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HYDROPROCESSED RENEWABLE JET FUEL EVALUATION, PERFORMANCE, AND EMISSIONS IN A T63 TURBINE ENGINE

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ABSTRACT

Due to potential beneficial environmental impacts and increased supply availability, alternative fuels derived from renewable resources are evolving on the forefront as unconventional substitutes for fossil fuel. Focus is being given to the evaluation and certification of Hydroprocessed Renewable Jet (HRJ), a fuel produced from animal fat and/or plant oils (triglycerides) by hydroprocessing, as the next potential synthetic aviation fuel. Extensive efforts have recently been performed at the Air Force Research Laboratory (AFRL) at Wright Patterson Air Force Base (WPAFB) to evaluate the potential of two HRJ fuels produced from camelina and tallow feedstocks. These have included characterization of the fuel chemical and physical fuel characteristics, and Fit-for-Purpose properties (FFP). The present effort describes general combustion performance and emission propensity of a T63-A-700 Allison turbine engine operated on the HRJs and 50/50 (by volume) HRJ/JP-8 fuel blends relative to a specification JP-8. In addition, engine and emission testing with a blend of the tallow-derived HRJ and 16% bio-derived aromatic components was completed. Fundamental engine performance characterization allows for determination of the suitability of potential synthetic fuels while quantitation of gaseous and particulate matter emissions provides an assessment of the potential environmental impact compared to current petroleum-derived fuels. In addition, an extended 150 hour endurance test was performed using a 50/50 blend of tallow-derived HRJ with JP-8 to evaluate the long-term operation of the engine with the synthetic fuel blend. This paper discusses the laboratory testing performed to characterize HRJs and results from the basic engine operability and emissions studies of the alternative fuel blends.

INTRODUCTION

The Department of Defense (DOD) established the Assured Fuels Initiative in FY06 to develop, test, certify and use jet fuels produced from alternative (non-petroleum) sources. The first alternative fuels considered under this initiative were Synthetic Paraffinic Kerosenes (SPKs) derived from coal or natural gas via the Fischer-Tropsch (FT) process. Extensive studies have shown that a 50/50 blend (by volume) of FT-derived SPK and JP-8 can satisfy the fuel specification with acceptable Fit-For-Purpose characteristics (e.g., material compatibility) while improving oxidative thermal stability characteristics and reducing engine particulate matter (PM) emissions[1]. Several Air Force aircraft (e.g., B-52, C-17, and B-1) have been certified for operation with the FT blend. In 2008, FT-SPK was approved for use in blends with JP-8 in MIL-DTL-83133G[2], and in blends with commercial Jet A in ASTM D7566[3] in September 2009. Due to potential improved sustainability, the next class of alternative fuel being considered for certification is "Hydroprocessed Renewable

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[1] Moses, C., "Comparative Evaluation of Semi-Synthetic Jet Fuels Addendum: Further Analysis of Hydrocarbons and Trace Materials to Support D7566. Final Reports for CRC Project No. AV-2-04a", April 2009.

[2] MIL-DTL-83133G, "Detailed Specification, Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37)," released 30 April.

[3] ASTM D7566-09, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," approved 1 Sept 2009.

Jet" (HRJ). HRJ is a hydrocarbon aviation fuel produced from animal fat and/or vegetable oils (triglycerides) by hydroprocessing. This fuel has also been called bio-SPK and "green jet".[4] Ground and flight tests were recently (August 2010) completed on the C-17 Globemaster III cargo aircraft operating on blends of a tallow-derived HRJ and JP-8 (50/50).[5] Both the military and commercial aviation fuel specifications are structured to support various classes of alternative fuels in Appendices, with HRJ anticipated to be added in the near future as more data become available. In support of the evaluation and certification of HRJ fuels, laboratory studies were performed in this effort to characterize the engine performance and emissions characteristics during operation with neat HRJ, HRJ/JP-8 blends, and a tallow derived HRJ additized with 16% trimethylbenzene. The latter was chosen to emulate aromatics in a drop-in HRJ fuel. A drop-in fuel is a substitute for conventional jet fuel that is completely interchangeable and compatible with conventional jet fuel and does not require adaptation of the aircraft/engine fuel system or distribution system.[6] Testing was performed using a T63-A-700 turbo shaft engine located at Wright Patterson Air Force Base (WPAFB) operated at two power settings. Engine operability was inferred by comparison of differences in fuel flow while emissions were assessed by measuring PM and gaseous emissions (including Hazardous Air Pollutants (HAPs)). In addition, an extended duration test (150 hours) of the engine with a tallow HRJ/JP-8 blend was performed to investigate performance and emissions during long-term operation.

EXPERIMENTAL

Hydroprocessed Renewable Jet (HRJ) Fuels

The two research aviation HRJ fuels used in this study were produced by UOP using camelina and beef tallow as feedstocks. In the process, pressurized feedstock is mixed with hydrogen and undergoes catalytic deoxygenation to primarily produce *n*-paraffins. This product is then hydrocracked/isomerized to satisfy required freeze point characteristics, and separated to the desired volatility. The beef tallow HRJ fuel is very similar to the HRJ used in recent C-17 flight certification and emissions tests.[5] Various physical and chemical properties of these fuels were evaluated and compared to a typical specification JP-8. Selected neat fuel specification properties are shown in Table 1. These HRJ fuels had zero to very low aromatic content, negligible sulfur, lower density and higher hydrogen content compared to conventional JP-8. The density of the neat camelina HRJ (0.751 kg/L) was at the minimum limit for the synthetic SPK requirement in the military fuel specification while the 50/50 (volume) blend with JP-8 satisfied the JP-8 minimum density requirement. Gas chromatograms of the neat fuels (with the *n*-paraffin peaks identified) are shown in Figure 1.

