated on JP-8 and Alternative Fuel Blends

3.1.3 Particulate Mass Emissions and Carbon Burn-off Analysis

Measurements with both MAAP and LECO instruments show significant particulate mass emissions reduction with the use of the alternative fuel blends. Unfortunately, MAAP data for JP-8 operation were very limited due to insufficient time at condition and/or problems with the dilution system; as a result, only the relative comparisons at 63% max thrust are discussed. For this condition, reductions of 50 and 70% in particle mass EI (EI_m) compared to JP-8 were observed for the JP-8/HRJ and JP-8/HRJ/FT respectively. On average the EI_m for engine thrust levels of 45-63% were ~55% lower for the JP-8/HRJ/FT compared to the JP-8/HRJ blend; trend consistent will all other PM data showing higher PM for the JP-8/HRJ blend. Elemental carbon (EC) mass, measured via carbon burnoff (LECO), show average reductions of ~30% for the JP-8/HRJ and ~70% for the JP-8/HRJ/FT blend for engine conditions of 45-63% max thrust. The organic carbon (OC) concentration, also determined via carbon burnoff, is an indicator of the volatile component in the soot sample and thus, completeness of fuel burn. OC mass emission indices were relatively constant for each power setting for all three fuels. OC EI were 60-70% lower for the alternative fuel blends relative to JP-8, which suggest improved volatile organic combustion.

3.1.4 Smoke Numbers

Smoke numbers (SN) were measured for each engine setting for operation on JP-8 and the alternative fuel blends. A minimum of five measurements were performed per engine/fuel condition. For the measurement, raw exhaust samples (total of ~7.1 liters) were transferred via heated lines (150°C) to a smoke sampler where the smoke (carbon) sample was collected on a paper filter. Post-test analysis of each filter was performed using a reflectometer to compare the opacity between a clean and stained filter. Excellent data reproducibility was observed for most multiple runs for each engine/fuel condition (<±5%). The results, displayed in Figure 12, show that the F117 engine SN ranged from 1.5 - 18.0 for operation on JP-8 and the JP-8/HRJ blend, and from <0.4 – 9.6 for the JP-8/HRJ/FT blend. Engine smoke number varied directly with power setting to engine conditions up to 45% max thrust after which the values were fairly similar. As depicted, significantly lower SN were produced for the JP-8/HRJ/FT blend for all conditions tested. Reductions of ~70% at 33% max thrust to ~45% at 63% max thrust relative to JP-8 were observed. Differences in SN between the baseline JP-8 and JP-8/HRJ blend were negligible.

