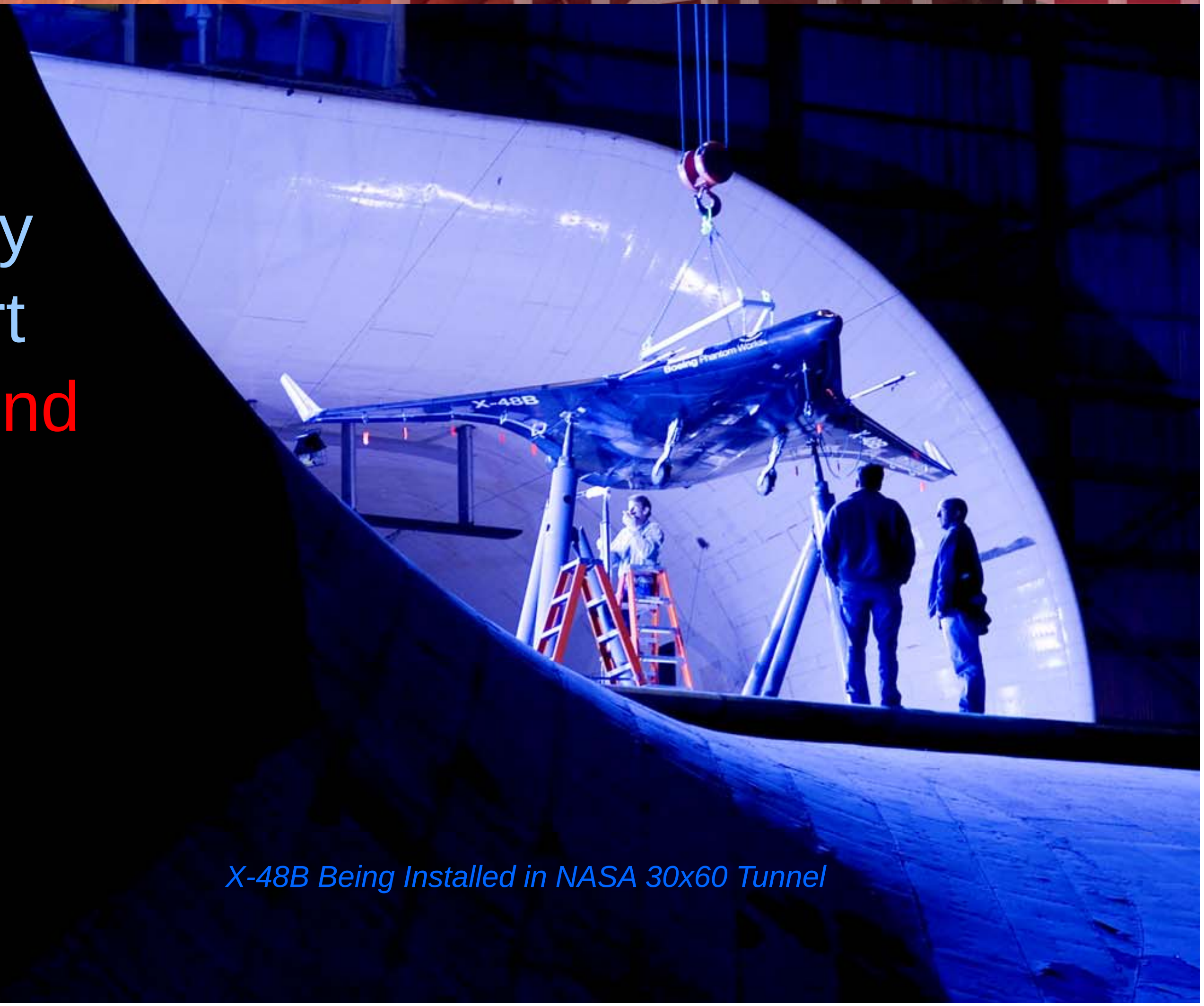
Blended Wing Body Subsonic Transport
Then, Now & Beyond



