Summary of Wind Tunnel Tests and Vehicle Analysis for Open Rotor Propulsion Systems

Presentation to ICAO’s Noise Technology Independent Expert Panel
February 1, 2012

National Aeronautics and Space Administration
U.S.A.
Acknowledgements

General Electric/CFM International

NASA
  Subsonic Fixed Wing Project
  Environmentally Responsible Aviation Project
  Aeronautics Test Program
Arctic Slope Research Corporation

Federal Aviation Administration

Specific NASA Contributors:
  Aeropropulsion Division
  Structures and Materials Division
  Facilities Division
  Testing Division
Model Scale Open Rotor Wind Tunnel Tests
Objective: Explore the design space for lower noise while maintaining the high propulsive efficiency from a counter-rotating open rotor system.

Approach: A model scale, low-noise open rotor system was tested in collaboration with General Electric (GE) and CFM International. Candidate technologies for lower noise were investigated. Installation effects such as pylon integration were investigated in partnership with GE and the Federal Aviation Administration (FAA).

Gen-1 Blade Sets (NASA/GE)
- Historical Baseline
- Modern Baseline
- 4 Advanced Designs

Gen-2 Blade Sets (NASA/FAA/GE)
- 6 GE Advanced Designs
- Pylon wake mitigation

Historical Baseline (12 x 10 Blade Count)
History (1/3)

2009

<table>
<thead>
<tr>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Drive Rig Checkout</td>
<td>Sep 24 – Oct 27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Research Run</td>
<td>Oct 28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Influence Body Tests</td>
<td>Dec 14</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Linear Array Checkout</td>
<td>Dec 7-11</td>
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</table>

Drive Rig Rehab and Installation
## History (2/3) 2010

**Continued Influence Body Tests Concluded – Apr 28**

**Flow Measurements**
- Jul 19 – Sep 7

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
</table>

**Drive Rig Muffler Implementation**

**NASA Glenn Annual Facility Shutdown**

**Open Rotor Installed in the 8x6 Wind Tunnel**

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History (3/3) 2011

8x6 Tare Runs
Feb 9

Gen-1 8x6 Test
Feb 28 – Aug 25

Gen-2 8x6 Test
Aug 26 – Sep 9

Gen-2 9x15 Test
Nov 10 – Jan 18

Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec

Diagnostic Tests

Jan. 18, 2012
End of Gen-2 Test

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Flow Measurements & Diagnostic Tests

The 3D PIV measurements provide a wealth of information about the blade wakes and vortex track.

A canonical Shielding configuration provides code validation data.

The location of peak noise level in the Phased Array map changes in the presence of the CFMI pylon indicating a change in the relative strength of sources.

The Pressure Sensitive Paint measurements show phase locked static pressure on the surface of the rotating blade.
Systems Analysis Results of an Open Rotor Propulsion System on an Advanced Single Aisle Transport
Background

• NASA’s systems analysis team has been investigating potential environmental benefits of advanced propulsion systems on “Advanced” Single Aisle aircraft
  – Direct Drive
  – Geared Turbofan
  – Open Rotor

• Open Rotor assessment is joint effort between NASA’s Subsonic Fixed Wing (SFW) & Environmentally Responsible Aviation (ERA) projects
  – SFW had FY11 milestone to assess fuel burn/noise characteristics of an open rotor propulsion system
  – ERA measured advanced open rotor blade performance/acoustic data

• ERA funded task with General Electric was conduit to NASA/industry partnership
  – Enabled NASA access to data for use in system assessment
  – Allowed coordination with industry on modeling approaches/technical assumptions
Historical Look at Propulsion Studies

- NASA has been conducting an on-going engine trade study to assess propulsion options for advanced single-aisle (B737/A320 class) aircraft
  - Multi-year, Multi-phase effort
  - Initial focus on ultra-high bypass ratio (UHB) turbofan concepts, followed by investigation of open-rotor engine architectures
  - Multiple interactions with industry over the years to obtain feedback
  - Numerous technical reports and conference papers produced, plus 1 journal article

