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Glenn Research Center

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Motivation and Objectives

High oil costs + the need to reduce pollution and dependence on foreign suppliers has spurred great interest and activity in developing alternative aviation fuels

NASA Fundamental Aeronautics supported efforts in studying the effects of fuel alternatives in combustion and in engines, including

*Alternative-Fuel Effects on Contrails and Cruise Emissions (ACCESS)*

*Alternative Aviation Fuels Experiment (AAFEX)*

**NASA ERA supports alternative fuels research:** develop and demonstrate a low NOx *Fuel flexible combustor* that provides a 75% reduction in oxides of nitrogen below the current CAEP 6 standard with no increase in particulate matter, while achieving a 50 percent reduction in fuel burned

**Task objectives**
—using GE TAPS single cup flame tube as a test bed

Ascertained visible luminosity, sooting, fuel spray pattern, liquid fuel penetration, flame zone location of Hydrotreated Renewable Jet (HRJ) fuel compared to JP-8.

**Means:**
1. high-speed imaging (grey scale) for structure, flame length, luminosity
2. Planar laser scatter of fuel drops
3. Fuel and OH planar laser-induced fluorescence (PLIF)
GE Twin Annular Premixing Swirler (TAPS) injector concept for low NOx emissions

Provides independent control of:

- Center pilot for low power operability, low CO, HC emissions
- Cyclone/main for high power operation, low NOx emissions

References:
Foust, Thomsen, Stickles, Cooper, Dodds—AIAA 2012-0936
Mongia—AIAA 2003-2657
## Comparing fuel physical properties

<table>
<thead>
<tr>
<th>Component</th>
<th>JP-8</th>
<th>HRJ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulfur (ppm)</strong></td>
<td>1148</td>
<td>&lt;3</td>
</tr>
<tr>
<td><strong>Olefins (%vol)</strong></td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Aromatics (%vol)</strong></td>
<td>18.6</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Naphthalenes (%vol)</strong></td>
<td>1.6</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Initial boiling point, °C</strong></td>
<td>158</td>
<td>165</td>
</tr>
<tr>
<td>10%</td>
<td>176</td>
<td>179</td>
</tr>
<tr>
<td>90%</td>
<td>248</td>
<td>243</td>
</tr>
<tr>
<td>End Point</td>
<td>273</td>
<td>231</td>
</tr>
<tr>
<td><strong>Flash Point °C</strong></td>
<td>46</td>
<td>55</td>
</tr>
<tr>
<td><strong>API Gravity</strong></td>
<td>41.9</td>
<td>54</td>
</tr>
<tr>
<td><strong>Specific Gravity</strong></td>
<td>0.816</td>
<td>0.758</td>
</tr>
<tr>
<td><strong>Freezing Point °C</strong></td>
<td>-50</td>
<td>-62</td>
</tr>
<tr>
<td><strong>Viscosity</strong></td>
<td>4.7</td>
<td>5.3</td>
</tr>
<tr>
<td><strong>Cetane Index</strong></td>
<td>41</td>
<td>67</td>
</tr>
<tr>
<td><strong>H Content (%mass)</strong></td>
<td>13.6</td>
<td>15.3</td>
</tr>
<tr>
<td><strong>Heat combustion (MJ/kg)</strong></td>
<td>43.3</td>
<td>44.5</td>
</tr>
<tr>
<td><strong>Fuel H/C ratio</strong></td>
<td>1.88</td>
<td>2.12</td>
</tr>
</tbody>
</table>

**Distillation characteristics**

- HRJ: Fewer aromatics:
  - Less luminous
  - Higher cetane index:
  - Shorter ignition delay

**Components**

- Similar reactivity

**Expectation:** more soot production from JP-8—greater luminosity

**HRJ constituents**—shorter ignition delay time
TAPS Gaseous Emissions Results—Fuel type comparison

- No discernable difference between fuel types in combustion efficiency or emissions.
- This result is similar to other fuel comparison tests using different fuel-air mixers.

