BLENDED WING BODY TRANSPORT AIRCRAFT RESEARCH & DEVELOPMENT

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Abstract

The Boeing Blended Wing Body transport class airplane concept can achieve significant environmental benefits in the form of lower fuel burn, lower community noise, and reduced CO2 & NOx emissions compared to current and previously generations of commercial aircraft. Research and development activities completed by Boeing over the past 10 years will be described in this paper. Advanced vehicle concept studies were completed to identify which technologies and configurations have the greatest opportunity for meeting and exceeding the fuel burn, noise and emissions goals laid out by NASA Aeronautics' Environmentally Responsibility Aviation Program.

1 Introduction

The Environmentally Responsible Aviation (ERA) Project within the Integrated Systems Research Program (ISRP) of the NASA Aeronautics Research Mission Directorate (ARMD) had the responsibility to explore and document the feasibility, benefits, and technical risk of air vehicle concepts and enabling technologies to reduce the impact of aviation on the environment. The primary goal of the ERA Project was to select air vehicle concepts and technologies that could simultaneously reduce fuel burn, noise, and emissions, Fig. 1. In addition, the ERA Project identified and mitigated technical risk and transferred knowledge to the aeronautics community at large so that new technologies and vehicle concepts could be incorporated into the future design of aircraft. ERA was to address aircraft performance (especially "green" technology) within the N+2 (2020) timeframe for entry into service with the objective of integrating the most viable technologies. [1]

2 Advanced Vehicle Concept Study

In 2011, Boeing performed a NASA sponsored study which compared several Blended Wing Body (BWB) configurations to current and futures tube and wing airplane designs utilizing similar technology readiness levels and projected entry into services time periods. The research indicates that key enabling technologies for the BWB vehicle are advanced composites for a light weight efficient flat sided pressure cabin; efficient propulsion-aerodynamic integration of ultra-high bypass ratio engines; propulsion aero-acoustics integration; flight control and actuation systems; and the high aerodynamic efficiency at transonic conditions that are inherent in the BWB configuration. Effectively combining these technologies can result in over 50% lower mission fuel burn, 40dB+ cumulative margin to FAR Part 36 Stage 4 noise limits, and 75% lower LTO NOx margin below CAEP/6 levels [1].

ERA Projects: 2011 AVCS; 2013 BWB UHB

Technology Benefits	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near Term (2015-2025)	Mid Term (2025-2035)	Far Term (beyond 2035)
Noise (cum below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NOx Emissions (below CAEP 6)	70 - 75%	80%	>80%
Cruise NOx Emissions (rel. to 2005 best in class)	65 - 70%	80%	>80%
Aircraft Fuel/Energy Consumption (rel. to 2005 Best in class)	40 - 50%	50 - 60%	60 - 80%

v2016.1

Figure 1. NASA System Level Metrics

3 Integrated Technology Demonstrations

In 2013 thru 2015, NASA and Boeing performed an integrated technology demonstration project called Ultra-High Bypass Ratio (UHB) Engine integration for Hybrid Wing Bodies. This technology demonstration addresses the ERA technical challenge to 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% fuel burn reduction at the aircraft system level. [2]

This UHB engine integration for Hybrid Wing Bodies technology demonstration seeks to quantify the impact of engine/airframe integration on HWB system performance and engine operability across key on- and off-design conditions. Its goal is to demonstrate BWB propulsion airframe integration (PAI) design concept that will enable fuel burn reductions in excess of 50% while providing noise shielding to meet ERA noise reduction metrics. NASA and Boeing have partnered to design and verify an HWB PAI concept that minimizes adverse propulsion/airframe induced interference effects that could result in high drag or poor aerodynamic characteristics. Boeing had the responsibility to develop the full scale concept vehicle that will be the basis of system level assessment and the scale model that will be tested by NASA in their low speed wind tunnels.

Boeing used high fidelity CFD tools and methods to revise the BWB-009A Preferred System Concept (PSC) developed in the ERA Phase I Advanced Vehicle Concept Study Program. Specific emphasis was placed on propulsion airframe integration challenges that are associated with integration of UHB engines.

As shown in Fig. 2, changes to configuration planform, wing, body, and nacelle outer mold lines to achieve a configuration that has the best chance to meet fuel burn goals. The specific areas that were changed including control surface layout, UHB geared turbofan propulsion aerodynamic integration, and high lift system.