UHB Phase I: Initial Feasibility Study
UHB Phase II: Engine Trade Study
UHB Phase IIb: Expanded/Refined Trade Study
Presentation at FAP Meeting
Results reviewed with P&W
Results reviewed with P&W
Detailed exchange w/ P&W
UHB Phase IIc/IId: Refinement to select IIb engines
NASA TM (UHB IIb)
FAP
NASA TM (UHB IId)
AIAA ATIO (UHB IIb)
Detailed exchange w/ P&W
AIAA Acoustics (UHB IIb)
Review w/ Williams
AIAA Acoustics (UHB IId)
Open Rotor (OR): Initial Feasibility Study
ISABE (OR)
ASME Turbo Expo (OR)
OR Results reviewed with GE
AIAA ATIO (OR)
AIAA ATIO (UHB IId)
NASA TM (UHB IId)
Presentation at FAP Meeting
J. Aircraft (UHB IId)
Open Rotor Cycle Model (NASA Notional Engine)

- A complete Numerical Propulsion System Simulation (NPSS) model was created for a geared, pusher open rotor engine.
- Core component performance assumptions are similar to those used in a recent NASA advanced turbofan study.
- Counter-rotating propeller data from a favored Gen-1 rotor set was used to create performance maps.

NPSS component block diagram

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC</td>
<td>Pressure Ratio</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Adiabatic Efficiency (%)</td>
<td>89.6</td>
</tr>
<tr>
<td>HPC</td>
<td>Pressure Ratio</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>Adiabatic Efficiency (%)</td>
<td>88.6</td>
</tr>
<tr>
<td>HPT</td>
<td>Adiabatic Efficiency (%)</td>
<td>91.9</td>
</tr>
<tr>
<td>LPT</td>
<td>Adiabatic Efficiency (%)</td>
<td>94.2</td>
</tr>
<tr>
<td>Power Turbine</td>
<td>Adiabatic Efficiency (%)</td>
<td>94.0</td>
</tr>
<tr>
<td>Counter-Rotating</td>
<td>Net Efficiency (%)</td>
<td></td>
</tr>
<tr>
<td>Rotating Propellers</td>
<td>Front Tip Speed (ft/s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Loading (shp/ft^2)</td>
<td></td>
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</table>

Proprietary Data
# Open Rotor Engine Performance

<table>
<thead>
<tr>
<th>Flight Condition</th>
<th>Engine Performance Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Climb (M0.78, 35kft)</td>
<td>Net Thrust (lbf)</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>TSFC (lbm/hr/lbf)</td>
<td>0.428</td>
</tr>
<tr>
<td></td>
<td>OPR</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>OR Advance Ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR Power Coefficient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR Thrust Coefficient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR Net Efficiency (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Proprietary Data</strong></td>
<td></td>
</tr>
<tr>
<td>Rolling Takeoff (M0.25, 0 ft, +27F)</td>
<td>Net Thrust (lbf)</td>
<td>19,000</td>
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<tr>
<td></td>
<td>TSFC (lbm/hr/lbf)</td>
<td>0.229</td>
</tr>
<tr>
<td></td>
<td>OPR</td>
<td>28.5</td>
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<tr>
<td></td>
<td>OR Advance Ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR Power Coefficient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR Thrust Coefficient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OR Net Efficiency (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Proprietary Data</strong></td>
<td></td>
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<tr>
<td>Sea Level Static (M0.0, 0 ft, +27F)</td>
<td>Net Thrust (lbf)</td>
<td>27,300</td>
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<td></td>
<td>TSFC (lbm/hr/lbf)</td>
<td>0.158</td>
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<tr>
<td></td>
<td>OPR</td>
<td>29.4</td>
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<td></td>
<td>OR Advance Ratio</td>
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<tr>
<td></td>
<td>OR Power Coefficient</td>
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</tr>
<tr>
<td></td>
<td>OR Thrust Coefficient</td>
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<tr>
<td></td>
<td><strong>Proprietary Data</strong></td>
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</tr>
</tbody>
</table>
Engine Flowpath and Weight