X-48B Being Installed in NASA 30x60 Tunnel

ICAS 2006

R. H. Liebeck

September 2006

THE ROYAL AERONAUTICAL SOCIETY

35th WILBUR WRIGHT MEMORIAL LECTURE

THE DEVELOPMENT OF ALL-WING AIRCRAFT

by

JOHN K. NORTHROP

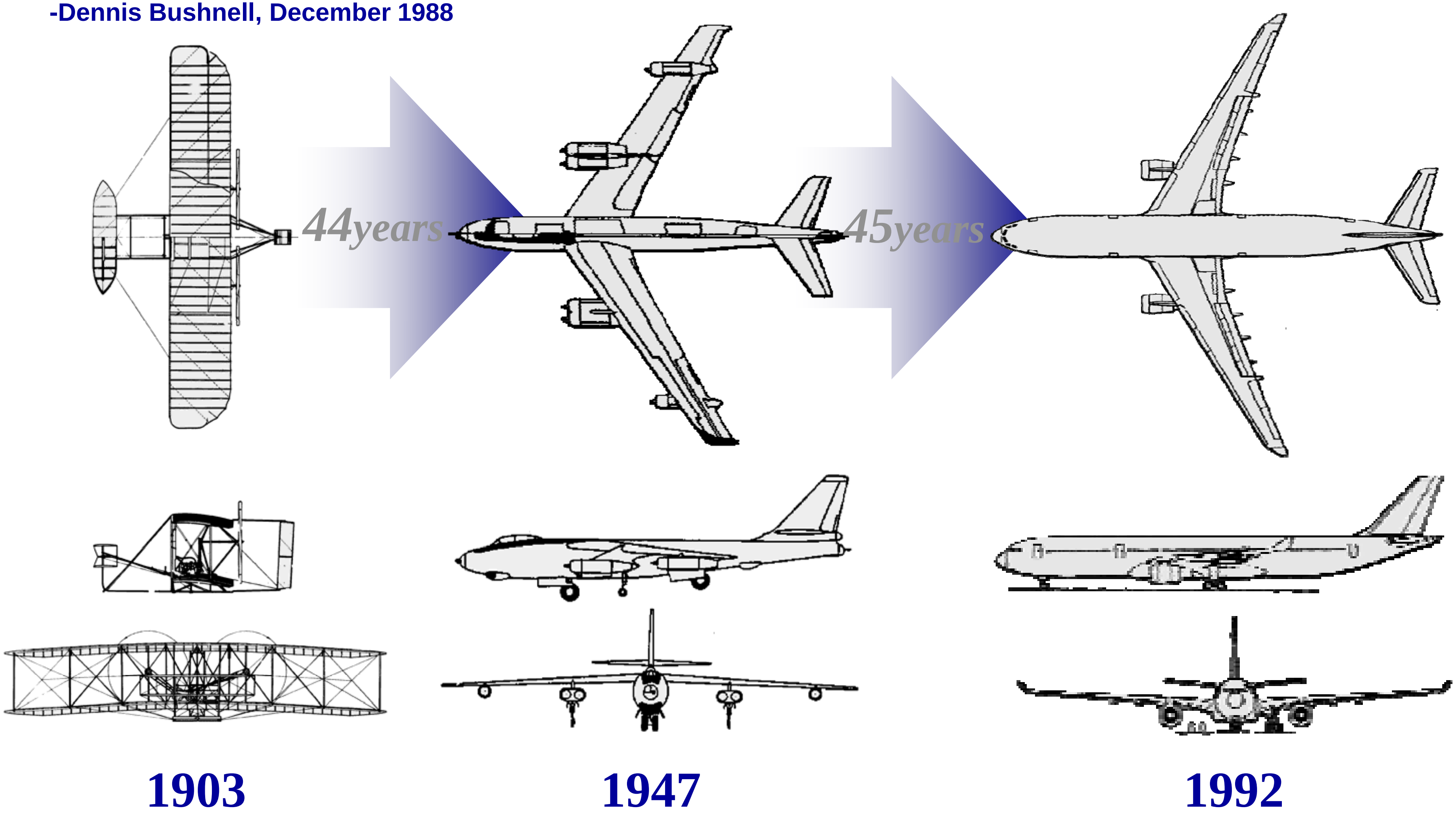
Mr. Northrop is President and Chief Designer of Northrop Aircraft Inc. He has been designing and experimenting with the all-wing type of aeroplane since 1923 *and built his first machine in* 1928.