TABLE 1. SELECTED ASTM SPECIFICATION OF FUELS

ASTM Tests	Standard	JP-8	Neat Tallow HRJ	Neat Camelina HRJ
Total Acid Number, mg KOH/g (D3242)	Max 0.015	0.005	0.002	0.002
Aromatics, % vol (D1319)	Max 25.0	17.2	0.4	0.0
Total Sulfur, % wt (D4294 or D2622)	Max 0.30	0.064	<0.0003	0.0018
Distillation, Initial Boiling Point (IBP), °C (D86)	Report	152	165	151
10% Recovered, °C (D86)	Max 205	173	179	161
20% Recovered, °C (D86)	Report	179	185	166
50% Recovered, °C (D86)	Report	198	210	182
90% Recovered, °C (D86)	Report	239	243	237
Final Boiling Point, °C (D86)	Max 300	260	255	259
Distillation-Residue, % vol (D86)	Max 1.5	1.1	1.2	1.1
Loss, %vol (D86)	Max 1.5	0.2	0.8	0.9
Freeze Point, °C (D5972)	Max -47	-49	-62	<-77
Existent Gum, mg/100mL (D381)	Max 7.0	0.4	<1	<1
Viscosity @ -20°C, cSt (D445)	Max 8.0	4.1	5.3	3.3
Lubricity Test (BOCLE) (D5001) wear scar mm	Report	0.54	0.76	0.76
Specific Gravity (D4052)	0.775-0.840	0.799	0.758	0.751
Smoke Point, mm (D1322)	Min 19.0	25	>40	50
Flash Point °C (D93)	Min 38	48	55	43
Heat of Combustion, MJ/kg (D3338)	Min 42.8	43	44.1	44.1
Hydrogen content, % mass (D3343)	Min 13.4	13.9	15.3	15.4

As shown in Figure 1 and Table 1, the HRJ fuels have a similar boiling point range to a typical JP-8. However, the *n*-paraffin distribution was shifted to slightly lower molecular weight with a lower overall *n*-paraffin content in the tallow (8.8 wt%) and camelina (10.2 wt%) HRJs as compared to a typical JP-8 (17-27 wt%). Gas chromatography/mass spectrometry analysis revealed the HRJs exhibited a mild degree of branching, consisting primarily of mono-methyl paraffins, and are similar in composition to the Syntroleum S-8 fuel used in the FT fuel certification of the B-52.[7] Additional physical and chemical properties of these fuels are available elsewhere.[8] During blending with petroleum-derived fuels, the addition of these HRJ fuels is expected to vary the fuel properties (except possibly freeze point) in a linear dependence proportional to the blend ratio due to the similar

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[4] Rekoske, J., "Production of Semi- and Fully-Synthetic Green Jet Fuel from Renewable Feedstocks", Presented at PetroTech2010, New Dehli, India, November 2010

[5] Corporan, E., DeWitt, M.J., Klingshirn, C.D., Anneken, D., Alternative Fuels Tests on a C-17 Aircraft: Emissions Characteristics, AFRL-RZ-WP-TR-2011-2004, Dec 2010

[6] http://www.caafi.org/resources/glossary.html#D accessed 28 January, 2011.

[7] DeWitt, M.J., Striebich, R., Shafer, L., Zabarnick, S., Harrison III, W.E., Minus, D.E., Edwards, T., "Evaluation of Fuel Produced via the Fischer-Tropsch Process for Use in Aviation Applications," Paper 58b, Proceed. Of AIChE Spring National Meeting, 2007.

[8] Corporan, E.; Edwards, J. T.; Shafer, L.; DeWitt, M. J.; Klingshirn, C.; Zabarnick, S.; West, Z.; Striebich, R.; Graham, J.; Klein, J. Chemical, Thermal Stability, Seal Swell and Emissions Studies of Alternative Jet Fuels. Energy & Fuels, 2011, submitted for publication.

volatility range and *n*-paraffin distribution. The expected behavior is based on similarity to previous studies using S-8.[7]

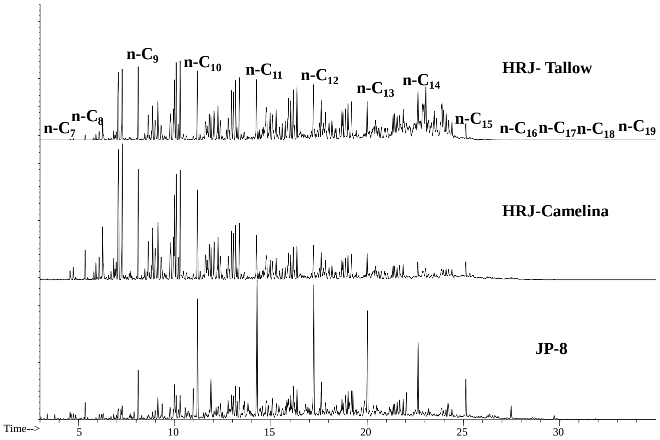

FIGURE 1. CHROMATOGRAMS OF HRJ TALLOW, HRJ CAMELINA, & JP-8 (*n*-PARAFFINS IDENTIFIED)

T63 Engine and Fuel System

A T63-A-700 turbo shaft engine, used primarily in helicopter applications, was used for emissions characterization. The engine is located in the Engine Environment Research Facility (EERF) in the Propulsion Directorate at Wright-Patterson Air Force Base, and is used to evaluate turbine engine lubricants, fuels, and sensors in an actual engine environment. A schematic of the engine is shown in Figure 2. The compressor draws atmospheric air through the inlet, compresses it via six axial stages and one centrifugal stage, and discharges it to two tubes which carry it to the combustor inlet on the aft end of the engine. The combustion gases flow forward through the combustor to two uncoupled two-stage turbine sections. The gas producer turbine drives the compressor, and the power turbine drives the output shaft, which is connected to a hydraulic dynamometer. After the power turbine the exhaust gases turn 90° to enter two exhaust collectors to route the gases out of the test cell.

