THE ROYAL AERONAUTICAL SOCIETY

35th WILBUR WRIGHT MEMORIAL LECTURE

THE DEVELOPMENT OF ALL-WING AIRCRAFT

by

JOHN K. NORTHRUP

Mr. Northrop is President and Chief Designer of Northrop Aircraft Inc. He has been designing and experimenting with the all-wing type of aeroplane since 1923 and built his first machine in 1928.

THE THIRTY-FIFTH Wilbur Wright Memorial Lecture was delivered before the Society by Mr. John K. Northrop on Thursday 29th May 1947 at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, S.W.1. The chair was taken by Sir Frederick Handley Page, C.B.E., President of the Society.
Concept Genesis

Is there an Aerodynamic Renaissance for the long-haul transport?

-Dennis Bushnell, December 1988

1903 1947 1992
Early BWB Concept
(NASA / Douglas Aircraft 1993)

Span Loading with Circular Pressure Vessels

“Batwing”
Payload Packaging

Conventional double-deck

Deck-and-a-half BWB

Single-deck Oblique All-Wing

Longitudinal Loading

Span Loading
Aerodynamic Efficiency

Wetted Area Comparison

<table>
<thead>
<tr>
<th>Component</th>
<th>Conventional</th>
<th>Blended Wing Body</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage</td>
<td>23,000 ft²</td>
<td>22,000 ft²</td>
<td>33%</td>
</tr>
<tr>
<td>Wing</td>
<td>12,000 ft²</td>
<td>6,000 ft²</td>
<td>1/3</td>
</tr>
<tr>
<td>Propulsion</td>
<td>4,000 ft²</td>
<td>1,200 ft²</td>
<td></td>
</tr>
<tr>
<td>Empennage</td>
<td>5,000 ft²</td>
<td>500 ft²</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>44,000 ft²</td>
<td>29,700 ft²</td>
<td></td>
</tr>
</tbody>
</table>

1/3 less wetted area than conventional configuration
First-Generation BWB
(NASA / Douglas Aircraft 1993)
Wing & Pressure Vessel Loads

Conventional Aircraft

- Ideal pressure loading
- Limited span loading
- Independent wing box and fuselage structure
- Fuselage has very little/no lifting capability
- Payload distributed normal to the wing

Blended Wing-Body

- “Square” pressure vessel
- Span loaded
- Pressure loads add ~25% to the weight of the existing wing box
- Centerbody lifts
- Payload distributed similar to the wing

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Centerbody Pressure Vessel Concepts

BWB SEPARATE PRESSURE SHELL CONCEPT

ARCH FOR SPANWISE AISLE
FRONT AND REAR FLAT OR CURVED PRESSURE BULKHEAD REQUIRED

3 + 3 SEATING

BWB INTEGRATED SKIN & SHELL CONCEPT

FLAT OR CURVED PRESSURE BULKHEAD REQUIRED

3 + 3 SEATING

SANDWICH UPPER STRUCTURE
SANDWICH FLOOR STRUCTURE
Structural Layout

Second Generation BWB

Exaggerated Cabin Skin Deflection at 2X Pressure
Fundamentals of BWB Aerodynamic Design

Lift, $C_l$ and $(t/c)_{\text{max}}$ Distribution

Narrow Wing Chord

Large Centerbody Chord

$(t/c)$

- 20%
- 15%
- 10%
- 5%
- 0%

$C_l$

- 0.5
- 0.4
- 0.3
- 0.2
- 0.1
- 0.0
Second-Generation BWB
(NASA / Douglas Aircraft 1994-97)
Conventional Baseline
(NASA / Douglas Aircraft 1994-97)
## Performance Comparison

*(NASA / Douglas Aircraft 1994-97)*

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>7,000 nmi</td>
<td>800 Pax in mixed class seating</td>
</tr>
<tr>
<td>TOGW</td>
<td>823,000 lbs</td>
<td>Double-deck cabin</td>
</tr>
<tr>
<td>Wing Area</td>
<td>7,840 sq-ft</td>
<td>Stitched RFI Structure</td>
</tr>
<tr>
<td>Wingspan</td>
<td>280 ft</td>
<td>Simple high-lift system</td>
</tr>
</tbody>
</table>

BWB performance relative to a Conventional Configuration.

- **TOGW**: - 15.2%
- **L/D**: +20.6%
- **Fuel-Burn**: - 27.5%
- **OEW**: - 12.3%
- **Thrust**: - 27%
- **DOC**: - 13%
Planform Trim

BWB has a near elliptic span load with the pitch trim achieved by reflex on the center “afterbody.”

