Overview of the Alternative Aviation Fuel Experiment

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NASA Langley Research Center
Motivation for Emissions Research

• Aircraft emit reactive gases and large numbers of black carbon and volatile aerosol particles; aircraft traffic expected to double over next 20 years

• Particle and gas emissions can effect climate (clouds, ozone) and local air quality

• Airports located in EPA non-attainment areas must assess environmental impacts before expanding

• New certification standards being considered by SAE—detailed observations needed to guide method development

• Europeans considering placing tighter controls on emissions including limits on number of particles emitted

• Better understanding of AC emissions needed for assessing effects
Total Hydrocarbons (THC) can be dominated by background methane

Smoke Number not representative of anything physical

Measurements from exit plane—ignores plume chemistry/condensation

Speciated hydrocarbon and detailed particle data needed for broad range engines, power settings, and ambient conditions to enable chemical and climate model assessments

### ICAO Archive Data for Typical Engine Cycle

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power Setting</th>
<th>Time minutes</th>
<th>Fuel flow kg/s</th>
<th>THC g/kg</th>
<th>CO g/kg</th>
<th>NOx g/kg</th>
<th>Smoke Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off</td>
<td>100%</td>
<td>0.7</td>
<td>0.38</td>
<td>0.22</td>
<td>0.77</td>
<td>19.6</td>
<td>1</td>
</tr>
<tr>
<td>Climb Out</td>
<td>85%</td>
<td>2.2</td>
<td>0.31</td>
<td>0.26</td>
<td>0.97</td>
<td>16.6</td>
<td>0.01</td>
</tr>
<tr>
<td>Approach</td>
<td>30%</td>
<td>4</td>
<td>0.11</td>
<td>0.66</td>
<td>3.93</td>
<td>7.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Idle</td>
<td>7%</td>
<td>26</td>
<td>0.05</td>
<td>3.85</td>
<td>23.8</td>
<td>3.5</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Engine Certification Data Not Much Use

ICAO Archive Data for Typical Engine Cycle
These experiments produced an extensive emissions data base, but many questions regarding sampling, measurements and plume chemistry remain.
Growing Impetus to develop Alternative Fuels

- Almost 60% of US oil is imported—will increase to 70% by 2025
- Large fraction of imported oil comes from unfriendly/unstable nations—leaves us vulnerable to embargoes and terrorist threats
- Worldwide demand is increasing—fuel prices have doubled in two years, causing large increases in transportation costs
- Increasing domestic oil production may come at a high environmental price (ANWAR, offshore, etc.)
- Fossil fuels are non-renewable, cause increases in atmospheric greenhouse gas concentrations

Fuel costs are now the largest expense in civil aviation—increasing and fluctuating prices are causing an economic crisis in the industry
AAFEX Objectives

1) Examine the effects of alternative fuels on engine performance and emissions
2) Investigate the factors that control volatile aerosol formation and growth in aging aircraft exhaust plumes
3) Establish aircraft APU emission characteristics and examine their dependence on fuel composition
4) Evaluate new instruments and sampling techniques
5) Inter-compare measurements from different groups to establish expected range of variation between test venues
## Summary of AAFEX Test Plan

<table>
<thead>
<tr>
<th>Location</th>
<th>NASA Dryden Aircraft Operation Facility</th>
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<tbody>
<tr>
<td>Dates</td>
<td>January 20 - February 3, 2009</td>
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<tr>
<td>Sponsors</td>
<td>NASA, Air Force, EPA, FAA</td>
</tr>
<tr>
<td>Scientist</td>
<td>Bruce Anderson and Science Team</td>
</tr>
<tr>
<td>Engineer</td>
<td>Robert Howard, AEDC</td>
</tr>
<tr>
<td>Manager</td>
<td>Dan Bulzan, NASA GRC</td>
</tr>
<tr>
<td>Operations</td>
<td>Frank Cutler and Mike Bereda, NASA DFRC</td>
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<tr>
<td>Aircraft</td>
<td>DC-8 with CFM-56 engines</td>
</tr>
<tr>
<td>Fuels</td>
<td>1--Standard JP-8</td>
</tr>
<tr>
<td></td>
<td>2--Shell Fischer-Tropsch Fuel from Natural Gas (FT1)</td>
</tr>
<tr>
<td></td>
<td>3--50/50 JP-8/FT1 blend</td>
</tr>
<tr>
<td></td>
<td>4--Sasol Fischer-Tropsch fuel from Coal (FT2)</td>
</tr>
<tr>
<td></td>
<td>5--50/50 JP-8/FT2 blend</td>
</tr>
<tr>
<td>Runtime</td>
<td>13 engine tests, ~35 total runtime</td>
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</tbody>
</table>
## Investigators