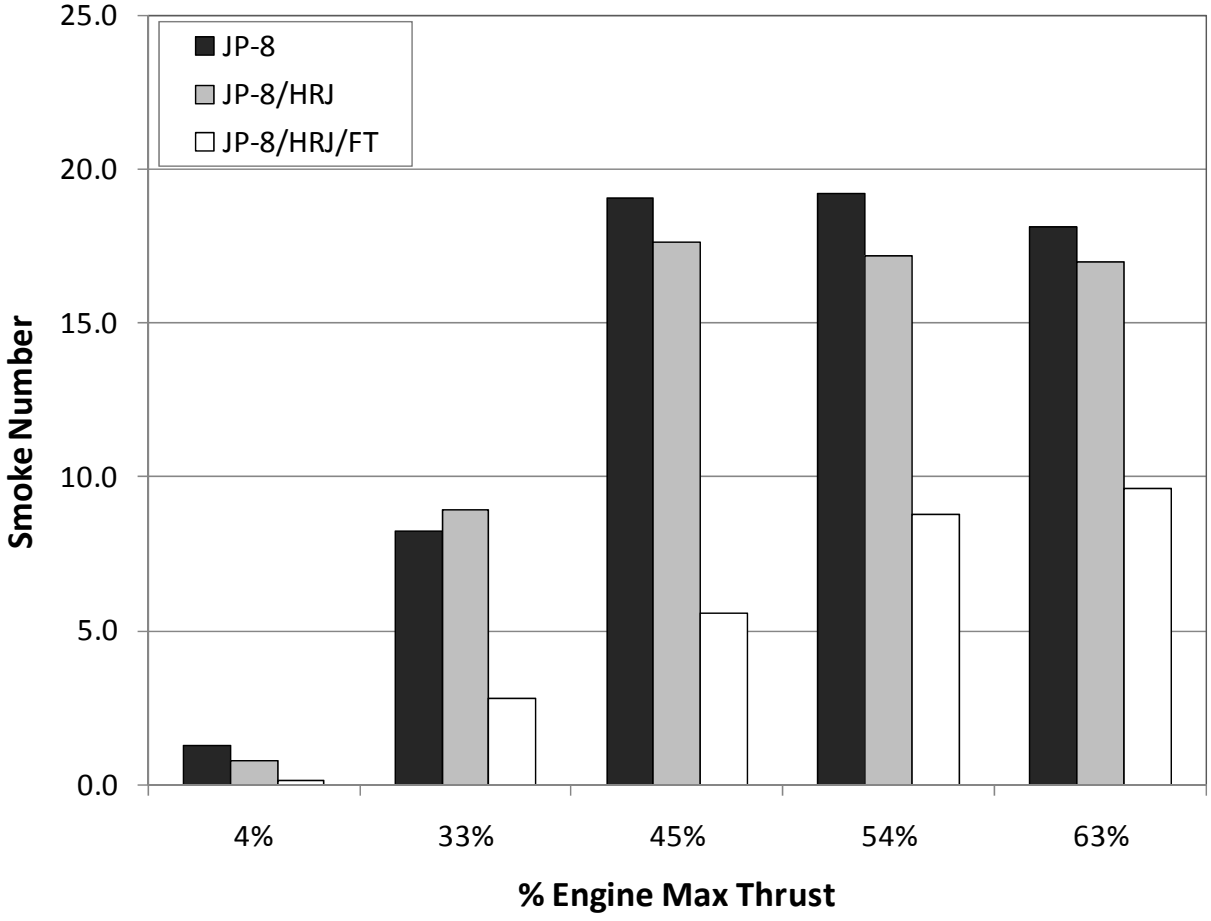

Figure12: Smoke Numbers of F117 Engine Operating on JP-8 and Alternative Fuel Blends at Several Engine Power Settings

Smoke samples for engine operation with all three fuels at the engine conditions tested are shown in Figure 13. The reduced soot emissions with the JP-8/HRJ/FT blend is evident, especially for the lower engine power conditions. These agree with all the particulate data collected.

