The Environmentally Responsible Aviation (ERA) Project – A technology development project

Dr. Dale Van Zante
Former ERA Project Engineer for Propulsion
NASA Glenn Research Center

Currently, Technical Lead for Aircraft Noise Reduction
Advanced Air Transport Technology Project

Fayette Collier, Ph.D., M.B.A.
Former ERA Project Manager
NASA Langley Research Center

Currently, Associate Director for Flight Strategy
Integrated Aviation Systems Program
New Aviation Horizons

Turbine Engine Technology Symposium
Dayton, OH
September 2016
NASA Aeronautics Six Strategic Thrusts
ERA - Ultra Efficient Commercial Vehicles

6 Strategic Research and Technology Thrusts

Safe, Efficient Growth in Global Operations
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft
- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance
- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications

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Grand Challenge for Commercial Aviation (1 of 2)
Reduce carbon footprint by 50 percent by 2050

...

.... in the face of increasing demand, and while reducing development, manufacturing and operational costs of aircraft & meeting noise and LTO NOx regulations

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Grand Challenge for Commercial Aviation (2 of 2)
Contain objectionable noise within airport boundary

Change in noise “footprint” area (within 85 dB) for a landing and takeoff

Contour area for aircraft meeting the Stage 4 rule
N: Stage 4 - 10dB CUM (= to 777 cert level)
Area-SEL = 49.5%

HWB N+2:
(Stage 4 – 42 EPNdB)
Area-SEL = 10.4%

80% Reduction in Noise Footprint Area

• All contours are for a 777-like aircraft weight and mission, N+2 achieved with HWB aircraft for same 777-like mission

• N and N+2 areas are rigorous predictions using analytical tool (ANOPP) with measurements for key installation effects

• Stage 4 and N+1 areas are computed from N aircraft to meet required EPNL
  • Source levels changed, assumed even distribution between three certification points

• Effects of source component directivity and aircraft configuration are included.

• Auralizations of ANOPP predictions for straight and level flight at conditions of takeoff and approach

N+1: Stage 4 – 32 EPNdB
Area-SEL = 13.2%

Stage 4 – 16.2dB CUM (= to 787 cert level)
Area-SEL = 38.8%


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Environmentally Responsible Aviation
Vision, Mission, & Scope

• Vision
  – expand the viable and well-informed trade space for commercial transport design decisions
  – enable *simultaneous* realization of national noise, emissions, and performance goals (N+2 timeframe)

• Mission
  – Execute integrated technology demonstrations
  – Partner w/Industry/Academia/OGA and transfer knowledge

• Scope
  – Mature technology for application in the 2020+ time frame
    • Advance the state-of-the-art, reduce risk of application
  – Perform system/subsystem research in relevant environments
Environmentally Responsible Aviation Project Flow

- FY09: Prior Research
- FY10: Formulation
- FY11: Phase 1 Investigations
- FY12: Adv. Vehicle Concept Study
- FY13: Phase 2 Planning
- FY14: Integrated Technology Demonstrations (ITD)
- FY15:

- $65.1M
- $74.2M
- $70.5M
- $70.1M
- $69.7M

Technical input from Fundamental Programs, NRAs, Industry, Academia, Other Gov’t Agencies

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Open Rotor technologies were studied during ERA Phase 1 in partnership with GE and FAA. (Aeronautical Journal, Oct 2014)

CMC mixer nozzle work in ERA Phase 1 in partnership with Rolls-Royce and AFRL.

