Improving Engine Efficiency Through Core Developments

Dr. James Heidmann
Project Engineer for Propulsion Technology (acting)
Environmentally Responsible Aviation
Integrated Systems Research Program
## NASA’s Subsonic Transport System Level Metrics

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

<table>
<thead>
<tr>
<th>CORNERS OF THE TRADE SPACE</th>
<th>Technology Benefits Relative To a Single Aisle Reference Configuration</th>
<th>Technology Benefits Relative To a Large Twin Aisle Reference Configuration</th>
<th>Technology Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
<td>-71 dB</td>
</tr>
<tr>
<td>LTO NO$_x$ Emissions</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>(below CAEP 6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance: Aircraft Fuel Burn</td>
<td>-33%</td>
<td>-50%</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>

Goals are relative to reaching TRL 6 by the timeframe indicated.  
Engine core research primarily focused on fuel burn metric (SFC).  
Core developments have positive and negative impacts on NOx.
ADVANCED CONFIGURATION 

Advanced Configuration #1
N+2 “tube-and-wing”
2025 EIS (TRL=6 in 2020)

Fuel Burn = 159,500 lbs
(-43.0%)

Advanced Engines
Δ Fuel Burn = -15.3%

Advanced Engine
Δ Fuel Burn = -18.5%

Advanced Engines with BLI Inlets
Δ Fuel Burn = -3.2%

Embedded Engines with BLI Inlets
Δ Fuel Burn = -16.0%

Advanced Configuration #2A
N+2 HWB300
2025 EIS (TRL=6 in 2020)

Fuel Burn = 140,400 lbs
(-49.8%)

Advanced Engines
Δ Fuel Burn = -15.3%

Advanced Configuration #2B
N+2 HWB300
2025 EIS (TRL=6 in 2020 assuming accelerated technology development)

Fuel Burn = 128,500 lbs
(-54.1%)

Advanced Engines
Δ Fuel Burn = -16.0%

Embedded Engines with BLI Inlets
Δ Fuel Burn = -3.2%
Propulsion Technology Enablers

Fuel Burn - reduced SFC (increased BPR, OPR & turbine inlet temperature, potential embedding benefit)

\[
\text{Aircraft Range} = \frac{\text{Velocity}}{\text{TSFC}} \left( \frac{\text{Lift}}{\text{Drag}} \right) \ln \left( 1 + \frac{W_{\text{fuel}}}{W_{\text{PL}} + W_{\text{O}}} \right)
\]

- Engine Fuel Consumption
- Aerodynamics
- Empty Weight

\[
\text{TSFC} = \frac{\text{Velocity}}{(\eta_{\text{overall}})}(\text{fuel energy per unit mass})
\]

\[
\eta_{\text{overall}} = (\eta_{\text{thermal}})(\eta_{\text{propulsive}})(\eta_{\text{transfer}})(\eta_{\text{combustion}})
\]

\[
\eta_{th} = 1 - \left( \frac{p_2}{p_1} \right)^{\frac{1-\gamma}{\gamma}} \quad \text{assuming constant component efficiencies}
\]

Core research impacts thermal efficiency through increased OPR
High power density cores enable higher propulsive efficiency cycles
Low pressure turbine improvements impact transfer efficiency
Propulsion system improvements require advances in both propulsor and core technologies.
Cycle Performance Improves with Temperature
Engine Thermal Trends

From Dr. Toyoaki Yoshida, National Aerospace Laboratory, Japan
Increase in operational temperature of turbine components.
Turbine Cooling Improvements

Figure 1.2: Variation of turbine entry temperature over recent years (Clifford, 1985: AGARD CP 390; collected in Lakshminarayana, 1996).
Turbomachinery Aero Design-Based Tech Enablers

Highly-Loaded, Multistage Compressor (higher efficiency and OPR)

Low-Shock Design, High Efficiency, High Pressure Turbine

Aspiration Flow Controlled, Highly-Loaded, Low Pressure Turbine

Low Pressure Turbine Plasma Flow Control

High-Efficiency Centrifugal Compressor (small high efficiency core)

Novel Turbine Cooling Concepts
Objective: To produce benchmark quality validation test data on a state-of-the-art multi-stage axial compressor featuring swept axial rotors and stators. The test in ERB cell W7 will provide improved understanding of issues relative to optimal matching of highly loaded compressor blade rows to achieve high efficiency and surge margin.

Approach:
Test a modern high OPR axial compressor representative of the front stages of a commercial engine high pressure compressor in partnership with General Electric. Test will enable improved high OPR designs for reduced engine SFC.
UTRC NRA – High Efficiency Centrifugal Compressor (HECC)

**m = 10.1 lbm/s**

Opportunity for improved rotary wing vehicle engine performance as well as rear stages for high OPR fixed wing application

<table>
<thead>
<tr>
<th>Metric</th>
<th>CC3+ Iteration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>target</td>
</tr>
<tr>
<td>Stage Pr</td>
<td>4.0 - 5.0</td>
</tr>
<tr>
<td>Inlet Corrected Flow (lbm/s)</td>
<td>10.0</td>
</tr>
<tr>
<td>Exit Corrected Flow (lbm/s)</td>
<td>2.6 - 3.1</td>
</tr>
<tr>
<td>Work Factor (\frac{DH_0}{U_2})</td>
<td>0.58 - 0.7</td>
</tr>
<tr>
<td>Poly Eff TT</td>
<td>(\geq 88%)</td>
</tr>
<tr>
<td>T3 (°F)</td>
<td>350-410</td>
</tr>
<tr>
<td>Dmax/Dtip</td>
<td>1.45</td>
</tr>
<tr>
<td>Stability Margin</td>
<td>13%</td>
</tr>
<tr>
<td>M&lt;sub&gt;exit&lt;/sub&gt;</td>
<td>0.15</td>
</tr>
<tr>
<td>(\alpha_{exit})</td>
<td>15°</td>
</tr>
</tbody>
</table>