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

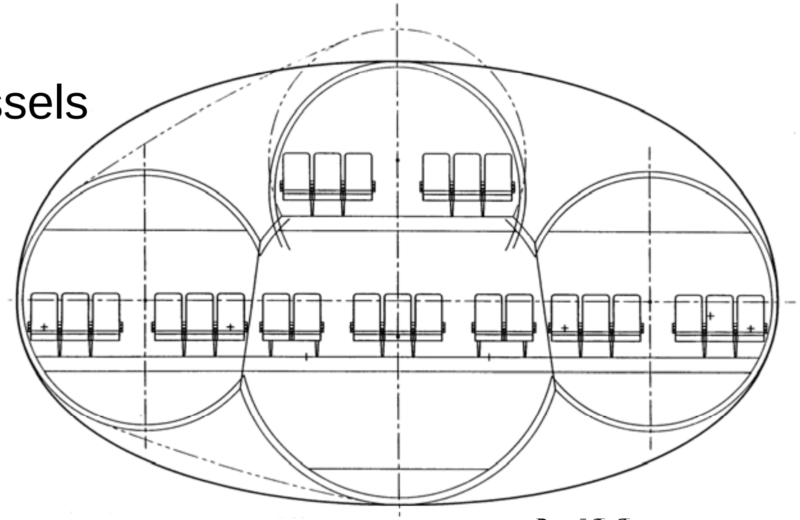


BOEING

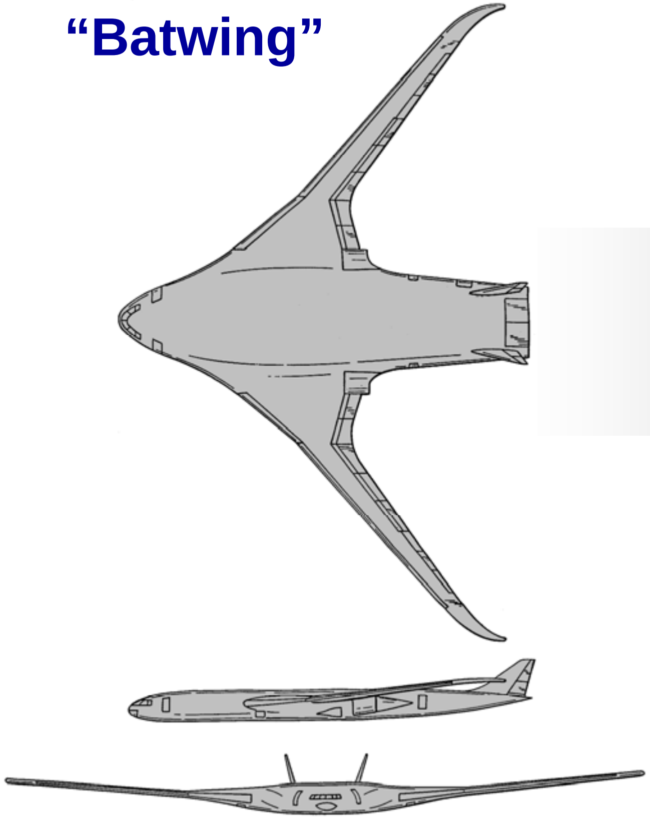
Early BWB Concept

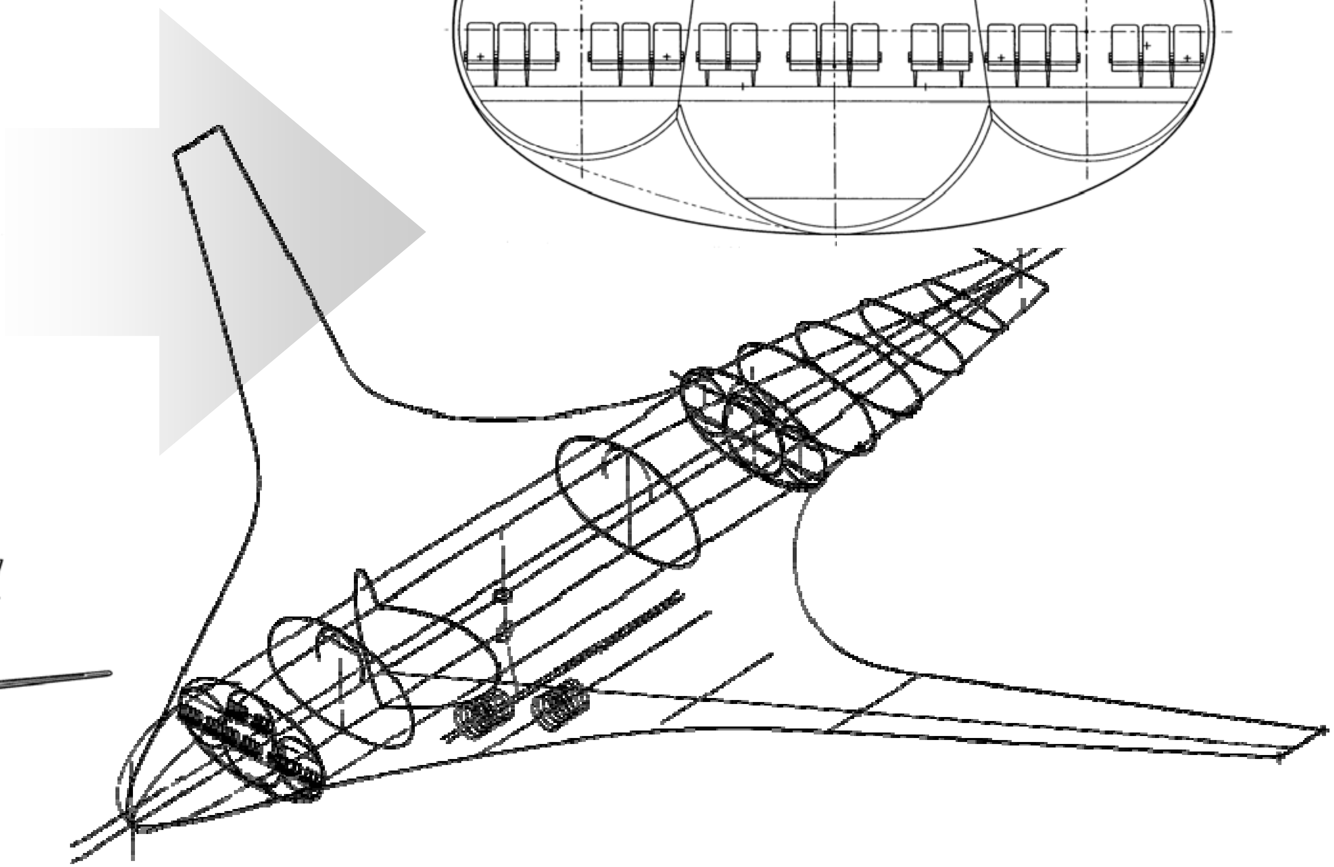
(NASA / Douglas Aircraft 1993)

Span Loading with
Circular Pressure Vessels



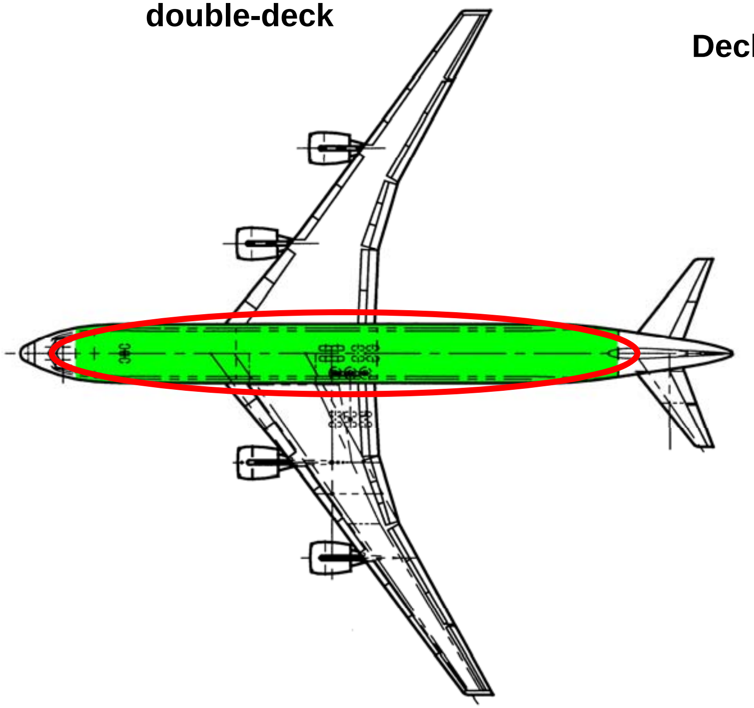
“Batwing”