+ CMC turbine vanes, CMC combustor liner, active combustion control, lean direct injection, boundary layer ingesting propulsor.
Noise measurements were obtained from Tower and Truss microphones, and from Microphone Phased Array at key streamwise locations.
HWB AIRFRAME MODEL

- 5.8% scale (12.35 ft span)
- Modular components (control surfaces and landing gear)
- High fidelity of geometric details
- Designed by a team led by Boeing under a NASA Research Announcement

Detailed characterization of:
- Jet noise and its shielding
- Airframe noise
- Broadband noise shielding
Measuring Progress in ERA Phase 2
Goal Decomposition and Technology Selection

2025 Vehicle System Level Goals

Technical Challenge

Progress Indicators

P2 Integrated Technology Demonstrations (TRL 4-6)

- Fuel Burn -50%
- NO\textsubscript{x} -75%
- Noise -42EPNdB

Technical Challenge Progress Indicators

TC 1: 8% Drag Reduction
TC 2: 10% Structural Weight Reduction
TC 3: 15% TSFC and 15 EPNdB Noise Reduction
TC 4: 75% LTO NOx Reduction
TC 5: 42 EPNdB Cum Noise Reduction and 50% Fuel Burn Reduction

Advanced Composites

- Innovative Flow Control Concepts
- Advanced UHB Engines
- Advanced Combustors
- Airframe & Engine Integration

KPP\textsuperscript{2025}

- Cruise Drag Reduction
- Structural Weight Reduction
- Wing Weight Reduction
- TSFC
- TSFC
- LTO NOx
- Airframe Component Noise Reduction
- Fuel Burn Reduction
- Cumulative Noise Reduction

ERA Technology Development & Maturation Plans – Phase 1 and 2

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Technical Challenges

**Innovative Flow Control Concepts for Drag Reduction**
- Demonstrate drag reduction of 8 percent, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, without significant penalties in weight, noise, or operational complexity

**Advanced Composites for Weight Reduction**
- Demonstrate weight reduction of 10 percent compared to SOA composites, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while enabling lower drag airframes and maintaining safety margins at the aircraft system level

**Advanced UHB Engine Designs for Specific Fuel Consumption and Noise Reduction**
- Demonstrate UHB efficiency improvements to achieve 15% TSFC reduction, contributing to the 50 percent fuel burn reduction goal at the aircraft system level, while reducing engine system noise and minimizing weight, drag, NOx, and integration penalties at AC system level

**Advanced Combustor Designs for Oxides of Nitrogen Reduction**
- Demonstrate reductions of LTO NOx by 75 percent from CAEP6 and cruise NOx by 70 percent while minimizing the impact on fuel burn at the aircraft system level, without penalties in stability and durability of the engine system

**Airframe and Engine Integration Concepts for Community Noise and Fuel Burn Reduction**
- Demonstrate reduced component noise signatures leading to 42 EPNdB to Stage 4 noise margin for the aircraft system while minimizing weight and integration penalties to enable 50 percent fuel burn reduction at the aircraft system level
Airframe Technology
Integrated Technology Demonstrators

ITD 21A: Damage Arresting Composite Demonstration
ITD 21A: Damage Arresting Composite Demonstration
Overall Approach – Technology Maturation Plan

Key Performance Parameters
• Reduce structural weight by 20 percent for LTA Class Aircraft w/GTF Engine

Technology Insertion Challenges Addressed
• Damage tolerance
• Post-buckled composite structure
• Integrated system weight
• Large scale flight weight infused composite parts

End TRL: 5

Assembled Multi bay Box in C-17 Factory

Multibay Box Assembly Complete
Fabrication Complete
Crown Panel Complete

Baseline
Completed

Multibay Box Assembly Start

Testing Complete

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NASA Super Guppy Aircraft picked up the MBB at the Long Beach Airport in Calif. and delivered it to NASA LaRC, where it was moved to COLTS and installed between the platens for testing.
ITD 21A: Damage Arresting Composites Demonstration Summary Technical Highlight

Requirements
- Fabricate an aerospace-quality large-scale pultruded rod stitched efficient unitized structural (PRSEUS) test article representative of a HWB centerbody.
- Demonstrate that the pristine PRSEUS multi-bay pressure box could support design ultimate load in five critical loading conditions.
- Demonstrate that the damaged PRSEUS multi-bay pressure box could support design ultimate load in five critical loading conditions.
- Demonstrate that analytical tools and modeling techniques are adequate for predicting structural response of complex PRSEUS structures.

