NASA Low NOx Fuel Flexible Combustor
Technical Challenges
NASA Green Aviation Summit

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Chief of Combustion Branch
NASA Glenn Research Center

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NASA AMES
ERA/SFW System Level Metrics

**... technology for improving noise, emissions, & performance**

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional Configurations relative to 1998 reference</td>
<td>Unconventional Configurations relative to 1998 reference</td>
<td>Advanced Aircraft Concepts relative to user-defined reference</td>
</tr>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
<td>-71 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>Performance: Aircraft Fuel Burn</td>
<td>-33%**</td>
<td>-40%**</td>
<td>better than -70%</td>
</tr>
<tr>
<td>Performance: Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metro-plex* concepts</td>
</tr>
</tbody>
</table>

***Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

**Approach**
- Enable Major Changes in Engine Cycle/Airframe Configurations
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools & Processes
- Develop/Test/Analyze Advanced Multi-Discipline Based Concepts & Technologies
CAEP6  ICAO NOx Regulations for Engines

LTO (landing and take-off) NOx Regulations Relative to CAEP 6 (@ 30 OPR for Engines >89.0 KN of Thrust)

- GEnx -1B  55% below CAEP 6
- RR Trent 1000  ~50% below CAEP 6 (Predicted)
- PW 810  ~50% below CAEP 6 (Estimated)

N+1, FAA CLEEN  55%
N+2 Goal  55%

Year
Motivation for NOx Technology Investment

- Environmental impact
  - Ground level LTO NOx affects local air quality (NO2, ozone and secondary PM)
  - NOx above 3000 ft accounts for 92% of total mission
  - Cruise NOx affects climate and “global” air quality
- Stringency increase for LTO and enroute NOx policies expected
- Balances SFC improvements (OPR ↑) and traffic growth

NOx emissions vs. the Overall Pressure Ratio and SFC
Balanced Combustor Design

- Smoke
- Dynamics
- Reliability
- Durability
- Auto-ignition
- Fuel System
- Coking
- Alternative Fuels
- Cost
- Weight
- Lean Blow Out
- Pressure Drop
- Efficiency
- Profile/Pattern Factor
- Ground Start
- Altitude Relight
- Emissions
ERA Technology Focus

- Significant further NOx reduction
- Leaner combustion through reduced cooling
- Improved fuel-air mixer designs
- Active control strategies
- Advanced CMC liners
Emissions Reduction - Technology to Product Transition

**NASA Program**

- **Industry Product Integration**
  - Market conditions and available technology improvements determine opportunity to launch new product engine

**NASA Project**

- **Combustor**
  - **Flametube Combustor**
  - **Full Annular Combustor**
  - **Engine Integration**

- **Technology to Product Transition**
  - “Off-Ramp” for Technology
    - **Industry**
      - Scaling to product engine size
      - Production engine design
      - Durability testing
      - Transient testing (altitude/flying test-bed)
      - Inclement weather testing
      - Manufacturing processes and tooling
      - Certification
      - Product support

- **NASA Project will develop and demonstrate low emissions to a technology readiness level (TRL) 6**

- **Certification and Entry Into service**

**NASA and Industry Partnership for Low-Emission Combustor Technology Development Followed by Possible Industry Certification and Product Implementation**
Fuel Flexible/Low Emissions

Combustor Technical Challenges

• Injector/Mixer Design
• Active Combustion Control
• High Temperature Combustion Liner
Injector/Mixer Design Challenge
TAPS Fuel Staging Enables Low Nox at Cruise

NOx flight cycle comparison (GE TAPS vs. traditional RQL combustor)
75% Nox Reduction Injector Development

- Advanced Injector Concept
- Fuel/Air Mixing
- Ignition
## Fischer-Tropsch & Jet A Fuel Analysis