Traditionally flying wings down load the wing tips for pitch trim.
Architecture

Outboard Verticals (Winglets)

Elevons

Rudders

Drag Rudders

Kink-Region

Outer-Wing

Mid-Wing

Afterbody

Centerbody

Krugers

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Upper Surface Pressure Distribution

Navier-Stokes

Cp

1.0

-1.0
BWB Wind Tunnel Testing

National Transonic Facility (NTF)
M=0.85
Performance & Design Tool Validation

Comparison of CFD Predictions with NTF Results

NASA LaRC 14x22-foot Tunnel
Power Effects, High Lift, Stability & Control, Ground Effects

April '97
August '97
Flight Control Testbed Built by Stanford University

Official First Flight
July 29, 1997 - El Marage, California

- Wingspan = 17 ft
- Gross Weight = 155 lbs
- Thrust = 36 lbs
- Dynamically Scaled Model

July '97
Current BWB-Baseline in the NTF Tunnel
Technical Focus Areas

**Flight Mechanics**

- Performance gain – reduced wing area and weight
- 777 controllable in post-stall region

**Composite Structures**

- Weight challenge from flat-sided pressure vessel
- Increased challenge to maintain control in unstable post-stall region

**BWB Fuselage Section**

- Validation of cost reductions needed
- Practical composite issues: lightning protection, thermal compatibility, fuel compatibility

BWB Spin Tunnel Test

BWB Control Surface
BWB X-48B

- Two vehicles built at Cranfield Aerospace
  - 20.4-foot wing span
  - Dynamically scaled
  - Remotely piloted
  - NASA/AFRL contributions include testing in 30x60 wind tunnel and at Dryden

- Investigate
  - Stall characteristics and departure boundaries
  - Asymmetric thrust controllability
  - Control surface hinge moments
  - Dynamic ground effects

• 250 hours of testing completed in Langley 30x60 wind tunnel
  - Data now being analyzed for use in X-48B simulation and flight control software
• First flight planned for 4Q ‘06 at Dryden
Current Boeing BWB-Baseline

6 - bays

247’ 6”

42’ 7”

157’ 10”
Centerbody Interior Cross-Sections
Structural Weight Fractions

Conventional Aircraft

- Empennage: BWB 82% Conventional 18%
- Wings: BWB 27% Conventional 73%
- Body: BWB 21% Conventional 79%
- OEW: BWB 9% Conventional 91%
- MTOW: BWB 11% Conventional 89%

Blended Wing-Body

- Tailless aircraft
- Approx. 170K lb payload
- Approx. 9,000 nm range
- Composite structure
- Advanced Technology

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Growing a Highly-Common Family

- Fuel volume available in wing
- Adds payload
- Adds wing area
- Adds span
- Balanced
- Aerodynamically Smooth
- Common Cockpit, Wing and Centerbody Parts

- Each bay in the BWB is an identical “cross-section” and thus lends itself to high part/weight commonality amongst the family members
- The BWB 6-bay retains 97% of the BWB 4-bay’s furnishings weight

BWB 6-bay/4-bay Common

BWB 6-bay T-plug

BWB 6-bay/4-bay Common
Definition of Common/Cousin Parts
Between BWB 4-bay and 6-bay

- **Total Aircraft by Weight**
  - 39% Common
  - 28% Unique
  - 33% Cousin

- **Non-Recurring Commonality Benefit**
  - 23%

- **Recurring Commonality Benefit**
  - 12%

- **Recurring Fleet Cost**
  - 58%

- **Non-Recurring Fleet Cost**
  - 42%

- **Gauge Changes**
- **Payloads - 80% Common**
- **- 14% Cousin**
- **Wing Inner Spars & Bulkheads - 100% Common**

- **Unique OML for Stretch**
\[ \frac{D}{q_0} \approx \frac{1}{2\pi} \int_0^1 \int_0^1 S''(x)S''(\xi) \log \frac{1}{|x - \xi|} dx d\xi \]
ML/D and MP/D Trends with Mach Number

M*L/D

M*P/(D*SFC)

Mach

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Effect of Mach Number

BWB 4-bay

$M_0.85$

$M_0.90$

$M_0.95$
Airplane Efficiency

Note: Lower efficiency of military transports due to aft ramps, high wing, large gear, etc.

