Alternative fuel test on PW308 engine

A Collaborative effort
NASA, AFRL, ARI, UTRC and P&W

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Tests performed to investigate impact of alternative fuels

- Primary test objective: determine the impact of synthetic fuel on performance and emissions
- Secondary test objective
  - Impact of heated fuel on emissions and performance
  - Spatial differences in emissions
- Measurements performed on PW 308 engine
- Sampling rake with multiple gas and particle probe used to collect sample at engine exhaust and at 50m
- Measurement team
  - NASA: PM and Gaseous emissions
  - AFRL: PM and Gaseous emissions
  - ARI: Volatile PM emissions
  - UTRC: Sampling System
  - P&W: Performance and test lead
All test objectives achieved

- Successful testing of all three fuels (JP8, Synthetic fuel or Fischer Tropsch (FT) fuel, and Blend)
  - No significant difference in engine performance or gaseous emissions with the three fuels
  - PM emission reduction with blend and synthetic fuel
  - Heated fuel had higher NO$_x$ emissions
- Excellent set of data to validate models
Agenda

- Tests conducted
- Results
  - Engine performance and gaseous emissions with the different fuels
  - Difference in non-volatile PM emissions
  - Volatile PM emissions
Agenda

- Tests conducted
  - Fuels tested
  - Sampling system
  - Test matrix
- Results
  - Engine performance and gaseous emissions with the different fuels
  - Difference in non-volatile PM emissions
  - Volatile PM emissions
Test setup

PW308 - B04 STAND - 03/27/08
Composition of synthetic fuel looks different from JP8
The three fuels have similar properties

<table>
<thead>
<tr>
<th>Property</th>
<th>JP-8</th>
<th>Blend</th>
<th>Synthetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (cSt)</td>
<td>1.38</td>
<td>1.14</td>
<td>0.96</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.8050</td>
<td>0.7734</td>
<td>0.7377</td>
</tr>
<tr>
<td>Net Heat of Combustion (Btu/lb)</td>
<td>18,533</td>
<td>18,735</td>
<td>18,960</td>
</tr>
<tr>
<td>Hydrogen % mass</td>
<td>13.95</td>
<td>14.78</td>
<td>15.71</td>
</tr>
<tr>
<td>Particulate contamination (mg/L)</td>
<td>0.71</td>
<td>0.21</td>
<td>0.11</td>
</tr>
<tr>
<td>Sulphur content (%)</td>
<td>0.123</td>
<td>0.065</td>
<td>0.003</td>
</tr>
<tr>
<td>Aromatic content (%)</td>
<td>19</td>
<td>10.1</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Properties of the blend are within the Aviation fuel Specs
Synthetic fuel doesn’t meet Aviation fuel spec
Test Setup

Control Room

Cooling H$_2$O

AFRL Trailer

NASA (+ARI) Trailer

Elevated Test Stand

PW 308

Rake

Valve Boxes

Gas lines

Aerosol lines

Communication lines

Air - Stand

GN2 - Stand

Power

208 Single Phase, 250 A

50 m Probe
Particle Probe Plumbing designed to minimize particle losses

Probes

Valve Box

3/8” PTFE, 10’

3/8” PVC

DILUTION GAS

FILTER

MFC

0 – 100 LPM

Dry N2

3/4” PTFE, 20’

MANIFOLD

NASA

ARI

50 M Probe

1” Conduit, 130’

3/4” PTFE, 20’

Vacuum Pump

Considerable effort expensed to insure that the sampling methodology follows the recent advancement made in PM emission measurement
Line loss estimation model predicts line losses within acceptable limits

Pretest Line Loss Prediction for 50 m probe

Pretest Line Loss Prediction for 1 m probe to NASA instruments

Pretest Line Loss Prediction for 1 m probe to AFRL instruments

Acceptable limit
Full suite of Aerosol Instruments used to characterize emissions