Accomplishments
- A high-quality 30-ft long, 6.5-ft wide, 13.5-ft tall multi-bay pressure box test article was fabricated from 11 PRSEUS panels, 4 sandwich panels, fasteners, metal fittings and load-introduction elements.
- The test article was installed in the NASA Langley Research Center Combined Loads Test System facility and loaded to design ultimate load in up-bending, down-bending, internal pressure and combinations of pressure and mechanical load in the pristine condition, with barely visible impact damage and with discrete source damage.
- Finite element analysis predictions showed good agreement with test data.
Propulsion Technology
Integrated Technology Demonstrators

30A: Highly Loaded Front Block Compressor (GE)
35A: 2nd Gen UHB Propulsor Integration (P&W and FAA)
40A: Low NOx, Fuel Flexible Combustor Integration (P&W)
Integrated Technology Demonstrator
Highly Loaded Front Block Compressor Demonstration

Key Performance Parameters
• Reduce TSFC by 2.5 percent

Technology Insertion Challenges Addressed
• Front block aerodynamic losses limit efficiency
• Identify loss mechanisms and interaction effects of highly-loaded compressor stages
• Trade-off OPR, Efficiency, and operability to optimize fuel burn
• Establish part-speed operability margin
• Integrated 1\textsuperscript{st} 3 stages of HPC

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ITD30A validated a 2.9% TSFC reduction for the technology.
Integrated Technology Demonstrator
2\textsuperscript{nd} Generation UHB Propulsor Integration

Key Performance Parameters
- Reduce noise by 15 EPNdB
- Reduce TSFC by 9 percent

Technology Insertion Challenges Addressed
- Noise reduction & aero performance of advanced liners validated: 1 – 2 EPNdB
- Comprehensive- modern database of propulsor multi-discipline performance characteristics for sys analysis created.
- Integrated performance of modern fan + advanced FEGVs + short inlet verified

<table>
<thead>
<tr>
<th>Weight</th>
<th>Drag</th>
<th>TSFC</th>
<th>Noise</th>
<th>NOx</th>
</tr>
</thead>
</table>

End TRL: 5

<table>
<thead>
<tr>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA VAN Prototype Demo</td>
<td>UHB OTR Perf. Risk Mitigation Test</td>
<td>UHB OTR/SV Noise Reductions Validation Test</td>
<td>Integrated System LS Test</td>
</tr>
<tr>
<td>UHB Gen 2 Test</td>
<td>Integrated Systems Design Task Start</td>
<td>UHB Integ. System DDR</td>
<td>UHB Low Loss FEGVs Test</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sys Analysis/Tech Mat Complete Approval for Public Release</td>
</tr>
</tbody>
</table>
Integrated Technology Demonstrator
2nd Generation UHB Propulsor Integration

Pressure & temperature sensitive paint utilized over range of operating lines

Image Credit: NASA

Oil pigmentation gave insight into aerodynamic behavior

Photo Credit: Pratt & Whitney

ITD35A validated performance and acoustics for the propulsor that exceeded the goals of 9% TSFC reduction and 15 EPNdB noise reduction for the technology.

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Integrated Technology Demonstrator
Fuel Flexible, Low NOX Combustor Integration

Key Performance Parameters

- Reduce LTO NOx by 75 percent

Technology Insertion Challenges Addressed

- Lean burn system operability concerns
  - Auto-ignition
  - Flame stability
  - Acoustic resonance
- Durability for lean burn configuration
- 50/50 jet/alt fuel mixture

FY12
- Single-injector flame tube screening

FY13
- GE Gen 1 ASCR Test

FY14
- MSR NOx Correlation
- Full Annular Comb CDR

FY15
- MSR ASCR Test

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Integrated Technology Demonstrator
Fuel Flexible, Low NOX Combustor Integration