*Using Maximum Payload, Range at Maximum Payload, and Cruise Mach Number
Fan Flow Deflection (FFD*)

(a) Jet Noise Suppression

Deflector vanes internal to fan duct tilt bypass plume downward and sideward relative to core plume

Thick layer of bypass flow on underside of jet hinders noise emission from hot core in the downward and sideline directions

• The FFD technology has been tested in subscale experiments in the Jet Aeroacoustics Facility at UCI. There is excellent agreement between the UCI baseline acoustic data and those from large-scale hot facilities at NASA Glenn.

• For a BPR=5 configuration, reductions of up to 5 EPNdB in takeoff noise and 4 EPNdB in sideline noise have been recorded.

• Analysis and computation predict thrust losses of around 0.1-0.3%.

*The FFD technology has been developed by Prof. Dimitri Papamoschou at U.C. Irvine (dpapamos@uci.edu; 949-824-6590). University of California Proprietary; U.S. Patent Pending.
**Fan Flow Deflection (FFD*)**

(b) Thrust vectoring for aerodynamic control

The FFD method offers the potential for thrust vectoring (longitudinal and/or lateral). Below are preliminary analytical estimates of side force and thrust loss for a BPR=8 configuration at 0.2 flight Mach number.

<table>
<thead>
<tr>
<th>Vane angle of attack (deg)</th>
<th>Side force/ Total thrust</th>
<th>Thrust loss (entire engine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
<td>0.2%</td>
</tr>
<tr>
<td>5</td>
<td>3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>10</td>
<td>6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>15</td>
<td>9%</td>
<td>1.0%</td>
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<tr>
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<td>5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>10</td>
<td>10%</td>
<td>1.0%</td>
</tr>
<tr>
<td>15</td>
<td>14%</td>
<td>1.8%</td>
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*The FFD technology has been developed by Prof. Dimitri Papamoschou at U.C. Irvine (dpapamos@uci.edu; 949-824-6590). University of California Proprietary; U.S. Patent Pending.
Cambridge-MIT Silent Aircraft

Current aircraft appears capable of sub 63 dBA on takeoff and approach.
Estimated fuel burn of 124 passenger miles per gallon.

Blended-Wing-Body type airframe.

Distributed, embedded propulsion system.

Each engine cluster has one core driving three fans.

Range: 5,000 nm
Pax: 215
Initial Cruise Alt: 40,000 ft
Cruise Mach: 0.8
Cruise ML/D: 20.1

Span: 207.4 ft
Gross Area: 8,998 ft²

OEW: 207,660 lbs
Payload: 51,600 lbs
Fuel: 73,310 lbs
MTOW: 332,560 lbs
Three Generation Comparison

First-Generation

Second-Generation

Current BWB Baseline
Issues and Areas of Risk

- Complex flight control architecture & allocation, with severe hydraulic requirements
- Large auxiliary power requirements
- New class of engine installation
- Flight behavior beyond stall
- High floor angle on take off & approach to landing
- Acceptance by the customer
- Performance at long range
- Experience & data base for new class of configuration limited to military aircraft

Douglas Aircraft Co. circa 1955 regarding the challenge of moving from the DC-7 to the DC-8
Potential Next Steps

- Lower engines & eliminate pylons
- Examine (once again) boundary-layer ingestion
- Replace verticals with thrust vectoring
- Pursue a low-noise configuration
- Develop a short-field configuration
- Consider LH2
Advanced BWB Configuration

Boundary-layer ingesting inlets

Thrust vectoring
Hydrogen-Powered BWB

- Compared to a tube & wing airplane, a jet fuel-powered BWB typically has 50% more internal fuel volume than needed for a mission.
- Thus, the incremental increase in fuel volume required for a BWB LH₂ version is less than required for the tube & wing airplane.
- Wing chord and thickness increased to maintain payload/range for a LH₂-powered BWB (< 3X net fuel volume compared to >4X for tube & wing).
- Aerodynamic, structural weight and fuel volume penalties for containing LH₂ require further study.
Innovation: Before & After

Initial Goal: Create a concept for a subsonic transport that may be distinct from tube & wing (DC-8, B707).

Initial Result: BWB that offered reduced fuel burn via a very high Lift/Drag ratio and large wingspan.

Developed Result: BWB that offers breakthrough fuel efficiency and noise reduction.

Unplanned Features: Natural family, low noise, low part-count and low cost.

Unplanned Liability: As a disruptive technology, the BWB may be regarded as a threat to existing airplanes.
Thank You

Boeing X-48B