- AFRL CPC, SMPS, TEOM, EC/OC, Smoke, PAH

**OVERALL**
- 6 number densities
- 5 size distributions
- 4 Mass
- 1 Composition
Each probe tip separated by 1.25”
PW308 Emissions Test Matrix designed to fulfill all objectives

Engine Power, %

Elapsed Time (hh:mm)

00:00 01:00 02:00 03:00 04:00 05:00 06:00

JP-8
FT Fuel
50/50

Heated fuel
Agenda

- Tests performed
- Results
  - Engine performance and gaseous emissions with the different fuels
- Difference in non-volatile PM emissions
- Volatile PM emissions
Engine and emissions data does not indicate major differences between the three fuels

GASEOUS EMISSIONS

- At low power
  - NO\textsubscript{x} emissions are within instrument measurement capabilities
  - Lower CO with FT/blend may be due to higher H/C ratio

- At intermediate/high power
  - Very low CO emissions make ratios irrelevant to evaluate differences between the fuels
  - No significant difference in NO\textsubscript{x} emissions

- Negligible UHC at all power conditions for both fuels
- SO\textsubscript{2} emissions indicate Sulfur content of the blend to be around 50% of JP8 while for 100% FT fuel a value of 0.1% indicates contamination
- ~2% fuel flow benefit with 100% synthetic fuel can be attributed to the higher heat content of synthetic fuel

Negligible differences in gaseous emissions & performance as expected due to similarity in the physical properties of the fuels (like heating value, specific gravity)
Agenda

Tests performed

Results

- Engine performance and gaseous emissions with the different fuels
- Difference in non-volatile PM emissions
  - For the different fuels (JP8/Synthetic/blend)
- Volatile PM emissions
Synthetic fuel reduces Particle Number Emission Index

As expected lower PM emissions with synthetic fuel due to its chemical composition (higher H/C ratio and no aromatics/Sulfur)
Particle Mass Emission Index goes down with synthetic fuel

As expected PM emission reductions not proportional to the fraction of FT fuel
Greater discrepancy in the measurements between the different teams
As expected greater SN changes with 100% Synthetic fuel than with the blend.
Measurement uncertainty is lower than PM EI reduction with synthetic fuel

FT produces >90% reduction at idle, 40% at high power
Particle size distribution for the different fuels at different powers show similar trends.

FT fuel makes lower number of particle emissions as well as particle of smaller size.
FT fuels provide larger percentage reductions at lower power conditions.

FT emissions are small, more difficult to discriminate from background at lower thrust conditions.

Differences at higher thrust conditions are less.
Particle mean diameter decreases with increase in FT fuel content

Particle mean diameter along with particle number count decreases from JP8 to Blend to FT fuel
Mass variability for synthetic fuel for the different instruments not well understood

- Mass EI estimated or measured with different instruments
  - EEPS and SMPS measure size distribution and numbers. Mass estimated using volume of particles and density
  - MAAP and UHSAS measure mass more directly (based on reflectivity index)
  - Estimations based on the assumption that all particles generated by the different fuels have same physical/chemical properties

- The differences in the observed mass may be due to
  - Particles generated with the different fuels may have different physical or chemical properties
  - The different instruments have different cut-off size ranges
Mass EI data for 100% synthetic fuel sensitive to instrument selection

Reduction in number EI very similar for the different instruments

Reduction in Mass EI much more sensitive and variable for the different instruments
Blend data shows more variability at low thrust while high thrust data similar to FT fuel.

Number EIs variability probably because of variations in instrument sensitivity.

