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

Drive Rig Rehab and Installation

First Research Run  
Oct 28

Influence Body Tests  
Dec 14

<table>
<thead>
<tr>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
</table>
| Drive Rig Checkout  
Sep 24 – Oct 27 |
| Linear Array Checkout  
Dec 7-11 |
**History (2/3)**

2010

<table>
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<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>
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<tbody>
<tr>
<td>Continued Influence Body Tests Concluded – Apr 28</td>
<td>Flow Measurements Jul 19 – Sep 7</td>
<td></td>
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</table>

Drive Rig Muffler Implementation

NASA Glenn Annual Facility Shutdown

Open Rotor Installed In the 8x6 Wind Tunnel

Approved for Public Release
History (3/3)

2011

<table>
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<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>
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</tbody>
</table>

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

Diagnostic Tests

Jan. 18, 2012
End of Gen-2 Test

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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
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

### Component Parameters

<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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Counter-Rotating Propellers</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Efficiency (%)</td>
<td>Front Tip Speed (ft/s)</td>
<td>Proprietary Data</td>
</tr>
<tr>
<td>Power Loading (shp/ft²)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Open Rotor Engine Performance

<table>
<thead>
<tr>
<th>Flight Condition</th>
<th>Engine Performance Parameter</th>
<th>Value</th>
</tr>
</thead>
</table>
| Top of Climb (M0.78, 35kft)      | Net Thrust (lbf)  
TSFC (lbm/hr/lbf)  
OPR  
OR Advance Ratio  
OR Power Coefficient  
OR Thrust Coefficient  
OR Net Efficiency (%)       | 5000  
0.428  
42.0 | Proprietary Data |
| Rolling Takeoff (M0.25, 0 ft, +27F) | Net Thrust (lbf)  
TSFC (lbm/hr/lbf)  
OPR  
OR Advance Ratio  
OR Power Coefficient  
OR Thrust Coefficient  
OR Net Efficiency (%)       | 19,000  
0.229  
28.5 | Proprietary Data |
| Sea Level Static (M0.0, 0 ft, +27F) | Net Thrust (lbf)  
TSFC (lbm/hr/lbf)  
OPR  
OR Advance Ratio  
OR Power Coefficient  
OR Thrust Coefficient       | 27,300  
0.158  
29.4 | Proprietary Data |
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 (lbm)</td>
<td>3244</td>
</tr>
<tr>
<td>Gearbox Weight (lbm)</td>
<td>1028</td>
</tr>
<tr>
<td>Total Engine Pod Weight (lbm)</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

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

1980s concepts with V2500 & GE36
NASA Open Rotor Airplane

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

- Engine models combined with airframe models

<table>
<thead>
<tr>
<th>Airframe: MD90-30like</th>
<th>CSAT-re</th>
<th>ASAT-re</th>
<th>ASAT-or</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine: V2525-D5</td>
<td>V2525-D5</td>
<td>Adv. GTF</td>
<td>Geared OR</td>
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**Design Mission:**

<table>
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<tr>
<th>Design Mission Range</th>
<th>nm</th>
<th>2040</th>
<th>3250</th>
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<tbody>
<tr>
<td>OWE</td>
<td>lb</td>
<td>88162</td>
<td>94450</td>
<td>79646</td>
<td>87817</td>
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<tr>
<td>Mission Fuel</td>
<td>lb</td>
<td>36825</td>
<td>49164</td>
<td>35803</td>
<td>31056</td>
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<tr>
<td>Passengers</td>
<td></td>
<td>158</td>
<td>162</td>
<td>162</td>
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<tr>
<td>Payload</td>
<td>lb</td>
<td>31000</td>
<td>32400</td>
<td>32400</td>
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<tr>
<td>Ramp Weight</td>
<td>lb</td>
<td>155987</td>
<td>176014</td>
<td>147849</td>
<td>151273</td>
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<tr>
<td>Wing Area</td>
<td>ft²</td>
<td>1278</td>
<td>1530</td>
<td>1240</td>
<td>1250</td>
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<tr>
<td>W/S</td>
<td>lb/ft²</td>
<td>122</td>
<td>115</td>
<td>119</td>
<td>121</td>
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<tr>
<td>Thrust(SLS)</td>
<td>lb</td>
<td>25033</td>
<td>25195</td>
<td>23075</td>
<td>26914</td>
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<tr>
<td>Engine scale factor</td>
<td></td>
<td>1.00</td>
<td>1.01</td>
<td>0.99</td>
<td>0.99</td>
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<tr>
<td>T/W</td>
<td></td>
<td>0.321</td>
<td>0.286</td>
<td>0.312</td>
<td>0.356</td>
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<tr>
<td>Cruise Mach</td>
<td></td>
<td>0.760</td>
<td>0.780</td>
<td>0.780</td>
<td>0.780</td>
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<tr>
<td>~Cruise L/D</td>
<td></td>
<td>14.0</td>
<td>17.0</td>
<td>16.2</td>
<td>16.6</td>
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<tr>
<td>~Cruise SFC</td>
<td>lb/(lb-h)</td>
<td>0.601</td>
<td>0.603</td>
<td>0.494</td>
<td>0.432</td>
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<tr>
<td>Land field length</td>
<td>ft</td>
<td>5527</td>
<td>5802</td>
<td>5944</td>
<td>6006</td>
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<tr>
<td>T.O. field length</td>
<td>ft</td>
<td>7000</td>
<td>7000</td>
<td>6996</td>
<td>6262</td>
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<tr>
<td>Block Fuel</td>
<td>lb</td>
<td>29410</td>
<td>41550</td>
<td>30396</td>
<td>26710</td>
</tr>
<tr>
<td>Block NOX</td>
<td>lb</td>
<td>217.18</td>
<td>292.38</td>
<td>205.16</td>
<td>215.73</td>
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<tr>
<td>LTO NOX</td>
<td>lb/cycle</td>
<td>27.59</td>
<td>27.77</td>
<td>9.96</td>
<td>6.41</td>
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**Active Sizing Constraint**