Planform changes were incorporated to better meet the weight, balance, stability and control requirements. Changes included a wing shift, revision of the trailing edge shape and control surface allocation. The vertical tails geometry was revised to include incorporation of an all moving tail design. [2]

The propulsion system selected is a variation of the Pratt & Whitney Geared Turbo-Fan design. Pratt and Whitney defined a concept engine that meet the thrust and geometry requirement for the upper surface podded mounting requirement of the Boeing's BWB design. Boeing developed the inlet, cowl, fan and core nozzles for the engine installation. The design requirements included high inlet recovery during the cruise portion of the mission, but also address the real-world design and operation requirement for the nacelle which include crosswind takeoff, ground operations, and high vehicle angle of attack operation. The unique upper surface mounting location of the propulsion system is the fundamentally different than an underwing mounted propulsion system.

Engine mounting location is a primary driver for two key metrics on the ERA program. Optimization of mission fuel burn and noise shielding are diametrically opposed regarding engine location on BWB configurations. In additions, there are other propulsion airframe integration challenges that are unique to the BWB. The forward positioning of the engine is required for noise shielding, but this location places the engine in a higher onset Mach number region, higher than free stream Mach number. The higher onset Mach number would typically result in higher nacelle and interference drag. The other integration challenges are related to the Ultra-High Bypass ratio of the geared turbo fan. The larger max diameter of the nacelle results in the lower fineness ratio of the nacelle and thus higher drag. Other integration challenges related to the BWB UHB integration are nacelle-body channel flow, nacelle to nacelle shocks, nacelle to tail shocks/interference, inlet air spillage and the variable area nozzle, Fig. 3.

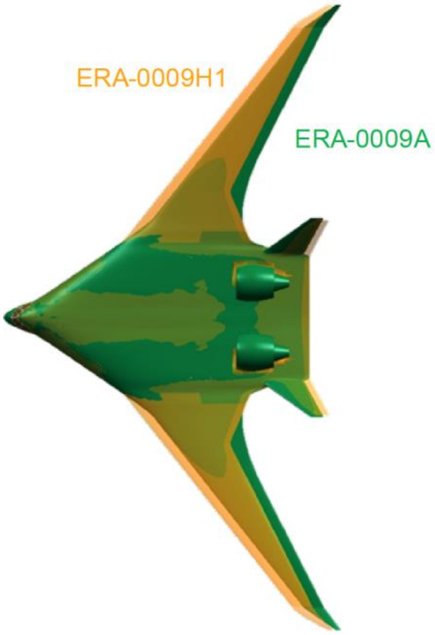

Figure 2. Evolution of the planform of ERA BWB 0009A (green) to 0009H1 (orange) configuration.

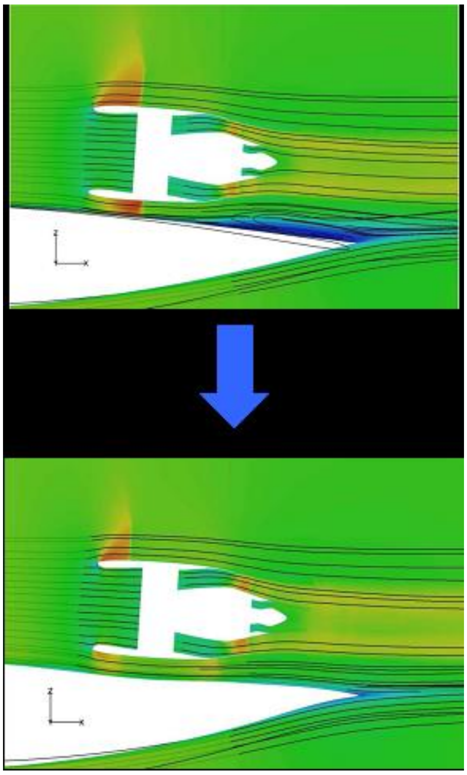

Figure 3. Nacelle & Fuselage Shaping to lower transonic drag - High speed conditions Mach 0.85 / 43K feet

3.1 FTN Wind Tunnel Test Programs

The overall objective of the flow through nacelle testing was to define the high-lift system for take-off and landing conditions with the goal to optimize Krueger settings for high lift. Flow through nacelle testing was conducted in both the 14 by 22 foot Subsonic Tunnel and the NFAC 40 by 80 foot test section. [3]