Legend: $P_3$, $T_3$, pilot/main split, fuel

- Red circle: 250 psia, 1000°F, 10/90 split, HRJ
- Red circle: 250 psia, 1000°F, 10/90 split, JP8
- Navy blue square: 250 psia, 1000°F, 10/90 split, HRJ
- Purple square: 250 psia, 1000°F, 10/90 split, JP8
- Pink triangle: 170 psia, 1000°F, 10/90 split, HRJ
- Pink triangle: 170 psia, 1000°F, 10/90 split, JP8
- Green triangle: 208 psia, 1000°F, 100/0 split, HRJ
- Light green triangle: 208 psia, 1000°F, 100/0 split, JP8

Combustion Efficiency

- g-NOx/kg-fuel
- EINOx

- g-CO/kg-fuel
- EICO

- FAR, sample
Optical Diagnostics Setup and Testing

Planar Laser induced fluorescence (PLIF) of OH and Fuel, 100-ns gate

Planar Laser Scatter (PLS) for Liquid Fuel, 100-ns gate

Instantaneous imaging of CH* chemiluminescence, 100-ns, 100-µs
  Camera: Princeton Instruments PIMAX, 1k x 1k pixel

High Speed Flame Imaging via Chemiluminescence of CH*, C₂*
  Camera: Photron Fastcam SA1, 1k x1k px, 10000 frames/s

Laser: 10-Hz Nd:YAG → dye → UV: ~282-nm

<table>
<thead>
<tr>
<th>Test Point</th>
<th>P₃ (psia)</th>
<th>T₃ (°F)</th>
<th>Fuel Split</th>
<th>FAR/FAR_{SLTO}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>166</td>
<td>650</td>
<td>100/0</td>
<td>0.48</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>925</td>
<td>10/90</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>1000</td>
<td>20/80</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>1000</td>
<td>10/90</td>
<td>0.94</td>
</tr>
</tbody>
</table>

FOV: mixing region between pilot and main

Test Point P₃ Fuel Split FAR/FAR_{SLTO}
Optical diagnostics expectations based on fuel composition

<table>
<thead>
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<th>Fuel</th>
<th>JP-8</th>
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- more aromatic content in JP-8: higher soot production
  → greater luminosity

Light is either absorbed, scattered, or transmitted through matter.

\[ I_{\text{trans}} = I_{\text{incident}} - I_{\text{absorbed}} - I_{\text{scattered}} \]

PLIF requires absorption by fuel constituents before the excited molecules can emit light.

Naphthalenes and Methylbenzenes used for Fuel PLIF, so
- fuel PLIF signal greatly reduced for HRJ
- OH PLIF signal may be increased
  but More laser energy available for scattering from liquid
- PLS signal increased
Flame Chemiluminescence: CH*

% pilot flow affects flame structure
CH* results—total signal per image column with downstream location

**Point 1**
100% Pilot

**Point 2**
925°F
10% Pilot
90% Main

**Point 3**
20% Pilot
80% Main

**Point 4**
1000°F
10% Pilot
90% Main
High speed flame imaging—$C_2^*$, $CH^*$ pilot only

Frame rate: 10000/sec, 100-μs exposure
Image Resolution 768 x 768 pixels
Flow direction left to right

- JP-8 flame more luminous than HRJ flame
- Central recirculation zone can be seen
High speed video results—100% pilot, test point 1
- high speed camera frames (9701 images) processed as time-resolved PIV
- flow: left to right

JP-8

HRJ

Vectors give bulk average direction of motion—correspond visually
Contour shows the relative degree of change, on average
High speed video results—100% pilot, test point 1

Fuel Mixture shows results intermediate to the neat fuels

![Graph showing fuel mixture results](image)