Engine scale polytropic efficiency is estimated as 87.9 - 88.9%
Turbine Film Cooling Experiments

Objective: Fundamental study of heat transfer and flow field of film cooled turbine components
Rationale: Investigate surface and flow interactions between film cooling and core flow for various large scale turbine vane models
Approach: Obtain detailed flow field and heat transfer data and compare with CFD simulations

**Trailing Edge Film Ejection:** IR images

**Large Scale Film Hole:** Film cooling jet downstream of hole

**Vane Heat Transfer:** Good agreement between GlennHT and experiment

**Streamwise Velocity (ft/s) at X=2.2 and X=5.28 from hole**
Anti-Vortex Film Cooling Concept

Comparison of round hole and “anti-vortex” turbine film cooling jet attachment

Auxiliary holes (yellow) produce counter-vorticity to promote jet attachment
Advantages: Inexpensive due to use of only round holes, hole inlet area unchanged
NASA/General Electric Highly-Loaded Turbine Tests

Turbine Testing in NASA Glenn Single Spool Turbine Facility (W6)

Unique High-Speed High Pressure Ratio Capability
NASA/General Electric Highly-Loaded Turbine Tests

Conventional HPT

Pressure Ratio (PTR/PS) = 3.25
Stage Pressure Ratio = 5.5

Reduced Shock Design

HPT: Reduced Shock Design
LPT: Flow-Controlled Stator & Contoured Endwall

Enables efficient high overall pressure ratio turbine capability with reduced cooling flow and reduced SFC
Dielectric Barrier Discharge Plasma Actuators

Low pressure turbine flow control – reduced weight and improved efficiency

Advantages of GDP actuators:

- Pure solid state device
- Simple, no moving parts
- Flexible operation, good for varying operating conditions
- Low power
- Heat resistance – w/ proper materials

Force Versus Pulse Repetition Rate & Bias

Princeton Nanosecond Pulsing NRA
Large force induced with voltage bias
CMC Engine Components Reduce Cooling Air Requirements

<table>
<thead>
<tr>
<th></th>
<th>Combustor</th>
<th>High Pressure Turbine</th>
<th>Low Pressure Turbine</th>
<th>Exhaust Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>2200-2700°F</td>
<td>2400-2700°F</td>
<td>2200-2300°F</td>
<td>1500-1800°F</td>
</tr>
<tr>
<td>CMC System</td>
<td>SiC / SiC</td>
<td>SiC / SiC</td>
<td>SiC / SiC</td>
<td>Oxide / Oxide</td>
</tr>
<tr>
<td>Engine Benefit</td>
<td>• Reduced cooling</td>
<td>• Reduced cooling</td>
<td>• Reduced cooling</td>
<td>• Light weight</td>
</tr>
<tr>
<td></td>
<td>• Reduced NOx</td>
<td>• Reduced SFC</td>
<td>• Strength / weight</td>
<td>• Noise reduction</td>
</tr>
<tr>
<td></td>
<td>• Pattern Factor</td>
<td></td>
<td></td>
<td>• Higher use temp</td>
</tr>
<tr>
<td>Challenges</td>
<td>• Durability</td>
<td>• Manufacturing</td>
<td>• Manufacturing</td>
<td>• Manufacturing</td>
</tr>
<tr>
<td></td>
<td>• Attachment &amp; Integration</td>
<td>• Durability</td>
<td>• Durability</td>
<td>• Durability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Attachment &amp; Integration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Prepreg lay-up assembly
- Hi-Nic type S fibers
- BN interface coatings
- Balanced ply lay-up
- 0/90° tapes
- Fiber volume ~ 28%

CVI SiC with MI SiC
- Hi-Nic Type S fibers
- CVI BN fiber coatings
- 5 harness satin weave
- Fiber volume ~ 35%

Durability comparison of candidate CMC material systems planned for 2011
CMC Nozzle Reduces Weight, Increases Temperature Capability, Potential Noise Benefit

- NASA teaming with Rolls Royce/LibertyWorks on CMC exhaust mixer nozzle development
- Subscale aero-rig component testing (<12” dia.)
- Example of a similar article fabricated by ATK COIC shown.
- Structural benchmark testing at NASA GRC, with stress & failure model validation to follow.

**18-inch dia. CMC Mixer Demonstration Article**

**CMC (Ceramic Matrix Composite)**
- ATK COIC Oxide/Oxide CMC: AS-N610 (Aluminosilicate matrix, Nextel 610 fabric reinforcement)
- Composition: 51% fiber, 24% matrix, 25% open porosity
Core Engine Research Summary

Core turbomachinery research directly impacts fuel burn reduction goals of ERA and other NASA Aeronautics projects

Compressor research focused on increasing overall pressure ratio while maintaining or improving aerodynamic efficiency

Turbine research focused on increased loading, reduced cooling flows, and improved aerodynamic efficiency

High OPR axial compressor testing with General Electric

Centrifugal compressor testing with United Technologies Research Center

Highly-loaded HPT testing with General Electric

Fundamental testing of turbine cooling flows and low pressure turbine flow control with universities and Department of Energy

Computational fluid dynamic development and assessment across all components, including advanced turbulence models such as LES and DNS