The model is a 5.75-percent geometrically scaled version of the Boeing Blended-Wing-Body BWB-0009G configuration. The model has thirteen control surfaces distributed along the trailing edge and vertical tails of the vehicle. The outboard elevons (elevon 6/7) have an upper and lower surface that can be split to provide directional control as a drag rudder or deflected as a standard elevon. The vertical tails are deflectable and have additional ruddervator panels along their trailing edge. The high-lift system for the model consisted of a leading edge Krueger slat extending along the extent of the outboard wing section. The Krueger position could be varied in deflection angle, gap and overhang, which were set by five mounting brackets on each wing. [3]

Three different tests were conducted with the 5.75% BWB-009G model in two different wind tunnels, Fig. 4 & 5. The two tests in the same wind tunnel used different internal strain gauge balances and the two tests with the same balance were in different tunnels. Three common configurations were tested in all three wind tunnel test entries. Those were the Cruise configuration, the 45° 3,2 landing Krueger configuration, and the 40° 1,1 takeoff Krueger configuration. Fig. 6 shows a comparison measured longitudinal forces and moments of the 45° 3,2 landing Krueger configuration from the three tests. The most apparent difference is the increased pitching moment of the NFAC tests and the increased minimum drag observed in T078. [3]

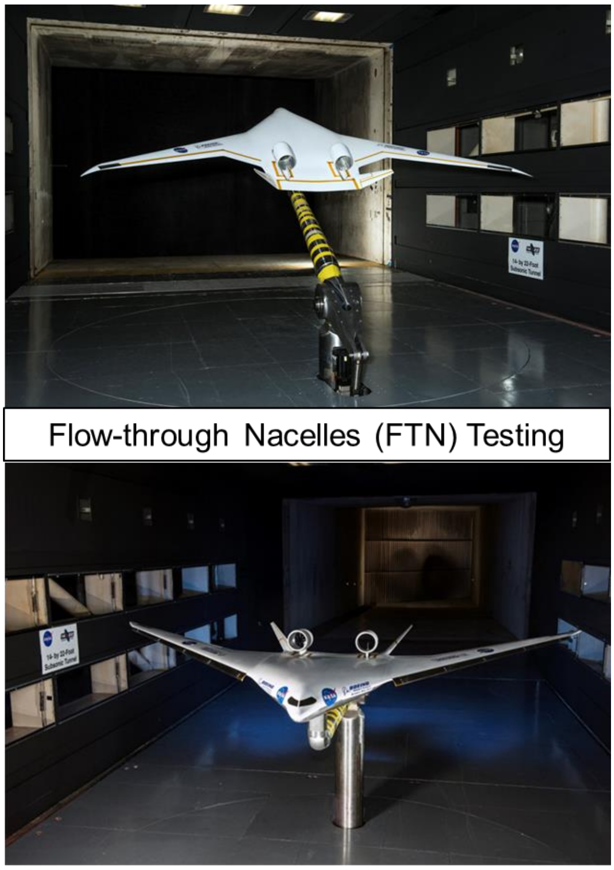

Figure 4. FTN testing in the NASA LaRC 14x22 foot tunnel

3.2 Ejector Wind Tunnel Test Programs

The ejector wind tunnel tests were conducted to collect flow surveys useful for characterizing engine operability.

Two jet engine simulation ejectors were used to simulate the expected inlet mass flow conditions. The TDI model 1900A ejectors operate by blowing high pressure air through multiple nozzles located inside a canister mounted downstream of the nacelle inlet. The nozzle flow entrains air drawn though the nacelle inlet. By varying the supply air pressure to the ejector, the air mass flow drawn through the inlet can be adjusted. The ejectors were mounted to long nacelles and attached directly to the model sting support system. Fig. 7 shows a view of the model with the long nacelles and the ejectors attached at the exhaust. [4]

Two successful tests of an HWB with jet engine simulation ejectors were conducted at the NASA Langley 14- by 22-foot tunnel and the NASA Ames 40- by 80-foot tunnel. Data were collected to characterize the inflow conditions for engine operability analysis. Mass flow sweeps showed a small vortex being ingested during spool up although distortion levels remained within acceptable limits. Tunnel to tunnel comparisons of the data further confirmed the quality of the results. The CFD studies conducted to compare to experimental data showed excellent agreement for the angle of attacks examined, although failed to match the experimental data for the lower speed beta sweep. Finally, swirl data were obtained, however, was not easily analyzed both due to uncertainty in the data from missing ports and the lack of established published acceptable swirl conditions for engines. Overall, the test results show that the distortion and pressure recovery levels were acceptable for engine operability.