Ratio of “Mass” EIs quite variable at low power, background particles may be a contributing factor.
Measuring PM emissions at 50m is difficult

Wind causes plume to waver back and forth across 50 m inlet probe
Comparison between 1m and 50 m data reveals useful information on PM formation

FT fuel produced significantly lower volatile PM emissions at 1m and 50m
Agenda

- Tests performed
- Results
  - Engine performance with the different fuels
  - Difference in non-volatile PM and gaseous emissions
    - Between hot and cold fuel
- Volatile PM emissions
Heated fuel (600 F) gives slightly better SFC

Heated fuel led to higher combustor inlet temperature and hence improved SFC by 0.5-1%
Heated fuel produced more $\text{NO}_x$ and slightly higher SN

- SN differences between the heated fuel and cold fuel was on the order of $\pm 10\%$ which is within measurement uncertainty
- $\text{NO}_x$ for heated fuel was $\sim 15\%$ higher for heated fuel
  - Combustor (nozzles) are not optimized for heated fuel
  - Higher stoichiometric flame temperature with heated fuel
Differences between heated and unheated fuels within experimental uncertainty

PM emission measurements indicate no significant difference between heated fuel and unheated fuel
Agenda

- Tests performed
- Results
  - Engine performance with the different fuels
  - Difference in non-volatile PM and gaseous emissions
    - Spatial variation
  - Volatile PM emissions
Spatial variation in the data captures the partial mixing of core and bypass stream.

Partially mixed exhaust leads to variation in actual emissions but EI’s are consistent across the exhaust.
Just like gaseous emissions, PM number EI indicate little spatial variation.

Instrument-instrument variability much higher than spatial variation.
PM emissions with different instruments may not give the same answers if instrument size cut-off is different.

Differences in total number count between different instruments can be attributed to differences in instruments “cut-off” sizes.
Summary of Non-volatile PM

- Negligible Thrust and Fuel Flow impact of FT fuel as compared to JP8
- No significant difference in Gaseous emissions for the different fuels
- PM emissions for the different fuels
  - Pure FT EI values are an order of magnitude lower in both number & mass at idle relative to JP8. Differences between the fuels diminish with increasing power.
  - Changes in observed Number EIs largely independent of instrument; “mass” EIs sensitive to measurement technique.
  - FT particles much smaller, appear to be more dense than JP8
  - Emission reductions not proportional to the fraction of FT
  - FT suppresses volatile aerosol formation in plume
  - At the 50 meter probe, JP8 idle Number EIs 45 times higher than FT; differences decrease with power.
Summary of Non-volatile PM (cont.)

• Spatial variation in emissions indicates unmixedness. Constant Emission EI across the exhaust indicates all emissions vary in a similar fashion
  • Useful information to determine mixer efficiency

• Heated fuel had a higher NOx EI than unheated fuel

• Excellent set of data to model/develop combustion kinetics and impact of fuel composition, thrust (temperature/pressure) on PM emissions
  • Consistent trends with changes in fuels (JP8 vs. blend vs. 100% FT fuel) can be used to resolve the impact of fuel composition on PM emissions
  • Heated unheated fuel data can be used to model impact of temperature on gaseous as well as PM emissions
  • Data collected at different power level can be used to model impact of f/a, temperature and pressure on emissions
Agenda

- Tests performed
- Results
  - Engine performance with the different fuels
  - Difference in non-volatile PM and gaseous emissions
  - Volatile PM emissions
Exit Plane Organic, Oil & Sulfate Emissions

PM Organic

PM Sulfate

PM Oil

$E_{m}^{\text{organic}} > E_{m}^{\text{sulfate}} > E_{m}^{\text{oil}}$ consistent with previous field measurements

Very little volatile PM emission concentration measured at engine exhaust
Detailed Spatial Profile of $E_{IM}$-organic made at engine exhaust

Organic EIs are relatively constant across the engine exit plane.