Particulate emissions were sampled via an oil-cooled sampling probe installed parallel to the exhaust flow duct 10 inch from the engine centerline. JP-8 fuel was supplied to the T63 from an external tank and the fuel flow rate was measured with a flow meter. The HRJ fuels (and respective blends) were supplied to the engine from 30 gallon pressurized tanks located within the engine cell and operated manually via mechanical valves. Fuel for the long duration tallow blend test was supplied from a 6,000 gallon underground tank. The engine was operated at two conditions, designated as Ground Idle (GI) and Normal Rated Power (NRP) (also referred to as cruise condition) to investigate the effect of power setting on fuel performance. Nominal values for operating parameters at these conditions are listed in Table 2. GI was attained by a fixed fuel control setting and no load on the dynamometer. NRP was attained by adjusting the governor control and dynamometer load to maintain the intra-turbine temperature (T_5) at 1280°F and output shaft speed at 6000 rpm. For all tests, the total flow of fuel was computer-feedback controlled to maintain a constant T_5. This approach assured the best run-to-run repeatability. P_3 and T_3 (see Table 2.) are the pressure and temperature at the compressor discharge respectively.

During each test, baseline engine operability and emissions data were first obtained at the two power settings using JP-8 fuel. The engine was then transitioned to operation with the test fuel and data were collected at each power setting. Upon completion, operation was returned to the baseline JP-8 to verify consistent engine performance during the test period. Differences in engine performance and emissions propensity were compared relative to this JP-8 baseline data as this minimized the effect of environmental conditions, such as ambient temperature and relative humidity, on inter-comparison of test fuels. The data for each test fuels were collected during ~2 hour test run except for the extended duration test of the 50/50 tallow/JP-8 blend, which was analyzed at 50 hour intervals.

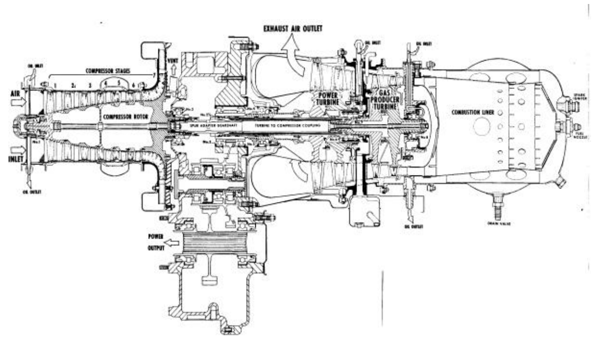

FIGURE 2. T63 A-700 ENGINE

TABLE 2. ENGINE OPERATING CONDITIONS WP STANDARD DAY (850 ft, 14.25 PSIA, 77 °F)

Power	P_3 psia	T_3 °F	T_5 °F	SHP hp	Fuel flow lb/min	Air flow lb/min	Overall F/A ratio	Burner F/A ratio
Idle	35	251	750	8	0.89	95	0.009	0.04
Cruise (NRP)	80	498	1280	238	2.92	169	0.017	0.062

Emissions Instrumentation

PM and gaseous emissions were sampled from the engine exit plane using oil-cooled probes maintained at 150°C, and transported to the analytical instruments via heated lines. The PM sample stream (mostly non-volatile) was maintained at 65° C and diluted with nitrogen near the probe tip to prevent water condensation, minimize particle losses in the sample lines and prevent saturation of the particle counting instruments. The PM emissions were characterized using conventional aerosol instruments shown in Table 3. A TSI Model 3022A Condensation Particle Counter (CPC) was used to provide a count of particles per unit volume (particle number [PN]), a TSI Model 3936 Scanning Mobility Particle Sizer (SMPS) with a nano-differential mobility analyzer (DMA) was used to obtain the particle size distribution from 5-150 nm. In addition, an in-house designed and built smoke machine was used to collect soot samples for determination of the engine Smoke Number per SAE ARP 1179.[9] The soot samples for chemical and carbon-type analysis were collected by passing a predetermined volume (57 standard liters) of undiluted exhaust sample through quartz filters via heated lines (150°C) using the in-house built smoke machine. A Thermo Electron 5012 (Multi Angle Absorption Photometer) MAAP was used to obtain real-time PM mass emissions.

TABLE 3. LIST OF INSTRUMENTS UTILIZED FOR EMISSIONS MEASUREMENTS

Instrument	Measurement
Condensation Particle Counter (TSI 3022A) CPC ± 20%	Particle Number
Scanning Mobility Particle Sizer (TSI 3936) w/TSI 3776 CPC ± 10-20%	Particle Size Distribution (D=7.0 - 289 nm)
Multi-angle Absorption Photometer ThermoElectron MAAP 5012	Particle Mass Concentration
FTIR Analyzer (MKS 2030) ± 2%	CO2, CO, NOx, SOx, HC species
NDIR Analyzer (CA 602P) ± 1%	Diluted Sample CO2
Smoke Sampler & Reflectometer (Photovolt Instruments Inc. 577)	Smoke Number
LECO Carbon Analyzer (RC-612)	Elemental/Organic Carbon
CAI FID Analyzer ± 1%	Unburned Hydrocarbon Concentration
Agilent GC-MS	HAPS
Agilent HPLC	Aldehydes-HAPS

Gaseous emissions were sampled with undiluted probes and transported through heated lines (150°C) per the SAE ARP 1256.[10] Major and minor gaseous species were quantified using an MKS Multi Gas 2030 Fourier Transform Infrared (FTIR) based analyzer and total unburned hydrocarbons were quantified using a CAI 600 Heated Flame Ionization Detector. A non-disperse infrared analyzer (NDIR) was used to measure the CO_2 for the diluted samples from the particle instruments to correct for dilution. Figure 3 illustrates the flow paths used for sample collection and dilution.