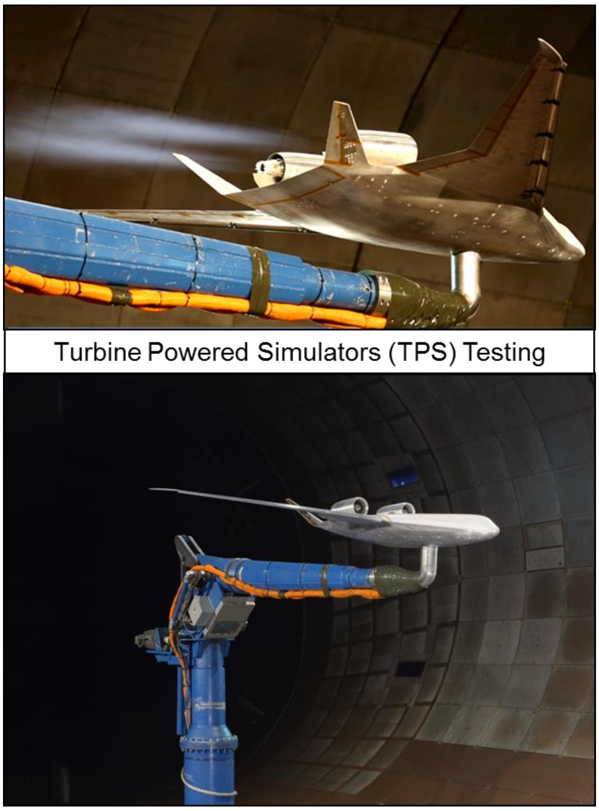

Figure 5. Turbine powered testing in Ames 40 x 80 foot tunnel

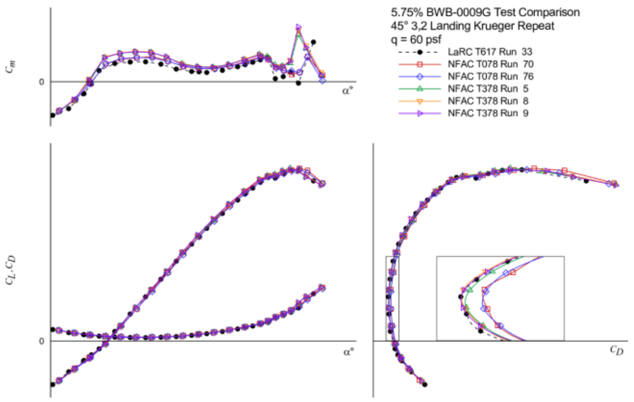

Figure 6. Comparison of Longitudinal forces in 3 wind tunnels

Figure 7. BWB model with ejectors nacelles in 14x22 tunnel

3.4 Integrated Tech Demonstration Summary

Summary of program accomplishments are:

Technical performance metrics established for the project:

- Low Speed Inlet Distortion
- Engine Installation Drag Penalty At Cruise
- Engine Position Relative To The Body Trailing Edge For Noise Shielding
- CLmax at Takeoff & Landing
- Cruise Lift to Drag Ratio (L/D)

Wind tunnel test programs completed - Low Speed (5.75% Model, 13' wingspan), Fig. 8

- Wing high lift configuration optimization
- Aero / Stability & Control database developed
- Inlet distortion and swirl characteristics measured at boundary of vehicle flight envelope (high alpha and beta)
- Jet effects on Aero / S&C measured
- High lift system noise database developed

Analytical Assessments Completed, Fig. 9

- Cruise Drag, L/D, PAI drag
- Engine and fan operability, fan stress analysis
- Mission Fuel Burn
- Community Noise