- Key cycle parameters passed to flowpath tool (WATE++) to calculate engine core weight
- Turbomachinery aeromechanical limits and materials consistent with those of previous N+1 turbofan studies
- Propeller weight estimates derived from data developed during the Advanced Turboprop Project in the 1980’s
- Gearbox (6:1 gear ratio) weight derived from NASA gearbox weight model (based on actual gearbox weight data from over fifty rotorcraft, tiltrotors, and turboprop aircraft).

Weights and Dimensions

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Rotor Weight (lbf)</td>
<td>3244</td>
</tr>
<tr>
<td>Gearbox Weight (lbf)</td>
<td>1028</td>
</tr>
<tr>
<td>Total Engine Pod Weight (lbf)</td>
<td>9219</td>
</tr>
<tr>
<td>Propeller Diameter (ft)</td>
<td>13.76</td>
</tr>
<tr>
<td>Nacelle Diameter (ft)</td>
<td>5.6</td>
</tr>
<tr>
<td>Overall Length (ft)</td>
<td>23.2</td>
</tr>
</tbody>
</table>
**Airframe Modeling and Analysis**

**Study Mission Requirements**

- Composite structures
- Variable camber TE
- 5000 psi hydraulics

**MD-90-30 Like Model**
- Improve Wing Aerodynamics
- Lengthen Fuselage for 162 Passengers
- Resize for 3250 nm Mission

**CSAT-re**
- Advanced Airframe Technology Assumptions

**ASAT-re**
- Open Rotor Airframe Impacts

**MD92V Model**
- 1980s concepts with V2500 & GE36

**MD92 Model**
- Calibrated to publicly available weight and performance data

**MD80 technology to 737NG-like performance**

**Nomenclature**
- CSAT: Current technology Single-Aisle Transport
- ASAT: Advanced technology Single-Aisle Transport
- re – rear engine
- or – open rotor

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NASA Open Rotor Airplane

See AIAA-2011-7058 for airplane design details
## Results (System Performance)

- Engine models combined with airframe models

<table>
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</thead>
<tbody>
<tr>
<td>Engine: MD90-30like</td>
<td>2040</td>
<td>V2525-D5</td>
<td>1.00</td>
<td>1278</td>
<td>122</td>
<td>25033</td>
<td>1.01</td>
<td>1530</td>
<td>115</td>
<td>25195</td>
<td>0.760</td>
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<tr>
<td>CSAT-re</td>
<td>3250</td>
<td>V2525-D5</td>
<td>0.321</td>
<td>1278</td>
<td>122</td>
<td>25033</td>
<td>0.780</td>
<td>1530</td>
<td>115</td>
<td>25195</td>
<td>0.780</td>
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<tr>
<td>ASAT-re</td>
<td>3250</td>
<td>Adv. GTF</td>
<td>0.321</td>
<td>1278</td>
<td>122</td>
<td>25033</td>
<td>0.312</td>
<td>1240</td>
<td>119</td>
<td>25195</td>
<td>0.312</td>
</tr>
<tr>
<td>ASAT-or</td>
<td>3250</td>
<td>Geared OR</td>
<td>0.321</td>
<td>1278</td>
<td>122</td>
<td>25033</td>
<td>0.356</td>
<td>1250</td>
<td>121</td>
<td>25195</td>
<td>0.356</td>
</tr>
</tbody>
</table>

| Block Fuel | lb | 29410 | 140543 | 14711 | 12.59 |
| Block NOX | lb | 27.59 | 146252 | 13205 | 27.77 |
| LTO NOX | lb/cycle | 27.59 | 126064 | 9648 | 9.96 |