ITD40A was fully successful in validating greater than 75% NOx reduction re/CAEP6 with a durable lean-lean combustor system that is compatible with alt fuel blends.
## Integrated Technology Demonstrators Summary Performance

<table>
<thead>
<tr>
<th>Integrated Technology Demonstrators</th>
<th>Partner(s)</th>
<th>Min Success</th>
<th>Full Success</th>
<th>Plan/Actual Impact (2025)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>12A+</strong> AFC Enabled Vertical Tail and Advanced Wing Flight Test</td>
<td>Boeing</td>
<td></td>
<td></td>
<td>-1.5 / -0.92+ % Tail Drag</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-3 / -3.3% Wing Drag (NLF)</td>
</tr>
<tr>
<td><strong>21A</strong> Damage Arresting Composites Demonstration</td>
<td>Boeing</td>
<td></td>
<td></td>
<td>-20 / -20+ % Structural Weight</td>
</tr>
<tr>
<td><strong>21C</strong> Adaptive Compliant Trailing Edge Flight Test</td>
<td>AFRL/FlexSys</td>
<td></td>
<td></td>
<td>-5 / -8+% Wing Weight</td>
</tr>
<tr>
<td><strong>30A</strong> Highly Loaded Front Block Compressor Demonstration</td>
<td>General Electric</td>
<td></td>
<td></td>
<td>-2.5 / -2.94% TSFC</td>
</tr>
<tr>
<td><strong>35A</strong> 2nd Generation UHB Propulsor Integration</td>
<td>Pratt &amp; Whitney/FAA</td>
<td></td>
<td></td>
<td>-9 / -10.9% TSFC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-15 / -20.9 EPNdB</td>
</tr>
<tr>
<td><strong>40A</strong> Fuel Flexible, Low NOX Combustor Integration</td>
<td>Pratt &amp; Whitney</td>
<td></td>
<td></td>
<td>-75 / -81% LTO NOX</td>
</tr>
<tr>
<td><strong>50A</strong> Landing Gear and Flap Edge Noise Reduction Flight Test</td>
<td>Gulfstream</td>
<td></td>
<td></td>
<td>LG - 1.0 / -1.0+ EPNdB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FE -3.0 / -3+ EPNdB</td>
</tr>
<tr>
<td><strong>51A</strong> UHB Integration on Hybrid Wing Body Aircraft</td>
<td>Boeing</td>
<td></td>
<td></td>
<td>-42 / -40+ EPNdB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-50 / -47+% Fuel Burn</td>
</tr>
</tbody>
</table>
Assessment of the Noise Reduction Potential of Advanced Subsonic Transport Concepts for the NASA Environmentally Responsible Aviation Project

Russell H. Thomas, Casey L. Burley, and Craig L. Nickol
NASA Langley Research Center

AIAA SciTech 2016
San Diego, California
January 5, 2016
AIAA Paper 2016-0863
Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA’s Environmentally Responsible Aviation Project

Craig Nickol
NASA Langley Research Center

Bill Haller
NASA Glenn Research Center

AIAA SciTech 2016
San Diego, California
January 6, 2016

AIAA Paper 2016-1030

Approved for Public Release
Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

RJ
T+W98-DD
(2) Small DD
OWN98-DD
(2) Small DD

SA
T+W160-GTF
(2) Small GTF
OWN160-GTF
(2) Small GTF

STA
T+W216-GTF
(2) Medium GTF
HWB216-GTF
(2) Medium GTF

LTA
T+W301
(2) Large DD
(2) Large GTF
HWB301
(2) Large DD
(2) Large HWB GTF
MFN301-GTF
(2) Large GTF

VLTA
T+W400-GTF
(4) Medium GTF
HWB400-GTF
(3) Medium HWB GTF

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# Potential Impacts

## Vehicle Level - Best Performers

### TECHNOLOGY BENEFITS*

<table>
<thead>
<tr>
<th>Benefit</th>
<th>TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
</tr>
<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption† (rel. to 2005 best in class)</td>
<td>-33%</td>
</tr>
</tbody>
</table>

*Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines. N+2 values are referenced to a 777-200 with GE90 engines.

**ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015.

CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used.

### Table 15. N+2 HWB-GTF Concept Performance Summary

<table>
<thead>
<tr>
<th>ERA Target</th>
<th>Noise</th>
<th>Fuel Burn</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWB301-GTF</td>
<td>-40.3</td>
<td>-47</td>
<td>-79</td>
</tr>
<tr>
<td>HWB400-GTF</td>
<td>-40.3</td>
<td>-49.4</td>
<td>-79</td>
</tr>
</tbody>
</table>
Potential Impacts
US Fleet Level – Carbon Footprint

Through 2050 the cumulative delta between RTC to ITD is 88 B gal = 264B dollars

BAU - Business as usual, no technology insertion
RTC - Potential impact of technology available prior to ERA
ITD - Potential impact of ERA Integrated Technology Demo’s

Notes – (1) This “what-if” scenario assumes ITD technology finds its way into the fleet in 2025.
(2) ITD wedge above based on transition of ITD techs to tube and wing only in 2025.

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Technical Accomplishments - Summary

- It is feasible that Open Rotor Systems will meet current noise standard
- Laminar flow applications have been applied by Boeing to B787
  - Main wing, high Rn applications are the final challenge
- Active flow control applications are still being investigated
- Compliant wing technology is feasible. Large impact on tube & wing
  - Aviation Partners has teamed with FlexSys
- A scalable low NOX, fuel-flexible combustor that exceeds the current regulation with an engine w/advanced fan blade system is feasible
  - Application to future engine products are being explored
- Highly loaded compressor blading is feasible
  - Application to future engine products are being explored
- The Rolls Royce UltraFan engine concept shows great promise
- Feasible noise reduction technologies for engine and airframe emerged
- The NASA/Boeing HWB / GTF configuration was matured further
  - Low speed aero, structures, and operability issues solved
- Less mature, over the wing configurations also show promise toward goals

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Future work/Collaboration opportunities
Propulsion specific

- Advanced Air Transport Technology Project (AATT)
  - Next Generation Propulsors – ducted/unducted propulsors and PAI
  - Boundary Layer Ingesting Propulsors – distortion tolerant
  - Advanced combustors – compact and low NOx for high P/T cores
  - Compact cores – stable and efficient
  - Hybrid Gas Electric Propulsion – new engine options

- Flight Demonstrations and Capabilities Project (FDC)
- New Aviation Horizons (NAH) – flight demonstrators
Potential Impacts
What does Stage 4 - 40 EPNdB sound like?

LTA Ref (NASA model of 777-GE90-110B) on Approach

HWB301-GTF w/ITDNR on Approach

LTA Ref (NASA model of 777-GE90-110B) on Sideline

HWB301-GTF w/ITDNR on Sideline

## Thrust 3 - Ultra-Efficient Commercial Vehicles

**ERA Project Focus**

The table below outlines the technology benefits and generations for ultra-efficient commercial vehicles.

### TECHNOLOGY BENEFITS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
<td>-52 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>-80%</td>
</tr>
<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
<td>-70%</td>
<td>-80%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)</td>
<td>-33%</td>
<td>-50%</td>
<td>-60%</td>
</tr>
</tbody>
</table>

**Notes:**

- Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines. N+2 values are referenced to a 777-200 with GE90 engines.
- ERA’s time-phased approach includes advancing “long-pole” technologies to TRL 6 by 2015.
- CO2 emission benefits dependent on life-cycle CO2e per MJ for fuel and/or energy source used.