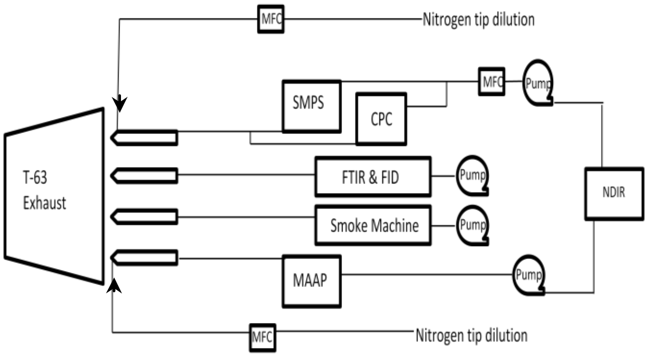

FIGURE 3. FLOW DIAGRAM OF SAMPLING LINE AND INSTRUMENTATION

PM mass was also determined off-line via Temperature Programmed Oxidation Analysis using a LECO Carbon Determinator. In this analysis, the soot collected on a quartz filter is oxidized in the presence of oxygen at a temperature of 325°C for 7.5 minutes and then ramped up to 750°C at a rate of 105°C/min. Species that oxidize at the lower temperature (325°C) are considered volatile carbon and the remaining species, which oxidize at the higher temperature (750°C), are considered elemental carbon. The total carbon mass is the sum of the volatile and elemental carbon.

Hazardous Air Pollutants (HAPs)

Measurement of selected HAPs was performed to investigate the propensity of HRJ fuels to produce these compounds. Specifically, efforts were made to quantify aldehydes and selected volatile organic compounds. Measurement of aldehydes was accomplished using the EPA Compendium Method TO-11A.[11] For this method, raw engine exhaust was sampled at 2 SLPM for five minutes through a silica gel cartridge treated with 2,4-dinitrophenylhydrazine (DNPH) preceded by an O_3 scrubber to prevent depletion of DNPH. The cartridges were capped and placed into foil lined bags and stored in a 4°C cooler for post-test analysis. The cartridges were subsequently treated with 5 mL of acetonitrile to extract the derivitized aldehydes and analyzed by HPLC. Standard solutions of aldehydes were prepared and analyzed to develop a calibration range between 0 and 15 µg/mL of each derivitized aldehyde.

Volatile organics were collected in an activated charcoal carbon tube at 1 SLPM for 5 minutes; the tubes were capped and stored in a 4°C cooler for post-test analysis. The volatile organics were extracted with 1 mL of carbon disulfide, spiked with a known quantity of C_{20}, and quantified via GC/MS. Standard solutions of organic HAPs 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 exhaust gas. Formaldehyde was also measured with the MKS Series 2030 Multi-Gas analyzer.

Emissions Index Calculation

Particle number (PN) emissions were quantified with a CPC and corrected for dilution based on the CO_2 measurement of the diluted and raw samples. Dilution ratios ranged from an average of 15:1 at idle to 25:1 at maximum power. Higher dilution was required to maintain the particle counts within the CPC measurement range. Particle number emission indices (PN_{EI}), the number of particles produced per unit mass of fuel consumed, were calculated using the following relationship derived from fluid flow fundamentals:

$$PN_{EI} = 2.883 * 10^3 * PN_{corrected} * \left(\frac{1+\left(\frac{F}{A}\right)}{\left(\frac{F}{A}\right)}\right) * \left(\frac{T}{P}\right) \quad \text{Eqn (1)}$$

Where PN_{EI} is the number of particles per kilogram of fuel, $PN_{corrected}$ is the dilution-corrected PN in number of particles per cubic centimeters, T is the sample temperature at the instrument in Kelvin (293 K), P is the sample pressure at the instrument in atmospheres, F/A is the engine fuel-to-air ratio, and 2.833 x 10^3 is a unit conversion factor. The engine *F/A*

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[9] SAE 1970, "Aircraft Gas Turbine Exhaust Smoke Measurement," SAE Recommended Practice ARP 1179. SAE, Warrendale, PA USA, 1970.

[10] SAE 2004, "Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines," SAE Recommended Practice ARP 1533A.

[11] EPA Compendium Method TO-11A 2nd Ed. "Determination of Formaldehyde in Ambient Air Using Adsorbent Cartridge Followed by High Performance Liquid Chromatography (HPLC)" Cincinnati, OH, 1999

ratios were determined based on the CO and CO_2 emissions following the SAE ARP 1533A guidelines.[10]

DISCUSSION

Particle Number Emissions and Size Distributions

Dilution-corrected total particle numbers of 7.68E+05 to 1.10E+08 were observed for the fuels characterized for the engine idle and cruise settings. The total particle counts were corrected for dilution and normalized to JP-8 for each engine condition. PN_{EIs} normalized to the corresponding JP-8 PN_{EIs} as a function of power setting are shown in Figure 4. The data comprise averages of three to five discrete measurements during the engine operation. Neat HRJ fuels displayed the greatest overall reduction in particle number relative to JP-8 at the lower power setting (90-98% reduction), with a considerable reduction (~80%) still achieved at cruise. The HRJ/JP-8 blends had intermediate emission levels. The PN_{EI} at idle for the blends was lower than predicted via linear averaging, while the behavior at cruise was linear with blend concentration. The reduction in PN_{EI} with the neat HRJs and fuel blends is believed to be primarily due to the reduction in aromatic compounds in the fuel, which are direct precursors to soot formation and growth[12]. The reduced impact on soot at the higher power setting is due to increased rates of PM production at the higher combustion temperatures, which allows soot formation from condensation and growth reactions of aliphatic compounds to become appreciable. Tests with the 16% trimethylbenzene/tallow fuel blend also showed lower PN_{EI} compared to JP-8 but with a lower magnitude than observed for the neat HRJs and blends. This was anticipated as this fuel blend had a much higher total aromatic content than the neat HRJs and HRJ/JP-8 blends. Although the overall aromatic concentration was comparable to that of the baseline JP-8 (17.2%); a reduction was still realized since the JP-8 also contained dicyclic aromatics (1.1% naphthalenes), which have been shown to have a higher influence on particulate production on this platform than single ring aromatics.[12]