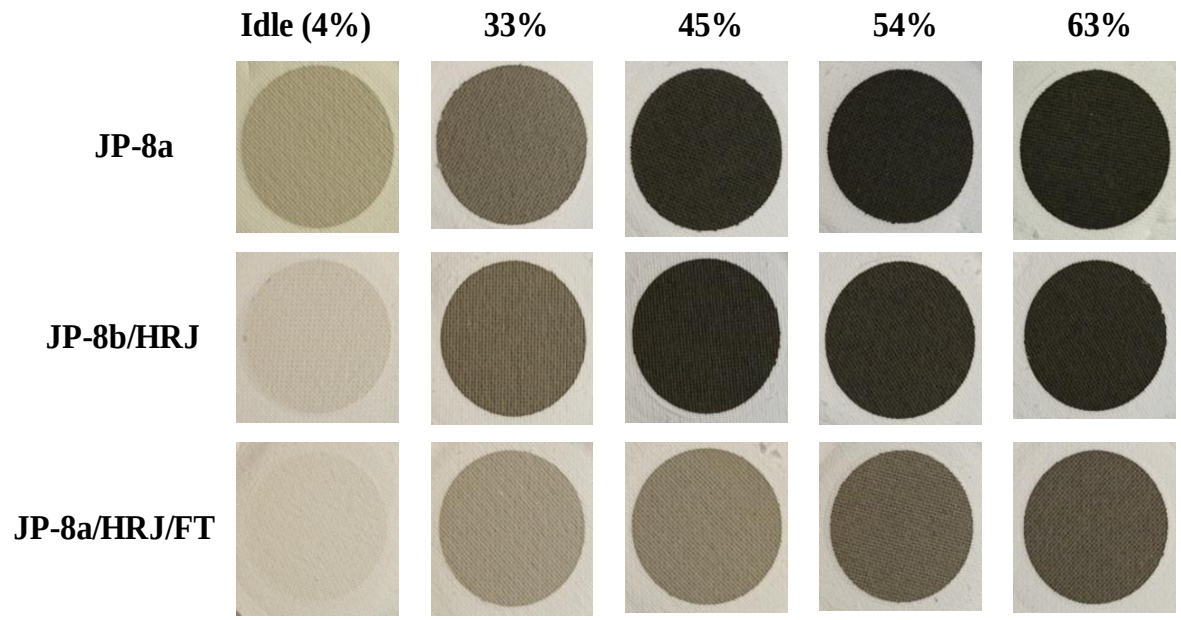

Figure 13: Smoke Samples for F117 Engine Operating on JP-8 and Alternative Fuel Blends

3.2 Gaseous Emissions

Gaseous emissions were measured using an FTIR-based MKS Type MultiGas 2030 Analyzer. The undiluted sample was drawn through a gas probe and transferred to the instrument via a heated sample line (150°C) following the guidelines of the SAE ARP 1256.[14]

3.2.1 Carbon Monoxide (CO), Nitrogen Oxides (NO_x) and Sulfur Dioxide (SO_2)

Comparison between CO and NO_x emission indices (EI) for the PW2040 engine (commercial variant of the F117) and the F117 engine in this effort (using JP-8) are shown in Figure 14. As anticipated, CO decreased and NO_x increased as a function of engine power. The PW2040 emissions data set, obtained from the ICAO Engine Emissions Databank Issue 16A[15], contained data only for engine conditions in the Landing and Take-off (LTO) cycle, i.e., 7%, 30%, 85% and 100% engine power, none of which were evaluated in these tests. However, the plot verifies