### Advanced Geared Turbofan (GTF)
(fan pressure ratio = 1.5)

### Nomenclature
CSAT: Current technology Single-Aisle Transport
ASAT: Advanced technology Single-Aisle Transport
re – rear engine
or – open rotor

### Active Sizing Constraint

<table>
<thead>
<tr>
<th>Economic Mission: 1000 nm,</th>
<th>Ramp Weight</th>
<th>Block Fuel</th>
<th>Block NOX</th>
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</thead>
<tbody>
<tr>
<td>lb</td>
<td>140543</td>
<td>14711</td>
<td>120.17</td>
</tr>
<tr>
<td>lb</td>
<td>146252</td>
<td>13205</td>
<td>114.86</td>
</tr>
<tr>
<td>lb</td>
<td>126064</td>
<td>9648</td>
<td>90.52</td>
</tr>
<tr>
<td>lb</td>
<td>131868</td>
<td>8229</td>
<td>75.95</td>
</tr>
</tbody>
</table>
Relative Improvements

- **ASAT relative to 1990s technology…**
  - Empty Weight: -16%(GTF); -7%(OR)
  - Gross Weight: -16%(GTF); -14%(OR)
  - Block Fuel: -27%(GTF); -36%(OR)
  - Total NOₓ: -30%(GTF); -26%(OR)
  - LTO NOₓ: -64%(GTF); -77%(OR)

- **Open rotor relative to advanced turbofan…**
  - Empty Weight: +10%
  - Gross Weight: +2%
  - Block Fuel: -12%
  - Total NOₓ: +5%
  - LTO NOₓ: -36%
Acoustic Data Processing Steps

1. Measured, narrowband spectral densities
2. Convert to flight conditions
3. Source strength corrections

Model scale to full scale

\[ \Delta \text{Amplitude} = 10 \log[\text{Area Scale Factor}] \]

freq shift = Linear scale factor

Convert narrowband to 1/3\(^{rd}\) octave band

IEC 225-1966 band filter

Aircraft system noise prediction (ANOPP)

Spectral basis for Part 36 Noise Certification
Part 36 Noise Certification

- Aircraft Noise Prediction Program (ANOPP)
- Source noise modeling: User-supplied
- Trajectory simulation
- Spectra propagation (spreading, atmospheric and lateral attenuation, ground effects, reflections)
- Frequency and Noy-scale integration
- Tonal content penalties
- Ground observer noise-time history

Noise certification points:
- Lateral (sideline)
- Flyover (with cutback)
- Approach

Observer PNLT (PNdB) vs. Observer Time (s)

Time integration to Effective Perceived Noise Level
Trajectory Modeling

- Open rotor propulsion system and airplane performance modeled
- Detailed takeoff and landing trajectory analysis using Flight Optimization System performance code
Impact of AoA and Pitch on Flyover EPNL

Sources modeled:
Open rotor, core, core jet, flaps, trailing edge
Rotor Inflow Angle and Airplane Angle of Attack

- Rotor inflow angle ($\alpha_{\text{inflow}}$) is needed to infer the correct rotor noise from wind tunnel data.
- Vortex-lattice code analysis used to determine relationship of open rotor inflow angle to airplane angle of attack ($\alpha$).
- Nose-up engine mounting angle ($\alpha_{\text{Cant}} = 2$ deg, re clean airplane waterline) gives $\alpha_{\text{inflow}} = 0$ at cruise.
- Downwash angle into rotor at $\alpha = 0$ ($\varepsilon_0$) and $d\varepsilon/d\alpha$ are functions of airplane configuration (i.e., $C_L$ with flaps/slats degree of extension).
  - $\alpha_{\text{inflow}} = \alpha_{\text{Cant}} - \varepsilon_0 + \alpha \left[ 1 - \frac{d\varepsilon}{d\alpha} \right]$

Departure:
- $d\varepsilon/d\alpha = 0.336$
- $\varepsilon_0 = 2.342$ deg
- $\alpha \approx 7$ deg
- $\alpha_{\text{inflow}} \approx 4$ deg