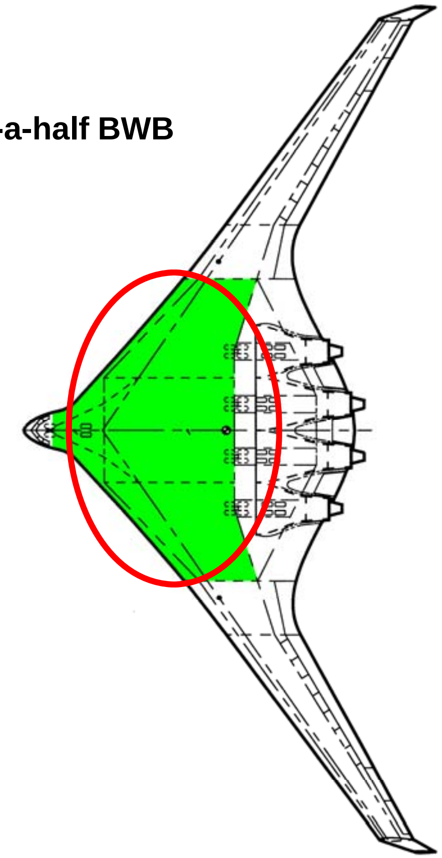


Payload Packaging

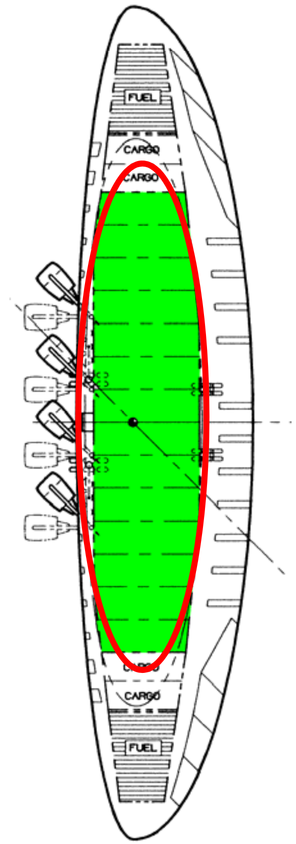
Conventional
double-deck



Deck-and-a-half BWB



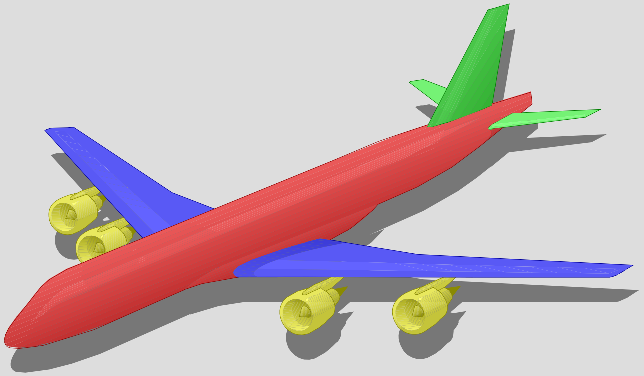
Single-deck
Oblique All-Wing



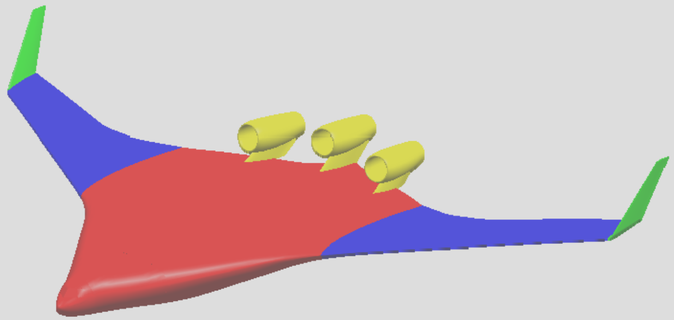
Longitudinal Loading ⟷ Span Loading

Aerodynamic Efficiency

Conventional Aircraft



Blended Wing Body



Wetted Area Comparison

	Conventional Aircraft	Blended Wing Body
Fuselage	23,000 ft^2	22,000 ft^2
Wing	12,000 ft^2	6,000 ft^2
Propulsion	4,000 ft^2	1,200 ft^2
Empennage	5,000 ft^2	500 ft^2
Total	44,000 ft^2	29,700 ft^2

-33%

1/3 less wetted area than conventional configuration

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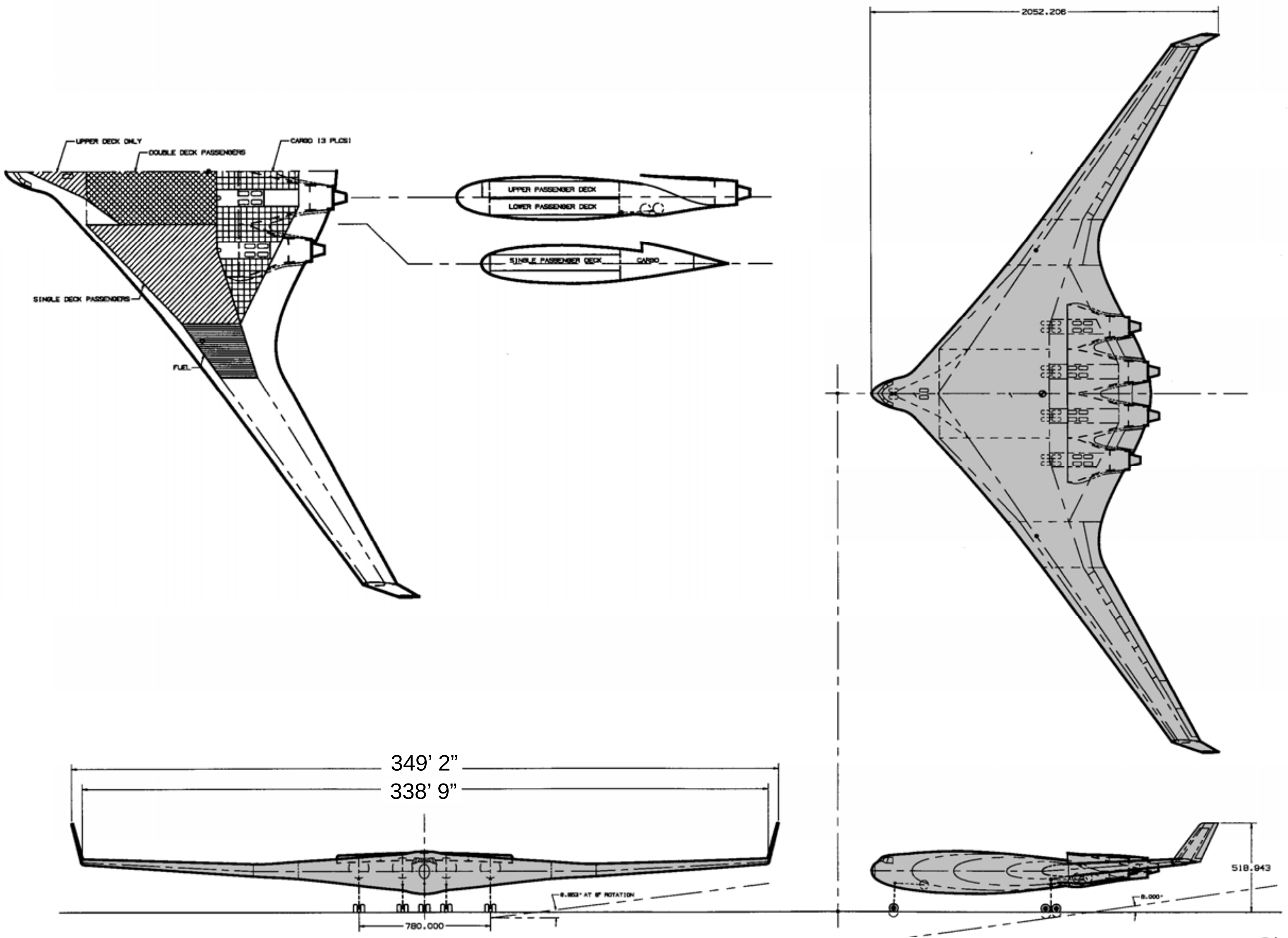
First-Generation BWB