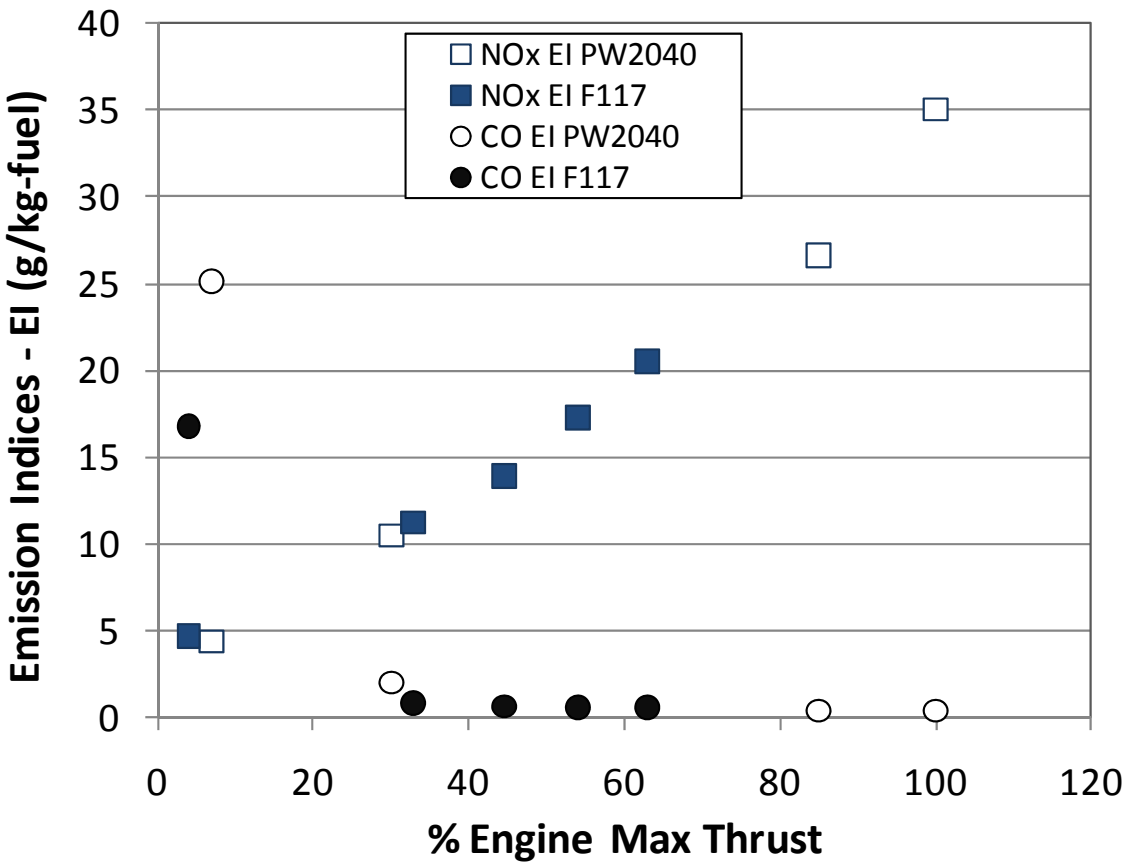

Figure 14: Comparison of CO and NO_x Emission Indices between the PW2040 (ICAO Engine Emissions Databank Issue 16A)[15] and the F117 (these tests)

that the trends and magnitudes of the CO and NO_x EIs measured here are comparable to those found in the ICAO databank. Figure 15 displays the CO and SO_2 emissions indices normalized to JP-8 data for all engine settings. The emission indices (EI) were calculated following the SAE ARP 1533.[16] As expected, SO_2 emissions were approximately 50% lower with the alternative fuel blends due to their 50% lower sulfur content. Also, significantly lower CO emissions (20-40%) were observed with the fuel blends. This could be attributed to the environmentally favorable chemical composition (lower carbon-to-hydrogen ratio, i.e., lower carbon number) and reduced ring compounds in the fuel blends, which contributes to improved combustion characteristics particularly at lower combustion temperatures (i.e., idle & 33% max thrust). Test data also show negligible differences in nitrogen oxide emissions between the fuels.