<table>
<thead>
<tr>
<th>Organization</th>
<th>POC</th>
<th>Measurements</th>
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<tr>
<td>AEDC</td>
<td>Robert Howard</td>
<td>Smoke Number</td>
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<tr>
<td>ARI/Harvard</td>
<td>Rick Miake-Lye, Scott Herndon</td>
<td>Aerosols and Gases</td>
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<td>Carnegie Melon</td>
<td>Allen Robinson</td>
<td>Aerosols</td>
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<td>EPA</td>
<td>John Kinsey</td>
<td>Aerosols</td>
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<tr>
<td>Missouri S&amp;T</td>
<td>Phil Whitefield, Don Hagen</td>
<td>Aerosols</td>
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<tr>
<td>Montana State</td>
<td>Berk Knighton</td>
<td>Hydrocarbons, HAPS</td>
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<td>NASA GRC</td>
<td>Dan Bulzan</td>
<td>Aircraft Parameters</td>
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<td>NASA GRC</td>
<td>Changlie Wey</td>
<td>Certification gases, Soot</td>
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<td>NASA LaRC</td>
<td>B. Anderson and A. Beyersdorf</td>
<td>Certification gases, Soot</td>
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<td>Penn State</td>
<td>Randy Vander Wal</td>
<td>Soot Morphology</td>
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<td>Pratt and Whitney</td>
<td>Anuj Bhargava</td>
<td>Measurement Comparisons</td>
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<tr>
<td>UCSD</td>
<td>Terri Jackson</td>
<td>Sulfate Isotopes</td>
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<tr>
<td>UTRC</td>
<td>David Liscinsky</td>
<td>Aerosols</td>
</tr>
<tr>
<td>WPAFB</td>
<td>Edwin Corporan</td>
<td>Aerosols and Gases</td>
</tr>
</tbody>
</table>

Will Dodds (GE), Anuj Bharava (PW) and Steve Baughcum made critical contributions to planning, operations, and data interpretation.
Carbon Spectra for AAFEX Fuels

Standard JP-8 Jet Fuel
19% Aromatics, 1150 ppm Sulfur

Shell Fischer-Tropsch Kerosene
0% Aromatics, 0 ppm Sulfur

Chromatographic Column Elution Time ->
### AAFEX Fuel Properties

<table>
<thead>
<tr>
<th>TEST Parameter</th>
<th>JP-8</th>
<th>FT1 Natural Gas</th>
<th>FT1 Blend</th>
<th>FT2 Coal</th>
<th>FT2 Blend</th>
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</thead>
<tbody>
<tr>
<td>Sulfur (ppm)</td>
<td>1148</td>
<td>19</td>
<td>699</td>
<td>22</td>
<td>658</td>
</tr>
<tr>
<td>Aromatics (%vol)</td>
<td>18.6</td>
<td>0</td>
<td>8</td>
<td>0.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Flash Point deg C</td>
<td>46</td>
<td>41</td>
<td>43</td>
<td>42</td>
<td>46</td>
</tr>
<tr>
<td>API Gravity</td>
<td>41.9</td>
<td>60.2</td>
<td>50.5</td>
<td>54</td>
<td>47.9</td>
</tr>
<tr>
<td>Freezing Point deg C</td>
<td>-50</td>
<td>-54</td>
<td>-60</td>
<td>&lt;-80</td>
<td>-60</td>
</tr>
<tr>
<td>Viscosity</td>
<td>4.7</td>
<td>2.6</td>
<td>3.3</td>
<td>3.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Cetane Index</td>
<td>41</td>
<td>58</td>
<td>46</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>Hydrogen Content (w%)</td>
<td>13.6</td>
<td>15.5</td>
<td>14.5</td>
<td>15.1</td>
<td>14.3</td>
</tr>
<tr>
<td>Naphtalenes (v%)</td>
<td>1.6</td>
<td>0</td>
<td>0.8</td>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>Heat of Comb (MJ/kg)</td>
<td>43.3</td>
<td>44.4</td>
<td>43.8</td>
<td>44.1</td>
<td>43.8</td>
</tr>
<tr>
<td>Olefins (%vol)</td>
<td>0.9</td>
<td>0</td>
<td>0.6</td>
<td>3.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Specific Gravity (g/cm3)</td>
<td>0.816</td>
<td>0.738</td>
<td>0.777</td>
<td>0.763</td>
<td>0.789</td>
</tr>
</tbody>
</table>