<table>
<thead>
<tr>
<th>Test</th>
<th>F-T</th>
<th>Jet A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Acid Number (mg KOH/g)</td>
<td>0.002</td>
<td>0.00</td>
</tr>
<tr>
<td>Aromatics (% vol)</td>
<td>0.0</td>
<td>19</td>
</tr>
<tr>
<td>Mercaptan Sulfur (% mass)</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Total Sulfur (% mass)</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>Distillation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Boiling Point (°C)</td>
<td>149</td>
<td></td>
</tr>
<tr>
<td>10% Recovered (°C)</td>
<td>162</td>
<td>180</td>
</tr>
<tr>
<td>20% Recovered (°C)</td>
<td>163</td>
<td></td>
</tr>
<tr>
<td>50% Recovered (°C)</td>
<td>168</td>
<td>212</td>
</tr>
<tr>
<td>90% Recovered (°C)</td>
<td>184</td>
<td>251</td>
</tr>
<tr>
<td>End Point (°C)</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>Residue (% vol)</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Loss (% vol)</td>
<td>0.4</td>
<td>0.9</td>
</tr>
<tr>
<td>Flash Point (°C)</td>
<td>44</td>
<td>51</td>
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<tr>
<td>API Gravity @ 60°F</td>
<td>60.5</td>
<td></td>
</tr>
<tr>
<td>Freezing Point (°C)</td>
<td>-55</td>
<td>-48</td>
</tr>
<tr>
<td>Viscosity @ -20°C (mm²/s)</td>
<td>2.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Net Heat of Combustion (MJ/kg)</td>
<td>44.2</td>
<td>42.8</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Test</th>
<th>F-T</th>
<th>Jet A</th>
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<tbody>
<tr>
<td>Hydrogen Content (% mass)</td>
<td>15.6</td>
<td>13.0</td>
</tr>
<tr>
<td>Smoke Point (mm)</td>
<td>40.0</td>
<td>21</td>
</tr>
<tr>
<td>Copper Strip Corrosion (2 h @ 100°C)</td>
<td>1a</td>
<td></td>
</tr>
<tr>
<td>Thermal Stability @ 260°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in Pressure (mmHg)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tube Deposit Rating, Visual</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Existent Gum (mg/100 mL)</td>
<td>&lt;1</td>
<td>0.2</td>
</tr>
<tr>
<td>Particulate Matter (mg/L)</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Filtration Time (min)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Water Reaction Interface Rating</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>FSII (% vol)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Conductivity (pS/m)</td>
<td>217</td>
<td>10</td>
</tr>
<tr>
<td>Lubricity Test (BOCLE) Wear Scar (mm)</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Net Heat of Combustion (MJ/kg)</td>
<td>44.0</td>
<td>43.2</td>
</tr>
<tr>
<td>Workmanship</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

### Workmanship
- F-T: Pass
- Jet A: Pass
Impact of fuel properties on emissions

Particulates
- Fuel carboning
- Fuel atomization

Aromatics content
- Spray evaporation
- Liner temperature
- Flame temperature

Sulfur content
- Gaseous, smoke, and particulate emissions

Viscosity
- Density
- Surface tension

Distillation profile
- Vapor pressure

Heat of combustion
- Smoke point
Fuel properties impact on atomization

- Notable expression for airblast atomizers is given by:
  \[
  \text{SMD} = (1 + \text{FAR}) (0.33 \left\{ \frac{\sigma}{\rho_A D_p U_A} \right\}^{0.6} \left\{ \frac{\rho_L}{\rho_A} \right\}^{0.1} + 0.068 \left\{ \frac{\mu_L^2}{\rho_L \sigma D_p} \right\}^{0.5}) D_h
  \]

- Notable expression for pressure swirl atomizers is given by:
  \[
  \text{SMD} = 2.25 (\sigma \cdot \mu_L \cdot W_L)^{0.25} \Delta P_L^{-0.5} \rho_A^{-0.25}
  \]
Alternative fuels density

- Density of JP-8 tested is close to mean value
- Both FT and HRJ fuels are below density specifications
## Additional key fuel

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Limits</th>
<th>MIL-DTL-83133F JP8</th>
<th>100% FT</th>
<th>100% HRJ</th>
<th>JP-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aromatics</td>
<td>%v/v</td>
<td>Max</td>
<td>25.0</td>
<td>0.6</td>
<td>0.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Specific energy (NHC)</td>
<td>MJ/kg</td>
<td>Min</td>
<td>42.8</td>
<td>44.3</td>
<td>44.3</td>
<td>43.5</td>
</tr>
<tr>
<td>Smoke point</td>
<td>mm</td>
<td>Min</td>
<td>25.0</td>
<td>50.0</td>
<td>&gt;40.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Hydrogen content</td>
<td>%w/w</td>
<td>Min</td>
<td>13.4</td>
<td>15.1</td>
<td>15.3</td>
<td>13.9</td>
</tr>
</tbody>
</table>