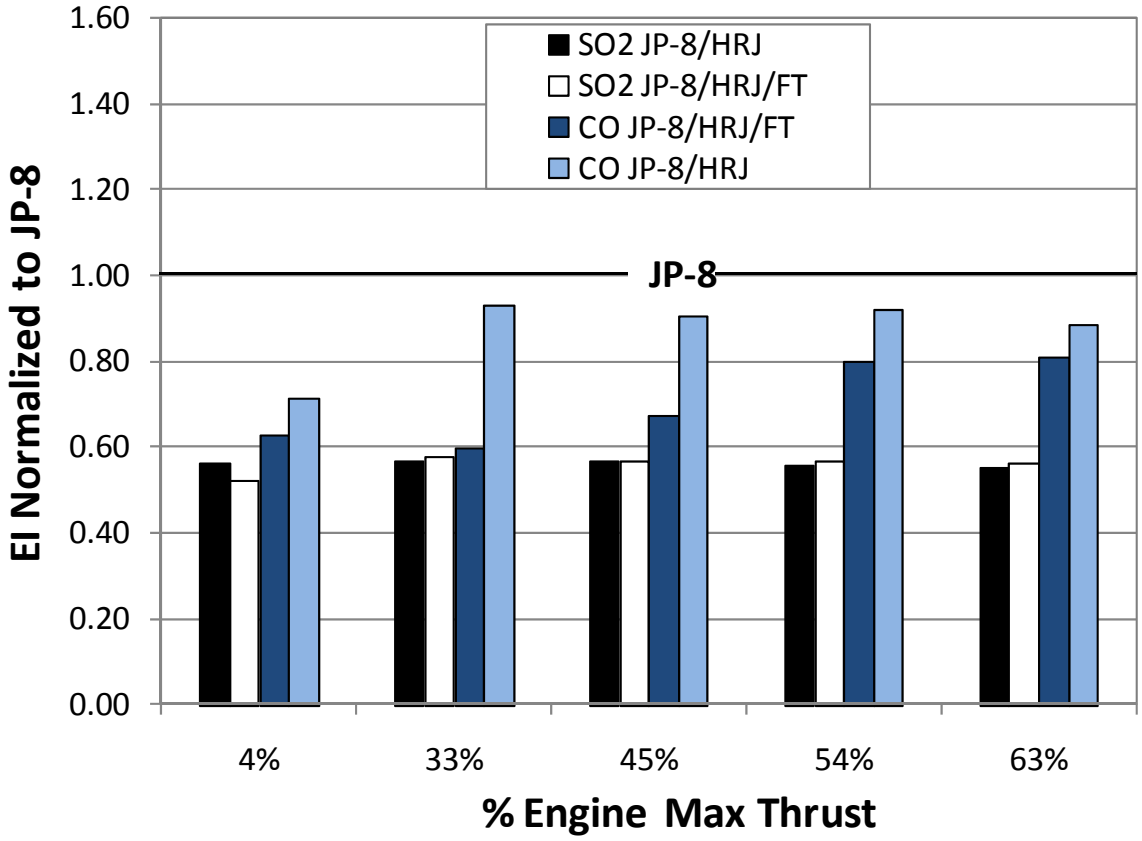

Figure 15: Normalized CO and SO_2 Emission Indices for F117 Engine Operated on the JP-8/HRJ and JP-8/HRJ/FT Fuel Blends

3.2.2 Polycyclic Aromatic Hydrocarbons (PAH) and HAPs Analysis

PAH compounds absorbed on soot samples were identified and quantified via GC/MS to evaluate the impact of engine power setting and fuel on the relative and absolute concentrations. Sample analysis shows that only pyrene and chrysene were above the quantifiable detection limit for JP-8 operation at engine power of 63% max thrust. Although no PAH compounds were detected in the soot from the fuel blends, no conclusion can be drawn regarding fuel impacts from these data due to the very low concentrations detected.

Aldehydes and other hazardous air pollutants (HAPs) are produced during the combustion of hydrocarbons, and several have been identified as toxic compounds. Analysis of combustion generated HAPs was performed by sampling in DNPH and activate carbon cartridges to assess any differences in concentration between the alternative fuel blends and JP-8. The HAPs studied in this effort are listed in Table 6.

Table 6. Hazardous Air Pollutants Investigated in F117 Engine Exhaust

HAP	BP (^oC)	MF	MW (g/mol)	MP (^oC)	Flash Pt (^oC)
Formaldehyde	-21	CH_2O	30.026	-92	flammable
Acetaldehyde	20.2	C_2H_4O	44.05	-123.5	-39
Propanal	48	C_3H_6O	58.08	-81	-26
Acrolein	53	C_3H_4O	56.06	-88	-26
1,3 butadiene	-4.4	C_4H_6	54.09	-108.9	-85
Benzene	80.1	C_6H_6	78.11	5.5	-11
Toluene	110.6	C_7H_8	92.14	-93	4
Ethylbenzene	136	C_8H_{10}	106.17	-95	-17.5
P, xylene	138.35	C_8H_{10}	106.16	13.2	25
M, xylene	139	C_8H_{10}	106.16	-48	25
O, xylene	144.4	C_8H_{10}	106.16	-24	32
Styrene	145	C_8H_8	104.15	-30	31
Isopropylbenzene	152	C_9H1_2	120.19	-96	102
Phenol	181.7	C_6H_6O	94.11	40.5	79
Naphthalene	218	$C_{10}H_8$	128.17	80.26	83
2, methylnaphthalene	241	$C_{11}H_{10}$	142.2	34.6	98

Unbolded – Analyzed via HPLC from DNPH samples
Bolded – Analyzed via GC/MS from charcoal tubes

Results show that HAPs are more prevalent at low engine power and that formaldehyde was the most dominant HAP for this engine, followed by acetaldehyde and benzene. Formaldehyde and acetaldehyde were the only two aldehydes measured beyond the sensitivity of the technique (EPA Compendium Method TO-11A) at concentrations of 2.5 – 0.6 and 1.0 – 0.06 ng/l respectively. The normalized EI for the compounds as a function of engine power are shown in Figure 16. Lower aldehyde emissions for both compounds (60- 80% at idle) were produced with both fuel blends compared to JP-8. Formaldehyde measurements with the FTIR analyzer were within 8% of the EPA method, which validate the concentrations and relative reductions observed. Measured benzene concentrations (found in the activated carbon cartridges) were also extremely low (<0.4 ng/l) and reductions up to ~85% at idle were observed with the fuel blends. Reduced benzene emissions were anticipated for the blends due to the aromatic-free nature of the alternative fuels.