(NASA / Douglas Aircraft 1993)



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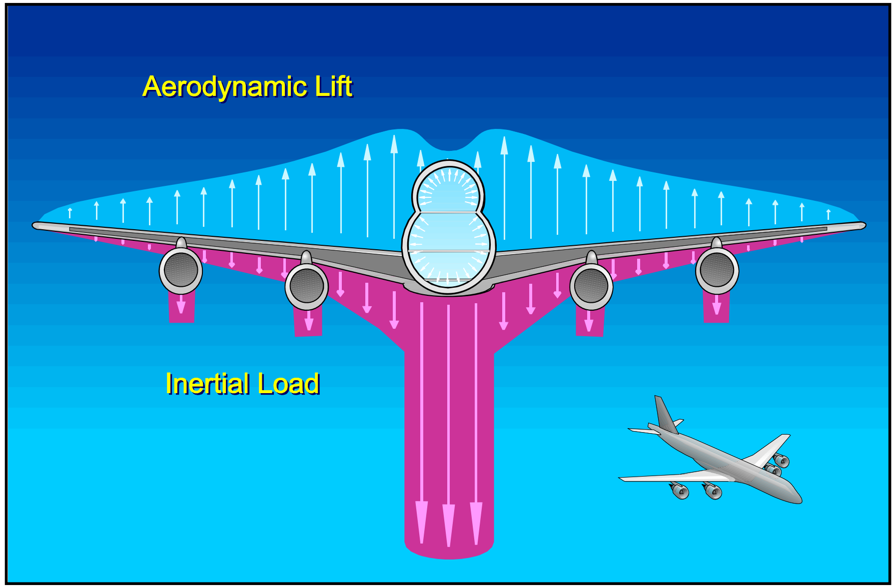
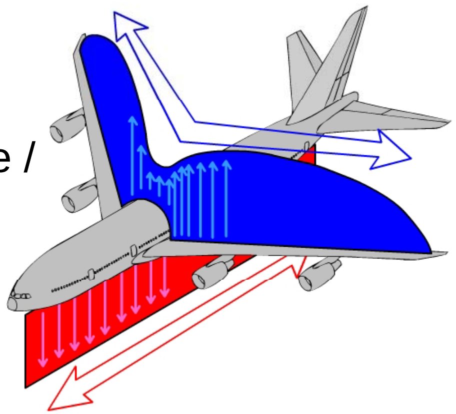
Wing & Pressure Vessel Loads

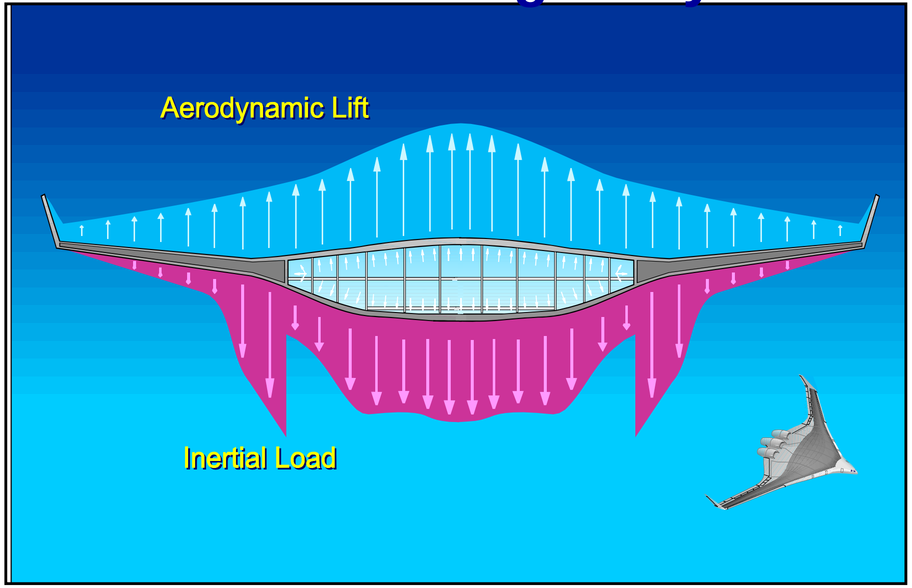
Conventional Aircraft



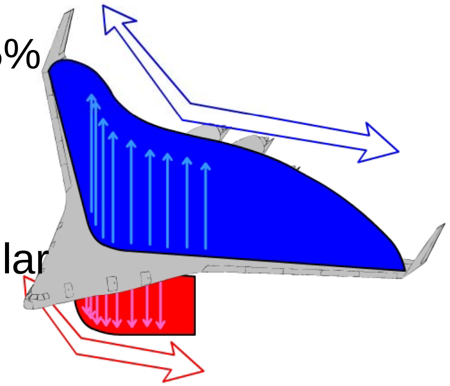
- Ideal pressure loading
- Limited span loading
- Independent wing box and fuselage structure
- Fuselage has very little / no lifting capability
- Payload distributed normal to the wing