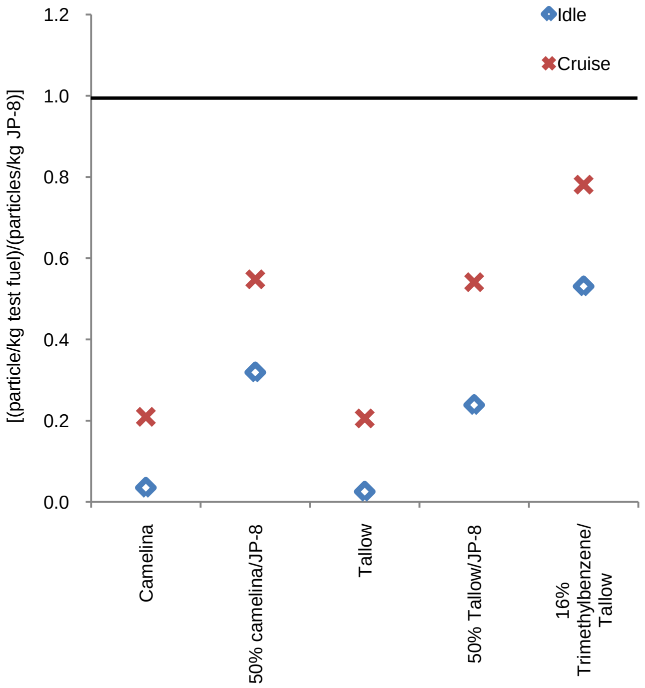

FIGURE 4. NORMALIZED PARTICLE EMISSIONS INDEX OF HRJ & RESPECTIVE BLENDS

The particle size distributions, shown in Figure 5 (idle) and Figure 6 (cruise), display a significant reduction in the total particle count (consistent with reported PN_{EI}) and slight reductions in mean particle diameter (distributions shifting left) for the neat HRJ and corresponding blends. Mean particle diameter reductions of up to 35% were observed for the neat and blended fuels compared to JP-8. The 16% trimethylbenzene/tallow blend also showed reductions similar to those observed for the total particle count data. All tests had a single log-normal size distribution consistent with typical aerosol emissions from turbine engines[13].

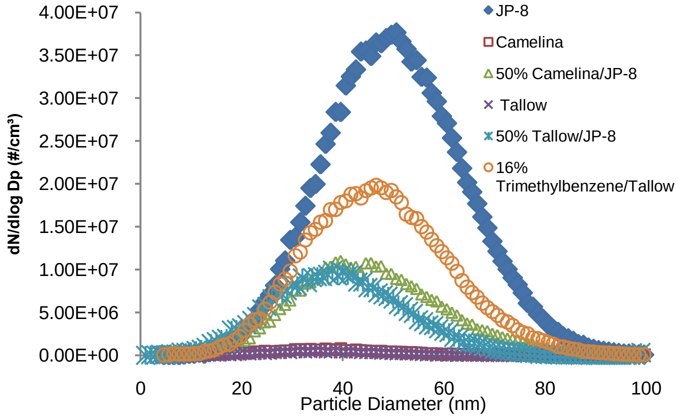

FIGURE 5. PARTICLE SIZE DISTRIBUTION AT ENGINE IDLE CONDITION

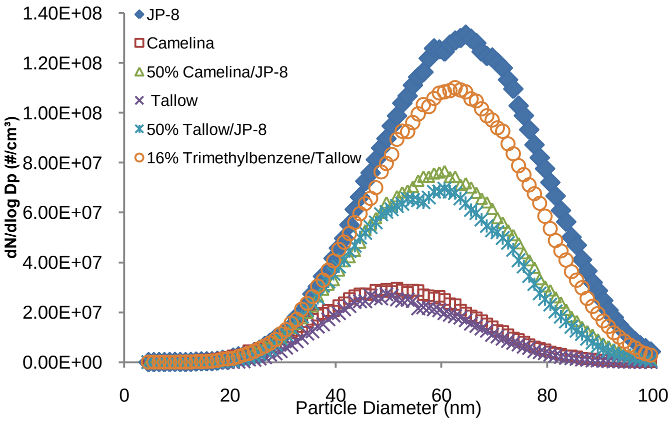

FIGURE 6. PARTICLE SIZE DISTRIBUTION AT ENGINE CRUISE CONDITION

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[12] DeWitt, M.J., Corporan, E., Graham J.L., Minus, D. "Effects of Aromatic Type and Concentration in Fischer-Tropsch Fuel on Emission Production and Material Compatibility," Energy & Fuels, Vol. 22, pp. 2411-2418, 2008.