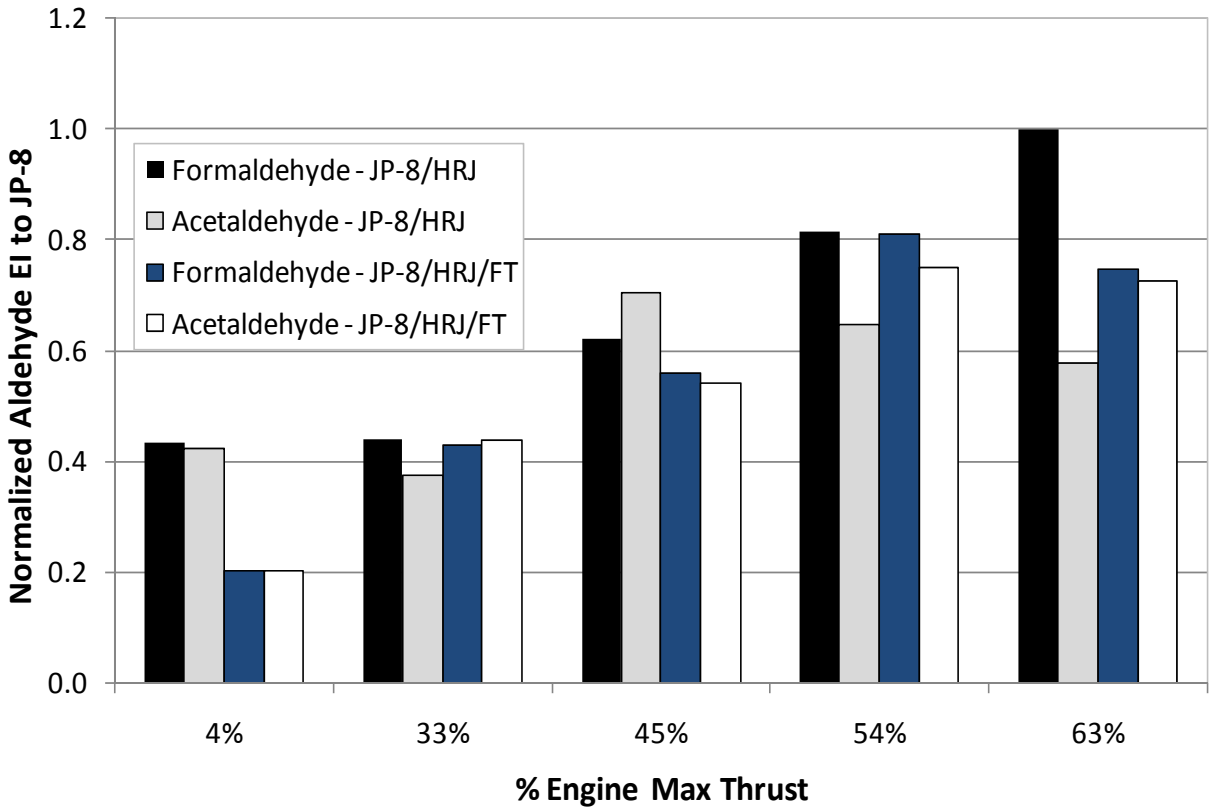

Figure 16: Normalized Formaldehyde and Acetaldehyde Emission Indices Measured using the EPA Compendium Method TO-11A for F117 Engine Operated on the JP-8/HRJ and JP-8/HRJ/FT Fuel Blends