<table>
<thead>
<tr>
<th>Takeoff Performance</th>
<th>Takeoff Performance, ICAC</th>
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</thead>
<tbody>
<tr>
<td>Ramp Weight</td>
<td>lb</td>
</tr>
<tr>
<td>Block Fuel</td>
<td>lb</td>
</tr>
<tr>
<td>Block NOX</td>
<td>lb</td>
</tr>
</tbody>
</table>

**Economic Mission: 1000 nm,**

- Engine models combined with airframe models

**Nomenclature**

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

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

Advanced Geared Open Rotor (OR)
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 NO\textsubscript{X}: -30%(GTF); -26%(OR)
  - LTO NO\textsubscript{X}: -64%(GTF); -77%(OR)

- Open rotor relative to advanced turbofan…
  - Empty Weight: +10%
  - Gross Weight: +2%
  - Block Fuel: -12%
  - Total NO\textsubscript{X}: +5%
  - LTO NO\textsubscript{X}: -36%
Acoustic Data Processing Steps

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

Model scale to full scale

ΔAmplitude = 10 log[Area Scale Factor]
freq shift = Linear scale factor

Convert narrowband to 1/3rd octave band

IEC 225-1966 band filter

Aircraft system noise prediction (ANOPP)

Spectral basis for Part 36 Noise Certification

Data with Facility Noise Removed
Brought to Simulated Flight Conditions
Scaled to Full Size

SPL, dB
Frequency, Hz

Processed and Scaled Narrowband
Processed and Scaled 1/3rd Octave Band

Measured, narrowband spectral densities

Spectral basis for Part 36 Noise Certification

Includes:
- SAE 866 absorption
- Spherical spreading
- Ground reflections
- Other sources

ΔAmplitude = 10 log[Area Scale Factor]
freq shift = Linear scale factor

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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

![Diagram showing noise certification points and time integration to Effective Perceived Noise Level](image)

Observer PNLT (PNdB)

<table>
<thead>
<tr>
<th>Time integration to Effective Perceived Noise Level</th>
<th>Lateral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer Time (s)</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>95</td>
<td>95</td>
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<td>90</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
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</table>
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).
- $\alpha_{\text{inflow}} = \alpha_{\text{Cant}} - \varepsilon_0 + \alpha \left[ 1 - d\varepsilon/d\alpha \right]$

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>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isolated</strong></td>
<td>88.8</td>
<td>88.2</td>
<td>80.1</td>
<td>257.1</td>
</tr>
<tr>
<td><strong>AoA Effects</strong></td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Flight Mach Effects</strong></td>
<td>0.1</td>
<td>1.2</td>
<td>1.3</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Pylon Effects</strong>†</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Mitigation</strong>‡</td>
<td>-1.4</td>
<td>-0.7</td>
<td>-1.4</td>
<td>-3.5</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td>90.0</td>
<td>91.2</td>
<td>83.5</td>
<td>264.7</td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td><strong>Stage 3 Rule</strong>**</td>
<td>100.3</td>
<td>96.5</td>
<td>91.0</td>
<td>287.8</td>
</tr>
<tr>
<td><strong>Stage 3 Margin</strong></td>
<td>-10.3</td>
<td>-5.3</td>
<td>-7.6</td>
<td>-23.1</td>
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<tr>
<td><strong>Stage 4 Margin</strong></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

1% drag reduction from drag cleanup and variable trailing edge

N+1 Tech
UHB TF
BPR ~14

N+1 Tech
Open Rotor
BPR >30

% Fuel Burn Benefit

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## Relationship to Prior UHB Study

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Model Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration Model</td>
<td>737-800 Like Model&lt;br&gt;calibrated to publicly available weight and performance data, and proprietary aerodynamic data; M=0.785, 3060 nm</td>
</tr>
<tr>
<td>Baseline Model</td>
<td>CSAT (CFM56-7B-Like)&lt;br&gt;resized for 3250 nm; M=0.80 cruise (Block Fuel = 42,605 lb)</td>
</tr>
<tr>
<td>Adv. GTF Model</td>
<td>ASAT (P1ldS2;Hi-g-1.5)&lt;br&gt;advanced airframe; advanced FPR=1.5 GTF; M=0.80 (Block Fuel = 30,420 lb)</td>
</tr>
<tr>
<td>Adv. OR Model</td>
<td>MD90-30 Like Model&lt;br&gt;calibrated to publicly available weight and performance data; M=0.76, 2040 nm</td>
</tr>
<tr>
<td></td>
<td>CSAT-re (V2525-D5-Like)&lt;br&gt;approx. updated wing aero, stretch fuselage, resized for 3250 nm; M=0.78 cruise (Block Fuel = 41,550 lb)</td>
</tr>
<tr>
<td></td>
<td>ASAT-re (P1ldS2;Hi-g-1.5)&lt;br&gt;advanced airframe; advanced FPR=1.5 GTF; M=0.78 (Block Fuel = 30,396 lb)</td>
</tr>
<tr>
<td></td>
<td>ASAT-or&lt;br&gt;advanced airframe; advanced open rotor engine; M=0.78 (Block Fuel = 26,709 lb)</td>
</tr>
</tbody>
</table>