[13] Corporan, E., DeWitt, M.J., Klingshirn, C.D., Striebich, R., and M.-D. Cheng, "Emissions Characteristics of Military Helicopter Engines with JP-8 and Fischer-Tropsch Fuels," Journal of Propulsion and Power, 26(2), p 317-324, 2010

Mass Measurements

The PM mass emissions from the on-line MAAP measurement and off-line carbon oxidation analysis normalized to those for JP-8 as a function of fuel type and power setting are shown in Figure 7. All fuels presented a reduction in the PM mass emissions compared to operation with JP-8, which is consistent to those previously discussed for the aerosol emissions. The relative trends between fuels were also consistent (with the exception of the LECO Quartz filter measurement for the 16% trimethylbenzene at GI). The neat HRJ fuels provided the largest reductions with intermediate levels for the fuel blends. The general trends in the mass emissions are consistent with previous studies and the effect of aromatic concentration on total mass emissions.[12]

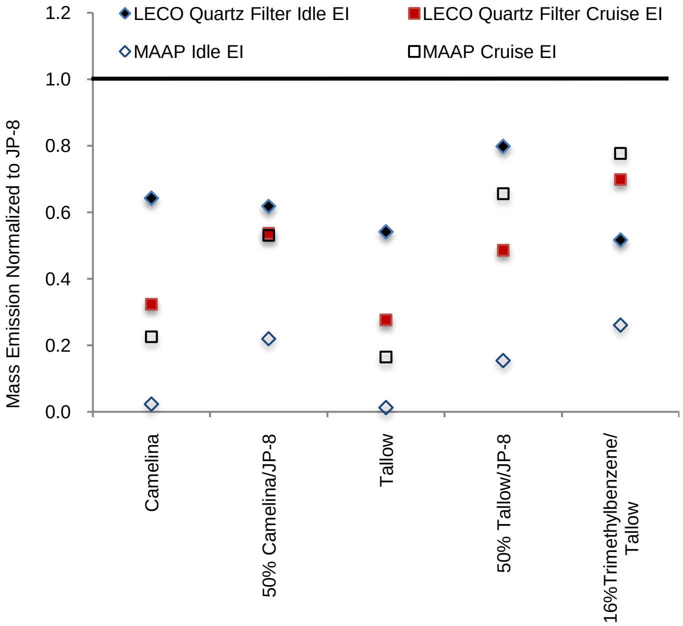

FIGURE 7. COMPARISONS OF NORMALIZED TOTAL PARTICLE MASS

As shown in Figure 7, the MAAP consistently measured lower relative concentrations compared to the off-line carbon oxidation. However, better agreement of the relative differences in PM mass between techniques was observed at the higher power setting. The disparities may be the result of inherent differences in the measurement techniques. The MAAP measurement is based on correlations developed for black carbon content while the off-line carbon oxidation analysis quantifies total carbon in the collected sample. At low power conditions, volatile organics can comprise a significant fraction of the total mass emissions, while these compounds are substantially reduced at the higher power setting.

Smoke Number

Smoke number results for the cruise condition follow a similar trend as in the MAAP and off-line carbon oxidation measurements. The neat camelina and tallow fuels provided a significant reduction when compared to JP-8, as shown in Figure 8. The 50/50 blended fuels provided nearly a 50% reduction of smoke number. The 16% trimethylbenzene /tallow blend produced the largest smoke number values of the SPK and blended fuels evaluated. The engine idle condition did not provide quantitative smoke number data due to low mass emissions at this engine condition.

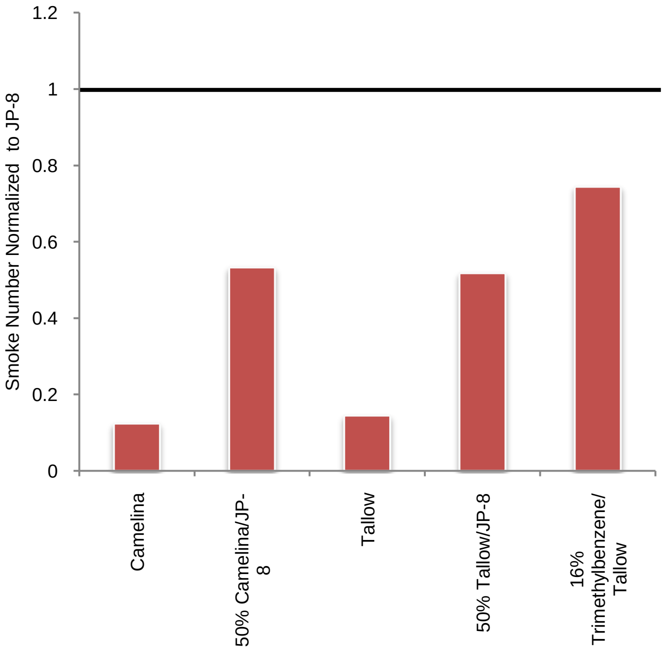

FIGURE 8. NORMALIZED SMOKE NUMBER RESULTS CRUISE ENGINE CONDITION

Gaseous Emissions

Most gaseous emissions produced by the alternative fuels were comparable to JP-8. CO emissions, shown in Figure 9, display slight reductions (~20%) at idle for the neat HRJs. The blends (including the trimethylbenzene/HRJ) showed small or negligible change in CO emissions compared to JP-8. The reductions in CO are believed to be due to the lower overall carbon content in the HRJs compared to JP-8. As anticipated, sulfur oxide emissions were significantly lower for the HRJs and fuel blends due to their respective lower sulfur concentrations. No significant difference was observed in NO_x emissions between the fuels. NO_x is strongly influenced by combustion temperatures, which were kept relatively constant for each power setting and fuel during this study.