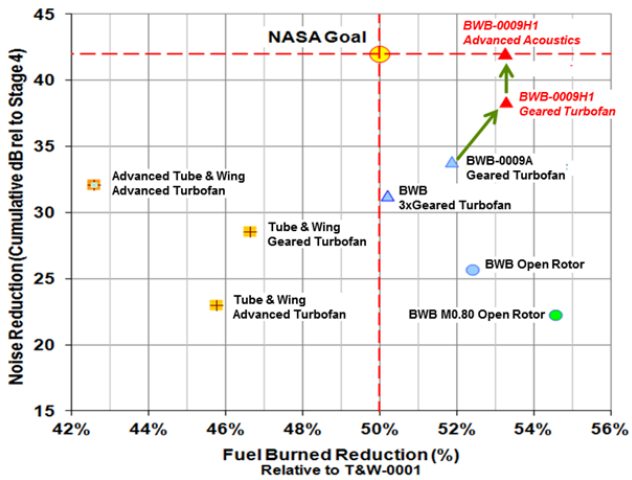

Figure 9. Performance Measures

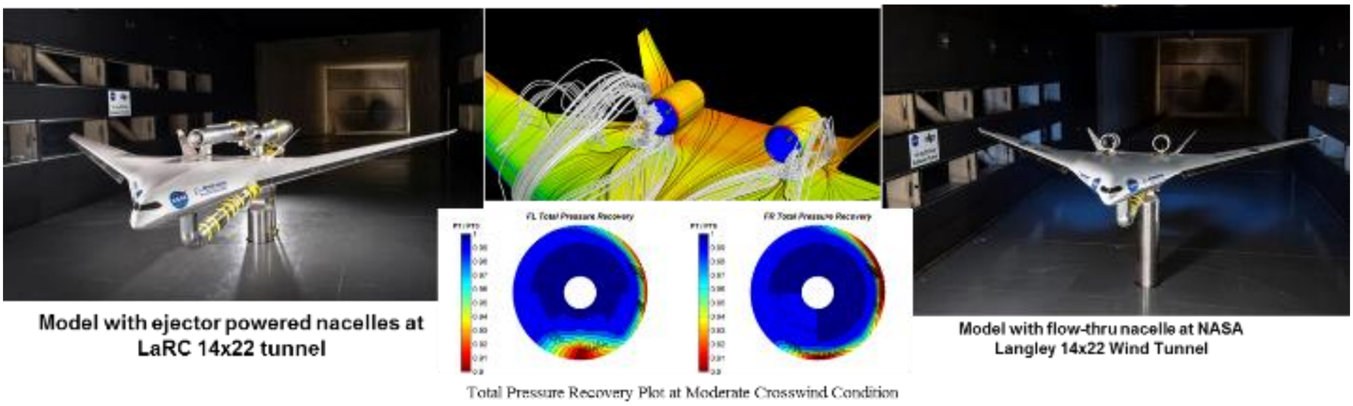

Figure 8. A common model was used for all tests - 2 National Test Facilities

4.0 Vision Vehicle

Boeing's Vision Vehicle for future transport aircraft are focused on two markets, Civil Transport / Airliner and a Military Transport / Tanker. Boeing has studied many versions of BWB transport aircraft and the current design for the Civil market is the ERA-009H1, developed on company funding starting in 2010, but fully refined as part of the 2013-2015 NASA ERA ITD-51A. It performs a long range transport mission with a design range of 8000 nm with a 50,000 lb passenger payload. Boeing's current vision vehicle for a future military transport and tanker mission has been designed in the 2017-18 time period. It has a much higher payload requirement with a design range that is less than the civil transport. Both aircraft share basic BWB features such as high aspect ratio outer wing, inboard vertical tail and podded high-bypass ratio engines, as seen in Fig. 10

Figure 10. BWB Vision vehicles

5 X-Plane Demonstrator

The BWB X-plane will be instrumental in maturing several key technologies that are fundamental and unique for a BWB concept. Maturation of technologies related to the BWB configuration in the areas of structures, aerodynamics, controls, and propulsion will be needed before development of a BWB vision vehicle to achieve NASA N+2 fuel burn goals. Additional maturation of BWB noise reduction technology is needed to meet NASA N+2 noise goals. Further developments are needed for a military configuration. The key technology developments needed are listed in Fig. 11, along with indication of whether flight test is required for maturation and whether the development would be covered by a potential X-plane demonstration program.

Key Technologies for Vision Vehicle

Technology	Key Development	Flight Test Required	X-Plane Demo
BWB Structures Stitched Resin Infusion	Demonstrate SRI composite centerbody structure	No[A]	Yes
BWB Aerodynamics	Cruise drag validation	Yes	Yes
BWB Stability & Control, Flight Controls, and Handling Qualities	Flight envelope stability and control assessment	Yes	Yes
	Full flight envelope handling qualities assessment	Yes	Yes
	Validate flight control secondary power	Yes	Yes
BWB Propulsion	Engine compatibility testing	Yes	Yes
Noise	Noise shielding benefit	Yes	Yes
	Airframe noise reduction	Yes	Yes
Military Configuration Technology	Alternate Engine Integration	Yes	TBD[B]
	Aerial refueling handling qualities	Yes	Yes

[A] Structural technology will be validated on ground but requires flight representative design for TRL6
[B] Demonstration anticipated for follow on military configuration demonstrator

Figure 11. Key Technologies for Vision Vehicle

All of the technologies required for realization of the vision vehicle, whether matured in the X-plane program or not, were reviewed to assess and rank the associated risks with each of these technologies. Fig. 12 shows an ordered list of the top 6 vision vehicle technology risks as determined by their likelihood and consequence.