Approach:
- $d\varepsilon/d\alpha = 0.349$
- $\varepsilon_0 = 5.194$ deg
- $\alpha \approx 7$ deg
- $\alpha_{\text{inflow}} \approx 1.5$ deg
## Gen-1 Rotor Noise Estimate

**13.67 foot diameter rotor**

<table>
<thead>
<tr>
<th></th>
<th>Approach</th>
<th>Lateral</th>
<th>Flyover</th>
<th>Cumulative</th>
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<tbody>
<tr>
<td>Isolated</td>
<td>88.8</td>
<td>88.2</td>
<td>80.1</td>
<td>257.1</td>
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<tr>
<td>AoA Effects</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>3.5</td>
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<tr>
<td>Flight Mach Effects</td>
<td>0.1</td>
<td>1.2</td>
<td>1.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Pylon Effects†</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Mitigation‡</td>
<td>-1.4</td>
<td>-0.7</td>
<td>-1.4</td>
<td>-3.5</td>
</tr>
<tr>
<td>Overall</td>
<td>90.0</td>
<td>91.2</td>
<td>83.5</td>
<td>264.7</td>
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<tr>
<td>Stage 3 Rule**</td>
<td>100.3</td>
<td>96.5</td>
<td>91.0</td>
<td>287.8</td>
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<tr>
<td>Stage 3 Margin</td>
<td>-10.3</td>
<td>-5.3</td>
<td>-7.6</td>
<td>-23.1</td>
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<tr>
<td>Stage 4 Margin</td>
<td></td>
<td></td>
<td></td>
<td>-13.1</td>
</tr>
</tbody>
</table>

†Estimated from F31/A31 data
‡Assumed “70%” reduction of the pylon penalty
**Rule based on NASA’s 151.3 klb airplane

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NASA Study Results – Fuel Burn vs. Noise

NASA modern airplane:
- 15% structural weight reduction from composites
- 5000psi hydraulic systems
- 1% drag reduction from drag cleanup and variable trailing edge
- Open rotor version has +2100lbs weight penalty

Advanced UHB Turbofan
- Fuel burn: 27%
- Noise: 25 dB cum margin to CH4

Open Rotor (modern blade set)
- Fuel burn: 36%
- Noise: 13 dB cum margin to CH4

NASA modern airplane
- 162 pax, 3250nm mission
- Cruise M= 0.78, 35kft
- Rear mount Turbofan

1998 technology reference vehicle
- 162 pax, 3250nm mission

% Fuel Burn Benefit

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Relationship to Prior UHB Study

**Calibration Model**
- **737-800 Like Model**
  - calibrated to publicly available weight and performance data, and proprietary aerodynamic data;
  - $M=0.785$, 3060 nm

**Baseline Model**
- **CSAT (CFM56-7B-Like)**
  - resized for 3250 nm; $M=0.80$ cruise
  - (Block Fuel = 42,605 lb)

**Adv. GTF Model**
- **ASAT (P1IdS2;Hi-g-1.5)**
  - advanced airframe; advanced FPR=1.5 GTF; $M=0.80$
  - (Block Fuel = 30,420 lb)

**Adv. OR Model**
- **ASAT-re (P1IdS2;Hi-g-1.5)**
  - advanced airframe; advanced FPR=1.5 GTF; $M=0.78$
  - (Block Fuel = 30,396 lb)

**MD90-30 Like Model**
- calibrated to publicly available weight and performance data;
  - $M=0.76$, 2040 nm

**CSAT-re (V2525-D5-Like)**
- approx. updated wing aero, stretch fuselage, resized for 3250 nm; $M=0.78$ cruise
  - (Block Fuel = 41,550 lb)

**ASAT-re**
- (Block Fuel = 26,709 lb)

**ASAT-or**
- advanced airframe; advanced open rotor engine; $M=0.78$