**JP-8**

**75%-HRJ**

**HRJ**

<table>
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<th>V_{ax}, a.u.</th>
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<tbody>
<tr>
<td>5</td>
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</table>

**distance from center**

**distance from dome**
Liquid fuel results, Planar Laser Scatter

Above: average of 100 single shot images

Point 1
100/0
650°F

Point 2
10/90
925°F

Point 3
20/80
1000°F

Point 4
10/90
1000°F

Light scatter signal as a function of percent HRJ

Liquid signal decay →

Point 4

% HRJ fuel

Normalized Signal

Distance from dome

Distance from center

Distance from dome
Next: OH, fuel PLIF Results and Field of View Perspective:

Left: laser sheet oriented with flow, traversed across flow, side view images

Right: resulting traverse block sliced at fixed axial positions to produce End View images

Laser-induced Fluorescence or Scattering Data

Left: laser sheet oriented with flow, traversed across flow, side view images

Right: resulting traverse block sliced at fixed axial positions to produce End View images
Comparing HRJ and JP8 via Planar Laser Induced Fluorescence

*Fuel PLIF*

**Point 1, pilot only**

*Notch due to N2 purge*

- **Side view**
- **End view**

**Point 2, 10/90 split, $T_{in} = 925^\circ F$**

- **Side view**
- **End view**

**JP8**
- Uniform distribution within annulus

**HRJ**
- Most fuel observed near wetted annular walls
- Possibly only HRJ liquid seen because greater number density than in gas phase

For pilot only, JP8, HRJ have similar spray pattern.
Comparing HRJ and JP8 via Planar Laser Induced Fluorescence

**OH PLIF**

**Point 1, pilot only**

<table>
<thead>
<tr>
<th>Side view</th>
<th>End view</th>
<th>End view</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HRJ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distance From Dome</th>
<th>Distance From Center</th>
<th>Distance From Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td></td>
<td></td>
</tr>
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**Point 2, 10/90 split, \( T_{\text{in}} = 925^\circ \text{F} \)**

<table>
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<tr>
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<td>HRJ</td>
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**OH PLIF signal not as strong in CRZ for HRJ, but stronger on air side of spray cone:**

- Similar patterns for JP8, HRJ
- HRJ signal stronger than for JP8 likely because little absorption by fuel
JP8: Compare four test points using PLIF

**Fuel PLIF**

Side view                End views

Point 1

Point 2

Point 3

Point 4

**OH PLIF**

Side view                End views

Point 1

Point 2

Point 3

Point 4

Distance From Dome    Distance From Center    Distance From Center

Distance From Dome    Distance From Center    Distance From Center
Summary

• A single-cup GE TAPS injector used to compare JP-8 and tallow HRJ, using sample gas analysis, flame chemiluminescence, PLS, OH and fuel PLIF

• Consistent with other flame tube combustor and engine tests, little or no difference in gaseous emissions of NOx, CO, UHC

• Flame luminescence shows flame structure changes most affected by pilot flow. JP-8 flame ~4x brighter than HRJ flame for 20/80 split. Other splits have comparable luminoscity

• When flow is split between pilot and main, we see liquid from main circuit but not from the pilot. Main circuit fuel does not completely vaporize before exiting the dome.
Summary, cont

Fuel PLIF:

• For HRJ, more fuel observed along the wetted walls of annulus, whereas with JP8, uniformly distributed

• Likely for HRJ, PLIF results primarily from the liquid phase, where the number density of aromatics is greater than in the gas phase

• Future Fuel PLIF with low aromatic fuel will need to use shorter wavelengths (~266 nm) for better signal

OH PLIF:

• Similar patterns are observed for both fuels in the flow split case. Under pilot only operation, little OH is observed in the central recirculation zone for the HRJ
Acknowledgment

• The NASA ARMD Environmentally Responsible Aviation Program sponsored this work.

• Dr. Changlie Wey was the lead research engineer and provided the gas analysis results.
Questions?