Prioritized Technology Risks for Vision Vehicle

Priority	Label	Risk	Prioritization
1	S	Structures: If the chosen structural technology has difficulty meeting design or manufacturing requirements, then the vision vehicle may miss performance goals or may be unaffordable	Potential for manufacturing issues to affect viability of vision vehicle
2	C	Controls: If the power used by the control system grows significantly to meet handling requirements, then the vision vehicle may miss performance goals	Limited work on control system design raises likelihood relative to other technology risks
3	P	Propulsion: If alternate engine installations or engine operability requirements cause significant reduction in engine or nacelle performance, then the vision vehicle may miss performance goals	Limited work on alternate engine installation raises likelihood relative to aerodynamics
4	A	Aerodynamics: If the aerodynamic design requires significant modification to meet requirements for propulsion system operation, air drop, short field operations, or aerial refueling, then the performance of the vision vehicle may miss goals	Past work reduces likelihood of risk relative to propulsion and controls
5	N	Noise: If the benefits of noise shielding and airframe noise reduction concepts are less than estimated, then the vision vehicle may miss noise goals	Vision vehicle likely to retain noise advantage even if benefits are reduced

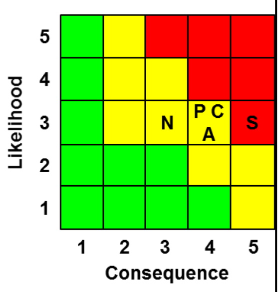

Figure 12. BWB Risk and Justification for an X-Plane

Figure 13. Learning from a BWB X-Plane

The X-plane program is essential for maturing the BWB technologies that are necessary for the military or commercial vision vehicle. Certain key technologies as previously listed in Fig. 11 are matured in the X-plane program and are required for successful vision vehicle development. These include composite structures for flat sided pressure vessels, ultra high bypass ratio engine integration, advanced controls and actuation, among others.

6 Market Interest

The BWB vision vehicles have great value for both commercial and military missions. Some of the key capabilities that can be provided by a BWB for military application include the following:

1. Fuel Efficiency that drives large payload fraction vs airframe weight
2. Superior Footprint/Spotting Factor vs cargo and offload fuel carried
3. Outsized/oversized Cargo Capacity with air operable (airdrop) Ramp and Cargo Door
4. Soft and Austere Field operations with minimal Ground handling and support equipment
5. Enhanced vulnerability and Survivability protection due to system architecture.
6. Short Field Length operationally suitable with enhanced aero controls.

The BWB concept has significant advantages for transition as an aerial refueling tanker platform. At 1500 nautical miles (nmi) radius, the BWB can provide 75% more offload than the KC-10 and 200% more offload than the KC-135. On the other hand, if the fuel load is constant at 100,000lbs, then the BWB can achieve 2250 nmi further radius than the KC-10 and 3500 nmi further radius than the KC-135.

A BWB has overall market interest due to its capabilities as a large transport aircraft. Such as:

- Superior aero efficiency over traditional configurations
- Studies indicate that BWB production will have manufacturing efficiencies (i.e. lower part count, out of autoclave composites)
- Large interior volumes offer many options for interior configuration customization
- Lower takeoff and landing noise; leading to potential for 24 hour airport operations
- Superior payload range and efficiency enables lower operating cost and increased capabilities for operators
- Potential part count reduction and part commonality reduce recurring production costs
- Non-recurring development costs for BWB will be higher, but lower recurring costs create a superior business case compared to conventional airplanes.

Conclusions and Recommendations

All of the technologies required for the BWB vision vehicles have been analyzed and/or tested on the ground over the past 25+ year history of BWB research. The ground based BWB research advanced the TRL to 4 or 5 for the key technologies, but it is impossible to move most technologies beyond these TRL levels without flight test research. Boeing has been partnering with NASA for much of the research completed to date. This paper summarizes only the most recent efforts by Boeing and NASA. In each of the main Phases of the ERA project, BWB configuration and technologies have been advanced and show the capability of the BWB civil transport can meet and exceed the NASA N+2 system level goals.

Recommendation for future work have been identified and would be focused on maturing the key critical technology through ground and sub-scale flight demonstrator test program.

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