- HRJ has lowest aromatics and highest hydrogen content
- JP-8 has lowest specific energy, SP, and hydrogen content
F-T Fuel Analysis

5172 F-T Kerosene

Syntroleum 4909 S-8
Fischer-Tropsch & JP-8 Fuel Analysis
## JP8, 50-50 Blend, and FT-2 Comparisons

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>T3°F 1030°F</th>
<th>T3°F 850°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>JP8</td>
<td>Video Images, with flow from left to right</td>
<td></td>
</tr>
<tr>
<td>50-50 Blend</td>
<td>Video Images, with flow from left to right</td>
<td></td>
</tr>
<tr>
<td>FT-2</td>
<td>Video Images, with flow from left to right</td>
<td></td>
</tr>
</tbody>
</table>

Comparison showing average flame length and luminous intensity for T3 = 1030°F
Advanced Subsonic Combustor Rig (ASCR) Alternative Fuels Establishment (cont’d)
### EXISTING AND REVISED CONFIGURATIONS

<table>
<thead>
<tr>
<th></th>
<th>Existing ASCR Sector Rig Assembly 28470M43A000</th>
<th>Revised ASCR Sector Rig Assembly Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature @ Pressure</td>
<td>1100°F @ 600-psig</td>
<td>1300°F @ 900-psig</td>
</tr>
<tr>
<td>Flow Conditions</td>
<td>5 to 50 pound per second</td>
<td>5 to 50 pounds per second</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>30 to 900-psig</td>
<td>30 to 900-psig</td>
</tr>
<tr>
<td>Maximum Allowable Working</td>
<td>1100-psig</td>
<td>1100-psig</td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion Flow Temperature</td>
<td>3400°F</td>
<td>3400°F</td>
</tr>
<tr>
<td>Exhaust Flow Temperature</td>
<td>500°F</td>
<td>500°F</td>
</tr>
</tbody>
</table>
Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur

Closed-Loop Self-Excited System

Combustion Process \( \Phi' \) \( \rightarrow \) Combustor Acoustics \( P' \)

Fuel-air Mixture system

Natural feed-back process

Artificial control process

Actuator \( \rightarrow \) Controller \( \rightarrow \) Sensor
Active Combustion Instability Control Via Fuel Modulation

High-frequency fuel delivery system and models

Advanced control methods

Physics-based instability models

Realistic combustors, rigs for research

High-temperature sensors and electronics

Sensor and sub-package

Sensor slides into housing and locked in place.
High Temperature Combustor Liner Challenge

Issues for CMC Liner –

Durability –
Insufficient data – both long term coupon and relevant engine environment

*Mitigation* – In-house durability testing, coupon creep/fatigue/etc testing, HPBR, Subcomponent (NRA) testing.

Advanced Coatings – improved coating compositions, erosion, spallation, *repairability*

*Mitigation* - In-house research effort on advanced coatings, HPBR investigations, insufficient funds for repairability

Integration – Attachment design & fretting coatings

*Mitigation* - NRA for attachment design, in-house investigation in fretting coatings, coeff friction, various materials etc
Low NO$_x$, Fuel-Flexible Combustion System

**System Design**
- Systems modeling
  - Flexible fuel staging
  - Mission profiling for emissions management

**Multi-Discipline Capabilities**
- Combustion System Contributions
  - Improved thermal mgt
  - Light weight structures
- Materials Contributions
  - CMC combustor liners with reduced cooling
  - Improved high temperature durability

**Propulsion Contributions**
- Improved propulsion efficiency
- Higher thermal efficiency

**Combustion Contributions**
- Lower NOx Emissions
- Improved fuel-air mixing
- Advanced Active Controls
- Fuel Flexibility

**Discipline Level Capabilities**
- Experimental validation / verification
  - Emissions and atmospheric mixing sampling
  - In-flight measurement

**Advanced Aircraft Concept**
- Hybrid Wing-Body Aircraft
- GTF Engine

**Fundamental research**
- CFD modeling; improved diagnostics; experimental techniques; acoustics physics; materials, etc