JP-8 85% power
Full scale is 0.02 to 2 mg kg$^{-1}$
Error bars scale with measurement uncertainty
Marker size scales with EIM-organic (ranges from 0.8 ± 0.14 to 1.3 ± 0.4 mg kg$^{-1}$)
Re-scaled Profile of $E_{1M}$-sulfate

Marker size scales with $E_{1M}$-sulfate (ranges from 0.06 ± 0.01 to 0.40 ± 0.06 mg kg$^{-1}$)
Full scale is 0.02 to 0.2 mg kg$^{-1}$
Error bars scale with measurement uncertainty

Plot shows that entrained bypass air is the source of sulfate at 1m
Signal too weak to generate particle size distribution with AMS

JP-8 85% power
Detailed Profile of $E_{IM}$-oil

Oil EIs are consistent with an intermittent source at the periphery

JP-8 85% power
Full scale is 0.02 to 2 mg kg$^{-1}$
Marker size scales with $E_{IM}$-oil (ranges from 0.036 ± 0.006 to 1.9 ± 3.3 mg kg$^{-1}$)
Error bars scale with measurement uncertainty
Organic PM Emissions at 50m

$E_{I_m}^{organics} \approx 25 \pm 10 \text{ mg kg}^{-1}$

- $E_{I_{organics}}$ only a small fraction of total PM emissions
- Significant amount of lubrication oil (>75%)
- $E_{I_{organics}}$ independent of thrust condition/fuel

Unusual level of lube oil may be due to test engine configuration
Organic at 50m is larger than soot

100% FT, 85% power

Similar results found at other power conditions and for other fuels
Organics at 50m have same particle size distribution as periphery of engine exit plane
Oil is not coated on the soot – consistent with emission as liquid droplets
Plumes for JP8 shows contribution of sulfate particles

JP-8 – CO₂/number peaks coincide with sulfate peaks

\( E_{I_m} \)-sulfate (JP8) = 3.5 ± 1 mg kg\(^{-1}\) (1200 ppm sulfur)
\( E_{I_m} \)-sulfate (50% FT) = 1.5 ± 0.5 mg kg\(^{-1}\) (600 ppm sulfur)
\( E_{I_m} \)-sulfate (100% FT) < 0.05 mg kg\(^{-1}\) (30 ppm sulfur)
PM Plumes for 100% FT fuel shows sulfate concentration less than background.

100% FT – CO₂/number peaks coincide with sulfate valleys, i.e. Sulfate concentration in plume is less than ambient sulfate levels.
PW308 Sulfate PM data shows that sulfate PM emissions relate directly to fuel sulfur.

PW308 sulfate data follows the trend seen in previous tests.

**CFM56 Engines**
- N817NA base sulfur (-2C1)
- N817NA high sulfur (-2C1)
- N353SW (-3B1)
- N695SW (-3B1)
- N14324 (-3B1)
- N70330 (-3B1)
- N429WN (-7B22)
- N435WN (-7B22)

**Other Engine Types**
- N75853 (RB211-535E4-B)
- N74856 (RB211-535E4-B)
- N729FD (PW4158)
- N616NA (CJ6108A)
- N616NA (CJ6108A)
- PW308
- AE3007

**Graphical Representation**
- Best-fit line $R^2 = 0.89$
- $\text{SO}_2 = \text{SO}_3$ conversion $0.09 \pm 0.1\%$
- $\geq 85\%$ thrust

**Equation**
$$E_{I,m} = \text{sulfate (mg kg}^{-1}\text{)}$$

**Fuel Sulfur Content (g kg}^{-1}\text{)}**
Volatile content of PW308 “organic particles” is lubrication oil, partially burned fuel.

Lubrication oil emitted as 100-400 nm droplets in the bypass flow – EI\textsubscript{m}-oil not a strong function of power or fuel.

Lubrication oil may be the dominant source of PM especially at low power conditions and especially for synthetic fuels.

Partially burned fuel characteristic of hydrocarbon.

At engine exit plane, partially burned fuel is coated onto soot.

At 50 m, EI\textsubscript{m}-sulfate depends linearly on fuel sulfur content.

At 50 m, plumes generated by FT combustion contain “less” particle sulfate than ambient air.
WOULD LIKE TO SAY
THANK YOU
TO THE WHOLE MEASUREMENT TEAM