Synthetic fuels don’t meet specific gravity specs; FT1 ~10% less dense than JP-8.
CMU, Harvard, MSU, UCSD, and UTRC shared space with other participants.
Exhaust Measurements

- Certification species (CO$_2$, CO, THC, Nox), SO2, HONO, H2O2, C2H4, HCHO, etc.
- Hazardous Air Pollutants (HAPS): Acrolein, Benzene, etc.
- Total Aerosol and Black Carbon Mass
- Particle Number Density and Size Distribution
- Single Particle Composition
- Bulk Aerosol Composition
- Black carbon morphology
Exhaust Sample Inlets at 1, 30 and 145 m
“Tinker” Rake used on #3 Engine

AEDC particle probes designed to introduce dilution gas near inlet tip

Tinker rake mounted on translation stage to allow horizontal profiling
“APEX-2 Rake Used on #2 Engine

Rake and Probes Developed by AEDC; Stand Designed Built by MST
Simple Tubing Inlets Used at 30-m

Aerosol instruments placed in “Death-Box” to evaluate sample line effects
Near-Field Sampling System Layout

Aerosol lines 24 to 46 m, terminated at MST sample distribution manifold

- 30 m Deathbox
- 30 m Probes
- 1 m Rakes
- Unheated Valve Boxes
- Heated Valve Boxes
- Unheated Aerosol Lines
- Heated Gas Lines

Institutes:
- AEDC
- MST
- ARI
- NASA
- AFRL
- U.S. EPA
ARI Van and 145 m Trailers Examined Plume Chemistry and Aerosol Microphysics

Under idle conditions, van was decoupled from common sampling manifold and used to profile emissions between 30 m probes and airport fence.

145 m inlet mainly picked up #3 engine plume at mid to high power; sampled idle plume only under low-wind conditions.

ARI, Harvard, NASA, MST and UTRC made measurements in 145 m Trailers.
Example Engine Test Sequence

**Sample Inlet**
- Left 30-m
- Left 1-m
- Right 1-m
- Right 30-m

Left engine always burned JP-8, right engine burned JP-8 or test fuel.
APU was also sampled while it burned JP8 and FT2

APUs are small, low-bypass turbojet engines; emissions are not regulated
The experiment matrix included 13 engine and 3 APU test runs; burned >25,000 gallons of fuel in over 35 hours of testing.
#3 Engine Performance Std Day Corrections
Heating Value Corrections for FT Fuels

Fuels effects equipment and certification gas emissions
When account for fuel flows, times-in-mode, and full flight profile: Net consumption of methane

For JP-8

Engines Remove Methane from the Atmosphere at Thrust > Idle
HAPS emissions much lower for FT Fuels

0930: Gas Phase Engine Emissions—Scott Herndon

JP8 slope = 0.060
Knighton et al. APEX 2004 = 0.060

Fischer Tropsch Fuel
FT Fuels Drastically Reduce Black Carbon Emissions
Engines #2 and #3 exhibit slightly different emissions characteristics.

**AFFEX CFM56 Particle Number EI**

**JP-8 Fuel**

1m Measurements

- **Engine Setting**
- **AFFEX CFM56 Particle Number EI**

- **JP-8 L (27 Jan)
- JP-8 L (28 Jan)
- JP-8 L (29 Jan)
- JP-8 L (30 Jan)
- JP-8 R (27 Jan)
FT fuels influence black carbon morphology
Downstream aerosol loading depends on fuel, temperature and time.
Downstream solubility depends on fuel sulfur, plume age and temperature
**FT Fuel Greatly Reduces APU Particle Emissions**

APU emits 25x more black carbon per kg fuel at idle than an aircraft engine.

Mass emissions 90% lower when burning FT fuel.
AAFEX included multiple overlapping measurements—did they agree?
Processes occurring in the sampling lines significantly impact measurements.
What is the bottom line?

1500: Rick Miake-Lye