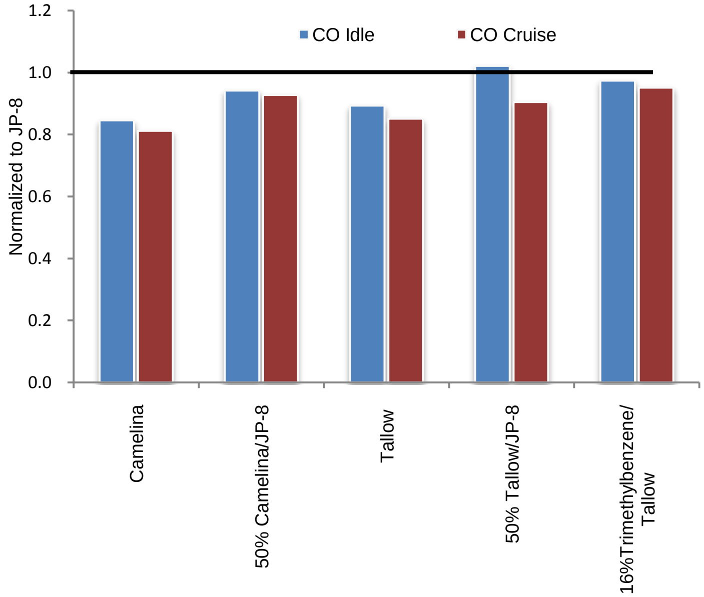

FIGURE 9. COMPARISON OF CARBON MONOXIDE EMISSIONS AS FUNCTION OF ENGINE CONDITION

Unburned Hydrocarbons

The alternative fuels provided substantial reductions in unburned hydrocarbon emissions at the engine idle condition, as shown in Figure 10. The reduction was attributed to the lower aromatic content in the alternative fuels, which results in improved combustion of the fuel components at lower engine temperatures. These results are consistent with previous observations in other engine operated with alternative fuels. Unburned hydrocarbons were below the detection limit of the FID analyzer at the cruise engine condition.

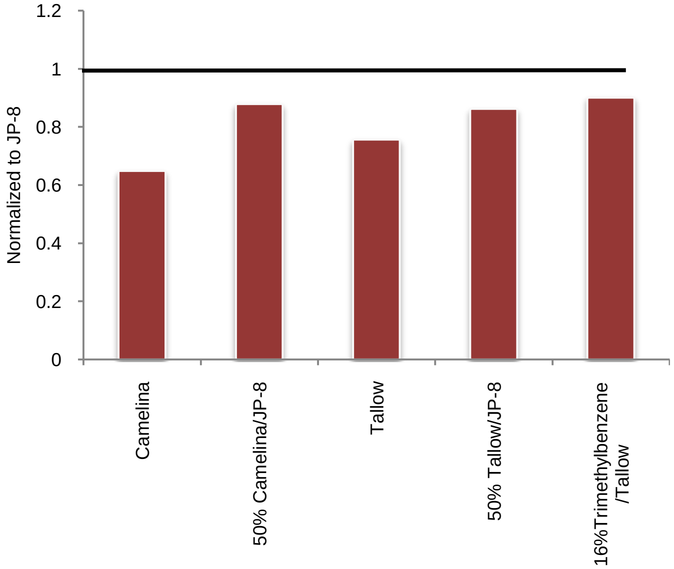

FIGURE 10. COMPARISONS OF UNBURNED HYDROCARBON EMISSIONS AT IDLE CONDITION

Hazardous Air Pollutants (HAPS)

HAPS measured in these studies included: benzene, formaldehyde, toluene, acetaldehyde, ethyl benzene, *m,p* xylene, and propionaldehyde. The data shown in Figure 11 (HAPs normalized to JP-8 at idle power), indicate significant reduction in the aromatic-type HAPs, and negligible change in the major aldehyde compounds from the combustion of alternate fuels relative to JP-8. Formaldehyde levels, as measured by on-line FTIR, were generally in good agreement with the EPA Method. Formaldehyde and acetaldehyde were the major aldehyde components observed; propionaldehyde levels are less accurately measured due to their low concentrations. The observed impacts of the alternative fuels on the aldehyde emissions are in contrast to those observed in a more modern engine, which showed significant reductions with similar alternative fuel blends[5]. This suggests that the impact of alternative fuels on aldehyde emissions is strongly influence by combustor design and operation. Further research in this area is warranted. As expected, benzene, toluene, ethylbenzene and xylene (BTEX) emissions were all reduced with the alternative fuels due to the reduced aromatic content in the fuels. At 50% blending of camelina with JP-8, the BTEX HAPs results are approximately 50% of the average of the neat fuel BTEX values. One exception was the xylene formed from tallow fuel with the added trimethylbenzene. Xylene is likely a decomposition product of the added trimethylbenzene.

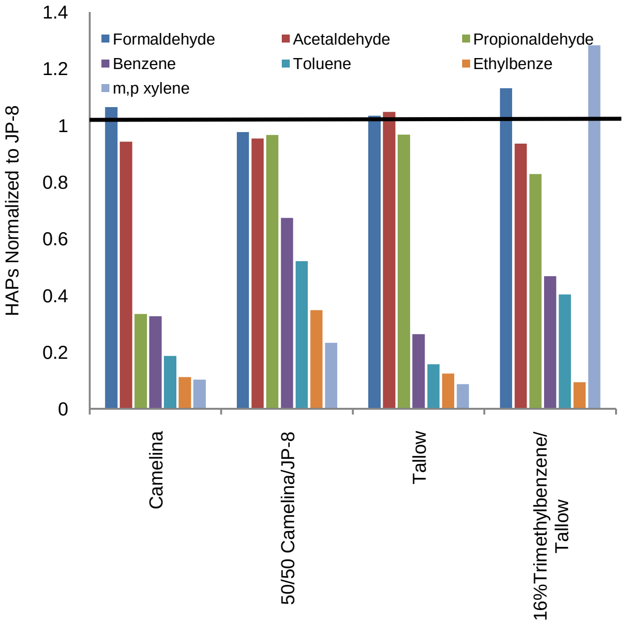

FIGURE 11. COMPARISONS OF HAPS NORMALIZED TO JP-8 AT IDLE ENGINE CONDITION

Engine Performance

No discernable differences in engine performance, such as required fuel flow or power output, were observed between the tested fuels. Power specific fuel consumption (SFC) was computed and corrected for inlet air temperature. These data show negligible change in SFC as a function of fuel type. This result is reasonable considering the relatively consistent energy content in the various fuels evaluated.