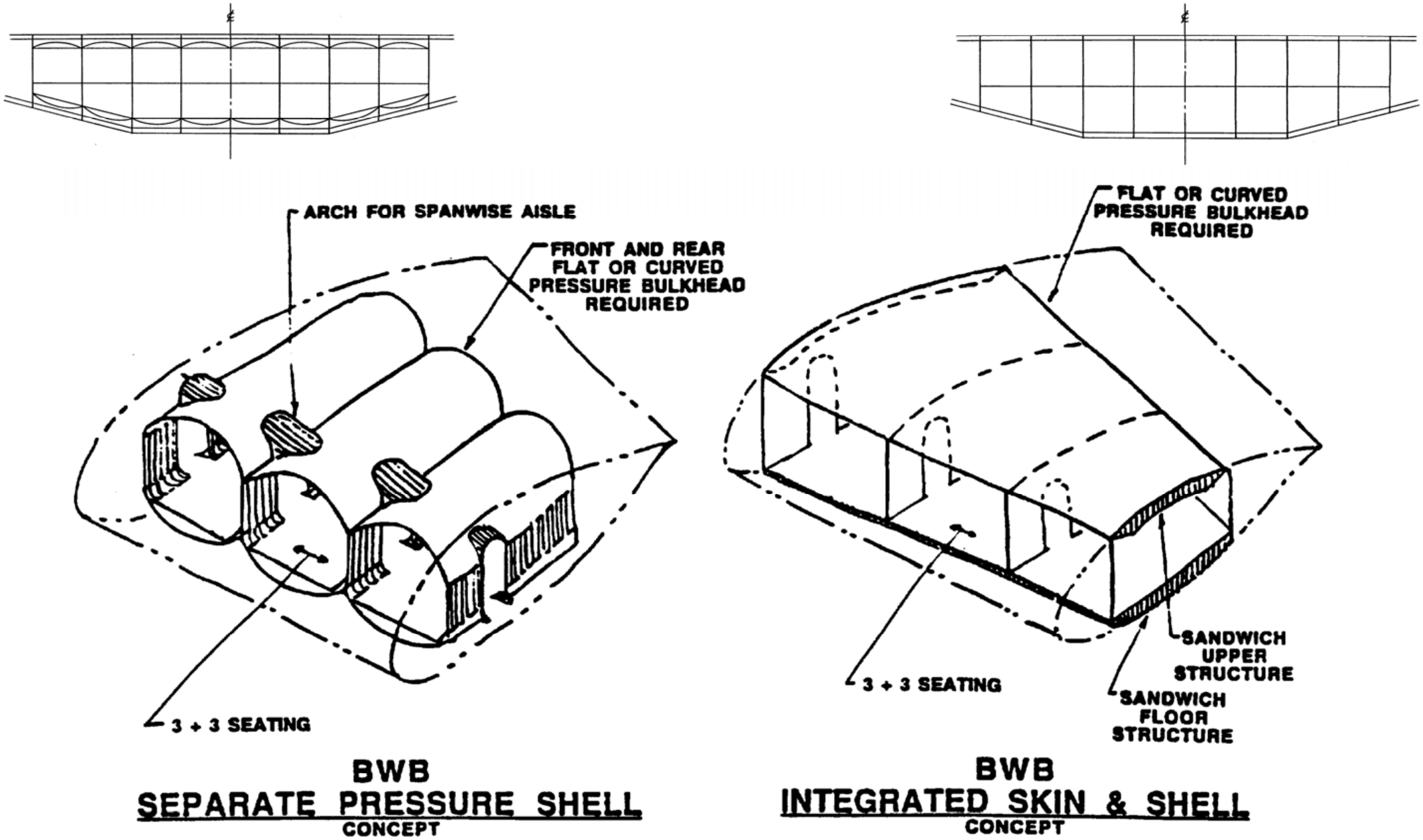
Blended Wing-Body



- "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

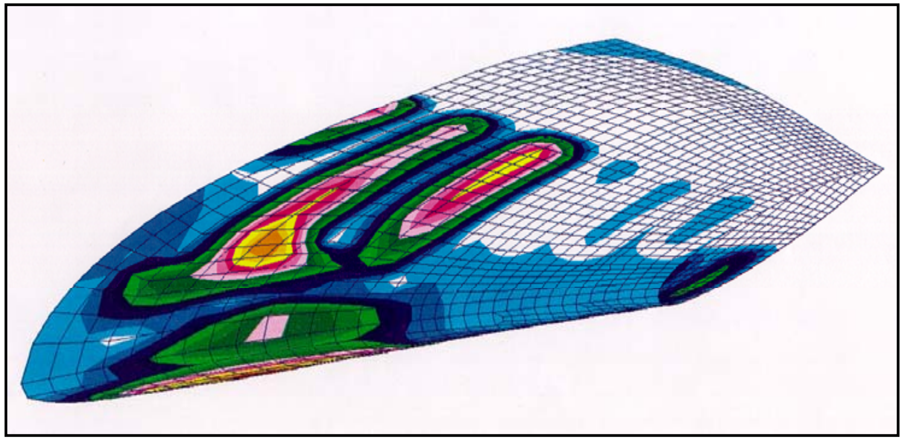


Centerbody Pressure Vessel Concepts