---

**ERA Focus**

Complete Alignment with the NASA Strategic Implementation Plan & The National Aeronautics R&D Plan
Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

- NPSS – Numerical Propulsion Simulation System
  - ITD and partner data utilized to help create input assumptions

- WATE++ - Weight Analysis for Turbine Engines

- FLOPS & OpenVSP – Flight Optimization System & Vehicle Sketch Pad
  - HCDStruct utilized for HWB weights analysis
  - FUN3D corrections utilized for HWB aero analysis
  - ITD and partner data utilized to help create input assumptions

- HCDStruct – Hybrid Wing Body Conceptual Design and Structural Optimization
  - New capability developed under ERA
  - Wing-tip to wing-tip HWB finite element model with NASTRAN solver
  - Validated using Boeing benchmark cases (OREIO, 9H1)

- MVL-15 – Modified Vortex Lattice for Low Speed Aerodynamic Performance Estimation
  - New semi-empirical capability developed under ERA
  - Provides low speed drag polars for tube+wing aircraft
  - Capable of analyzing multi-element high lift systems

- ANOPP2 – Aircraft Noise Prediction Program
  - ITD and partner data utilized to help create refined input assumptions and improved predictions
  - Shielding, fan noise, and noise reduction technology impact estimates supported by test data
  - New prediction capabilities developed

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Potential Impacts
Vehicle Level – AIAA 2016-1030 & 0863

Table 13. N+2 Large Twin Aisle class T+W and HWB Concepts

<table>
<thead>
<tr>
<th></th>
<th>T+W301-DD</th>
<th>T+W301-GTF</th>
<th>HWB301-DD</th>
<th>HWB301-GTF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Units</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>TOGW lb</td>
<td>570,195</td>
<td>570,533</td>
<td>537,641</td>
<td>534,491</td>
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<tr>
<td>OEW lb</td>
<td>265,290</td>
<td>270,084</td>
<td>251,281</td>
<td>253,326</td>
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<tr>
<td>Payload lb</td>
<td>118,100</td>
<td>118,100</td>
<td>118,100</td>
<td>118,100</td>
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<tr>
<td># Pax</td>
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<td>301</td>
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<tr>
<td>Range nm</td>
<td>7500</td>
<td>7500</td>
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<td>7500</td>
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<tr>
<td>Total Fuel lb</td>
<td>186,805</td>
<td>182,349</td>
<td>168,259</td>
<td>163,065</td>
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<tr>
<td>Block Fuel lb</td>
<td>168,687 (-39.1%)</td>
<td>164,748 (-40.6%)</td>
<td>151,597 (-45.3%)</td>
<td>147,011 (-47.0%)</td>
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<tr>
<td>Wing Area ft²</td>
<td>4664</td>
<td>4670</td>
<td>10169</td>
<td>10169</td>
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<tr>
<td>Wing Span ft</td>
<td>226.5</td>
<td>226.6</td>
<td>250</td>
<td>250</td>
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<tr>
<td>Wing Aspect Ratio</td>
<td>11</td>
<td>11.0</td>
<td>6.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Wing Loading lb/ft²</td>
<td>122.2</td>
<td>122.2</td>
<td>52.9</td>
<td>55.9</td>
</tr>
<tr>
<td>Cruise Mach</td>
<td>0.84</td>
<td>0.84</td>
<td>0.84</td>
<td>0.84</td>
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<tr>
<td>Start of Cruise L/D</td>
<td>22.1</td>
<td>22.0</td>
<td>23.8</td>
<td>23.7</td>
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<tr>
<td>Number of Engines</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Thrust per Engine lb</td>
<td>71800</td>
<td>74,000</td>
<td>66,989</td>
<td>69,398</td>
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<tr>
<td>Start of Cruise SFC</td>
<td>0.483</td>
<td>0.467</td>
<td>0.49</td>
<td>0.475</td>
</tr>
</tbody>
</table>

Notes – (1) Impacts also modeled all other seat classes. (2) HWB- GTF vehicles provided the best overall performance.

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