150 Hour Evaluation

Due to relatively short durations using alternative fuels on the T63 engine during operability and emissions tests, an endurance analysis was warranted using a 50/50 blend of tallow feedstock fuel and JP-8. This was performed to assure proper engine operation over an extended period of time since most fuel candidates were only evaluated for approximately 1-3 hours. A 150 hour endurance assessment was performed over the course of 24 days, consisting of 100 cycles of 1.5 hour each. Each cycle consisted of 15-minutes at GI, followed by 60-minutes at NRP followed by 15-minutes at GI. At the end of each cycle, the engine was either shut down or a new cycle was started. The number of cycles run each day was 3 to 6, depending on facility scheduling. The corrected power specific fuel consumption range was ±4% throughout the 150 hour assessment.

Combustion Section

The engine was removed and combustion section and fuel nozzle cleaned prior to the 150 hour endurance investigation. The combustion section, as displayed in Figure 12, was also removed and inspected after the 150 hour endurance run. Overall, the engine operated normally on the HRJ blend (compared to typical operation on JP-8) with no discernable differences or changes in engine performance or fuel usage over the extended duration of operation. Combustor and fuel nozzle images following the 150 hour evaluation (see Figures 13a and 14a), display very similar heating and sooting patterns compared to those observed for operation with JP-8 for 175 hours (Figure 13b and 14b).

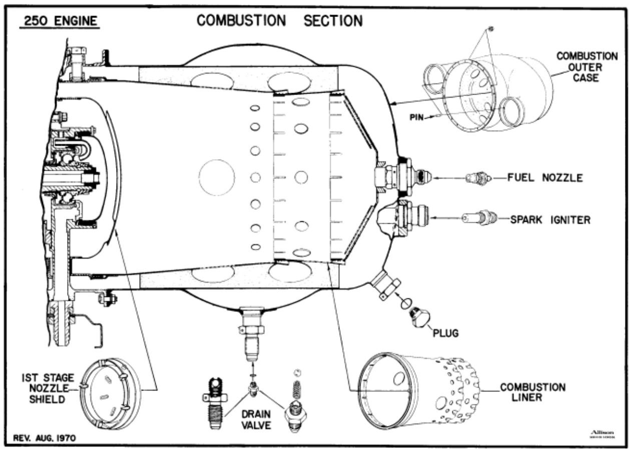

FIGURE 12. DETAILED DRAWING OF T63 COMBUSTION SECTION

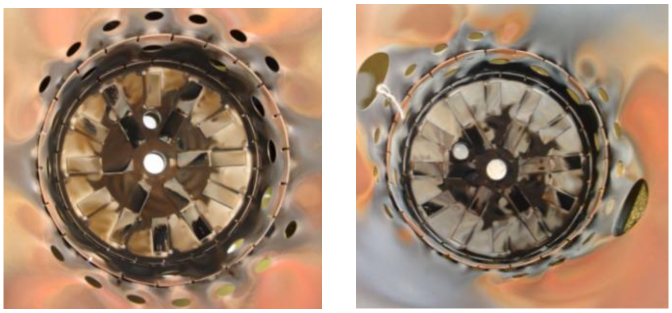

FIGURE 13. COMBUSTOR T63 ENGINE OPERATED ON: (a) HRJ BLEND FOR 150 HRS, (b) JP-8 FOR 175 HRS

FIGURE 14. FUEL NOZZLE OF T63 ENGINE OPERATED ON: (a) HRJ BLEND FOR 150 HRS, (b) JP-8 FOR 175 HRS

During testing, starting with cycle 10 (15 hours), it was observed that fuel leaked from a seal (comprised of Buna-N-Nitrile) located in the engine fuel control at the start of each run day. The leak consistently stopped after the engine warmed up (10-15 minutes), possibly due to heat induced ring swell. The fuel leak was observed to be worse when starting the engine after a 48 plus hours soaking fuel contact. At the end of the HRJ blend evaluation, a 1.5 hour cycle test with JP-8 was completed after the combustion section inspection was performed. This resulted with an initial fuel leak from the fuel control for the first 15 minutes of run time. Subsequent tests with JP-8 produced no leaks, which confirmed that the HRJ tallow blend had been responsible for the failed seal performance. The reduction in seal-swell propensity with paraffinic synthetic fuels has previously been observed and is believed to be due to a reduction in fuel compounds (aromatics and polar compounds) which selectively interact with the elastomeric materials.[8,12]

SUMMARY

Tests were conducted to evaluate the performance and emissions characteristics of a T63 engine operated on camelina and tallow HRJ fuels, 50/50 blends by volume with JP-8, and a 16% aromatic/tallow-HRJ blend. In addition, a long duration (150 hr) test was completed. As anticipated no anomalies in engine performance were observed with the alternative fuels and blends. Due to the lack of aromatics and sulfur in the HRJ fuel, and consistent with previous studies, reduced soot and sulfur oxide emissions were observed with the neat and blended fuels compared to operation on JP-8. Reductions in HAPS (except for formaldehyde and acetaldehyde) were observed for the alternative fuels and blends. For the 150 hours endurance test with the 50/50 HRJ/JP-8 fuel, emissions measurements at 50, 100, and 150 hours of test operation, demonstrated adequate engine performance with no degradation (i.e. increase) in emissions as a function of run time.

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