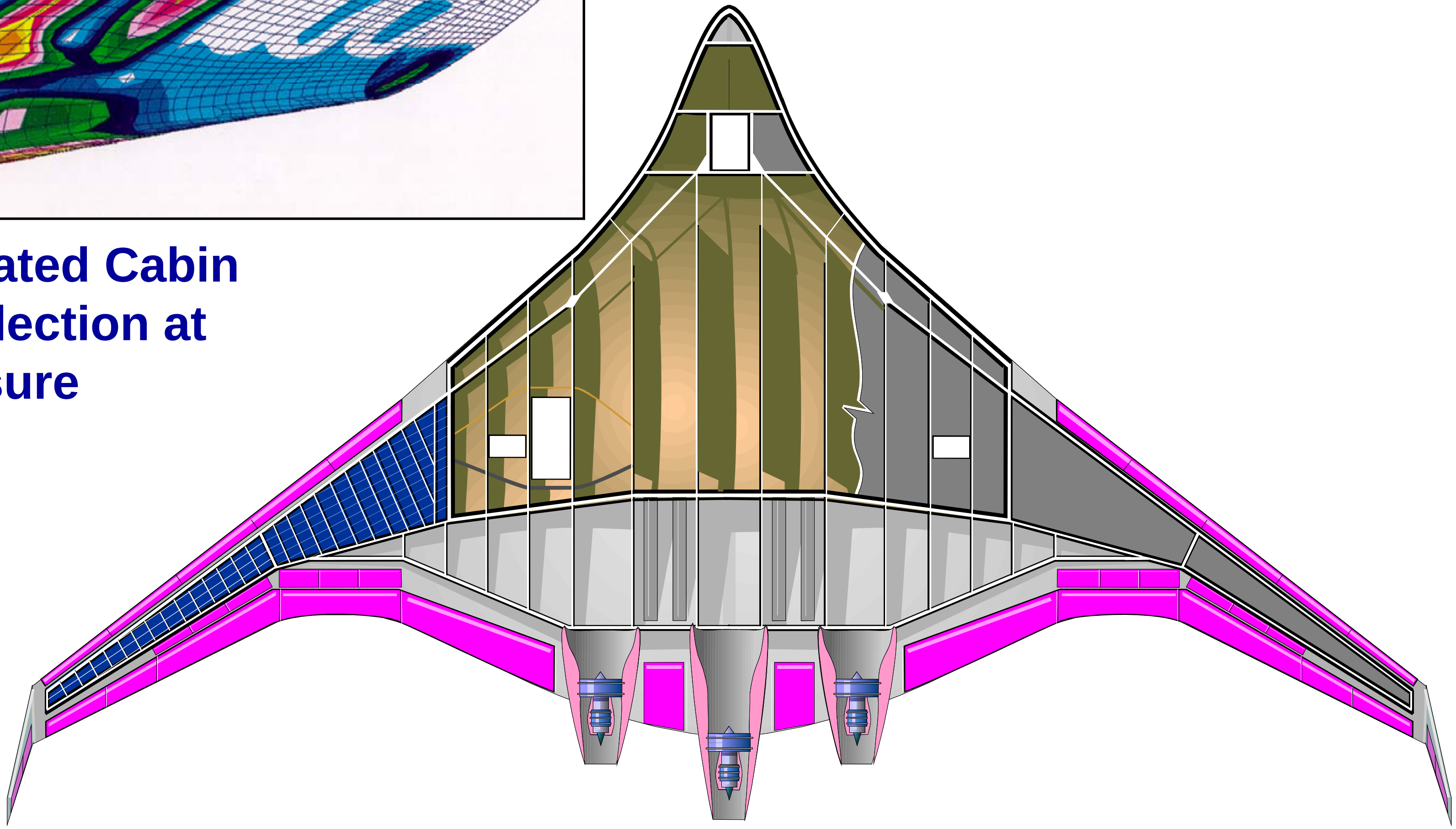


Structural Layout

Second Generation BWB

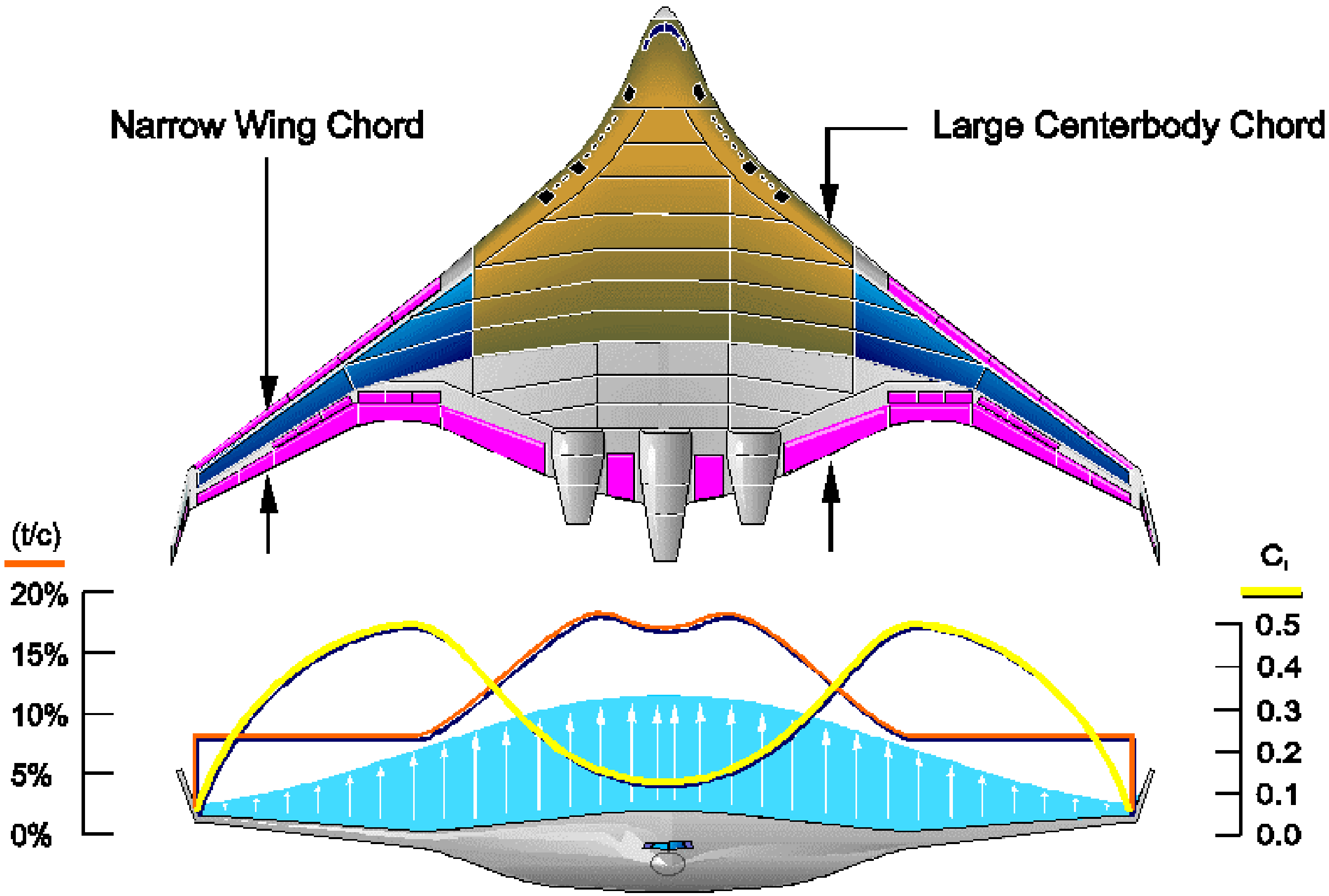


Exaggerated Cabin Skin Deflection at 2X Pressure