4.0 CONCLUSIONS

Emissions evaluations were conducted on a C-17 Globemaster III F117-PW-100 engine operated on conventional JP-8 and 50/50 blends of JP-8 and a beef tallow-derived HRJ, and a 50/25/25 blend of JP-8, HRJ and a coal-derived Fischer-Tropsch (FT) fuel for engine powers of 4, 33, 45, 54 and 63% of max rated thrust. The HRJ and FT fuels were comprised primarily of paraffinic compounds and were free of aromatics and sulfur. Results show that use of the alternative fuel blends resulted in no operational anomalies or detrimental effects on the gaseous or PM emissions of the F117 engine for any of the conditions tested. Significant reductions in CO emissions (~30%) and more significant reductions in sulfur oxides (50%) and PM emissions (30-60%) relative to operation with JP-8 were observed. Slightly smaller mean particle diameters and reduced HAPs emissions were also observed with the alternative fuel blends. Lower soot emissions are largely due to the decreased aromatic compounds in the fuel blends. These findings are consistent with previous tests by the Air Force Research Laboratory (AFRL) and others on other turbine engines for military and civilian aircraft.

In conclusion, blends of JP-8 with HRJ and comingled HRJ/FT fuels resulted in no discernable differences in the operation of the F117 engine, while producing significantly lower combustion emissions.

5.0 REFERENCES

1. Pope, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., and Heath, C.W. (1995a), "Particulate Air Pollution As A Predictor Of Mortality In A Prospective Study In U.S. Adults," *Am. J. Respir. Crit. Care Med.* 151: 669-674.
2. SAE 2004, "Non-volatile Particle Exhaust Measurement Techniques," SAE Aerospace Information Report AIR 5892. SAE, Warrendale, PA USA, 2004.
3. SAE 1970, "Aircraft Gas Turbine Exhaust Smoke Measurement," SAE Aerospace Recommended Practice ARP 1179. SAE, Warrendale, PA USA, 1970.
4. www.epa.gov/ttn/amtic/files/ambient/airtox/to-11ar.pdf accessed 21 March 2008.
5. http://www.pw.utc.com/ accessed 12 October 2010.
6. MIL-DTL-83133G released 30 April 10.
7. ASTM D7566-09, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," approved 1 Sept 2009.
8. Bittner, J.D., Howard, J.B., "Role of Aromatics in Soot Formation," Alternative Hydrocarbon Fuels: Combustion and Chemical Kinetics, Prog. Astronautics Aeronautics, 62, 335, Academic Press, 1978.
9. Corporan, E., DeWitt, M. J., Belovich, V., Pawlik, R., Lynch, A. C., Gord, J. R. and Meyer T. R., "Emissions Characteristics of a Turbine Engine and Research Combustor Burning a Fischer-Tropsch Jet Fuel," Energy and Fuels, 21(5), pp. 2615-2626, 2007.
10. Corporan, E., DeWitt, M., Klingshirn, C., Striebich, R, S., Cheng, M.D., "Emissions Characteristics of Military Helicopter Engines Fueled with JP-8 and a Fischer-Tropsch Fuel," Journal of Propulsion and Power, 26(2), pp. 317-324, Mar-Apr 2010.
11. Corporan, E., Monroig, O., "Reduction of Particulate Emissions in Turbine Engines Using the +100 Additive," ESTCP Project 200121 Final Report, AFRL-PR-WP-TR-2005-2179, 2005.
12. Bulzan, D., et al, "Gaseous and Particulate Emissions Results of the NASA Alternative Aviation Fuel Experiment (AAFEX)," ASME Paper #GT-2010-23524, ASME Turbo Expo Conference, Orlando, Fl, 2010.
13. Corporan, E., DeWitt, M., Klingshirn, C., Striebich, R, "DoD Assured Fuels Initiative: B-52 Aircraft Emissions Burning a Fischer-Tropsch/JP-8 Fuel Blend," 10th International Conference on Stability and Handling of Liquid Fuels, 2007.
14. SAE 1971, "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," SAE Aerospace Recommended Practice ARP 1256. SAE, Warrendale, PA USA, 1971.
15. Aircraft Engine Emissions, ICAO engine Emissions Database Issue 16A (090204) http://www.caa.co.uk/default.aspx?catid=702&pagetype=90 accessed 12 October 2010
16. SAE 2004, "Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines," SAE Aerospace Recommended Practice ARP 1533. SAE, Warrendale, PA USA, 2004.