Fundamentals of BWB Aerodynamic Design

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



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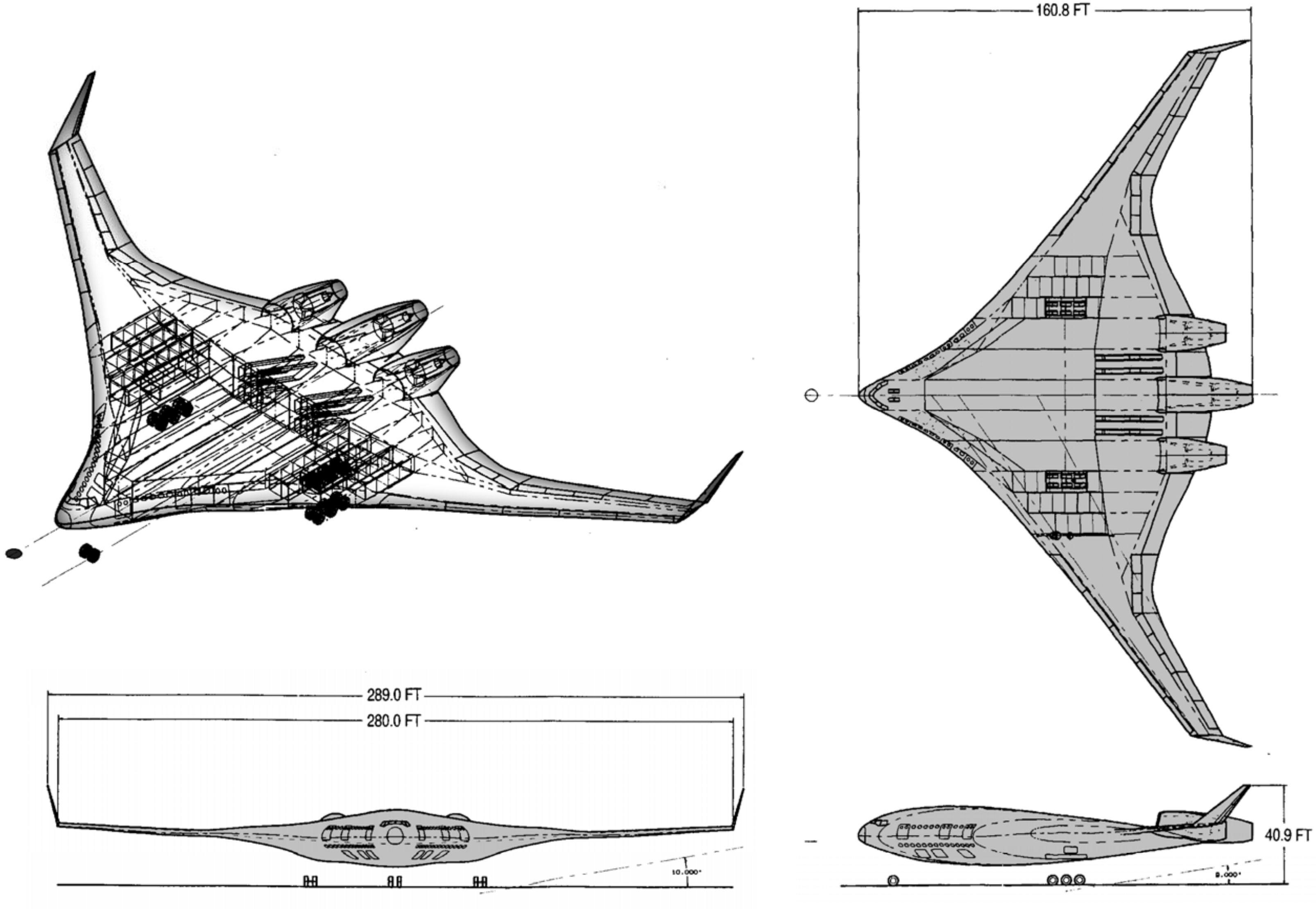
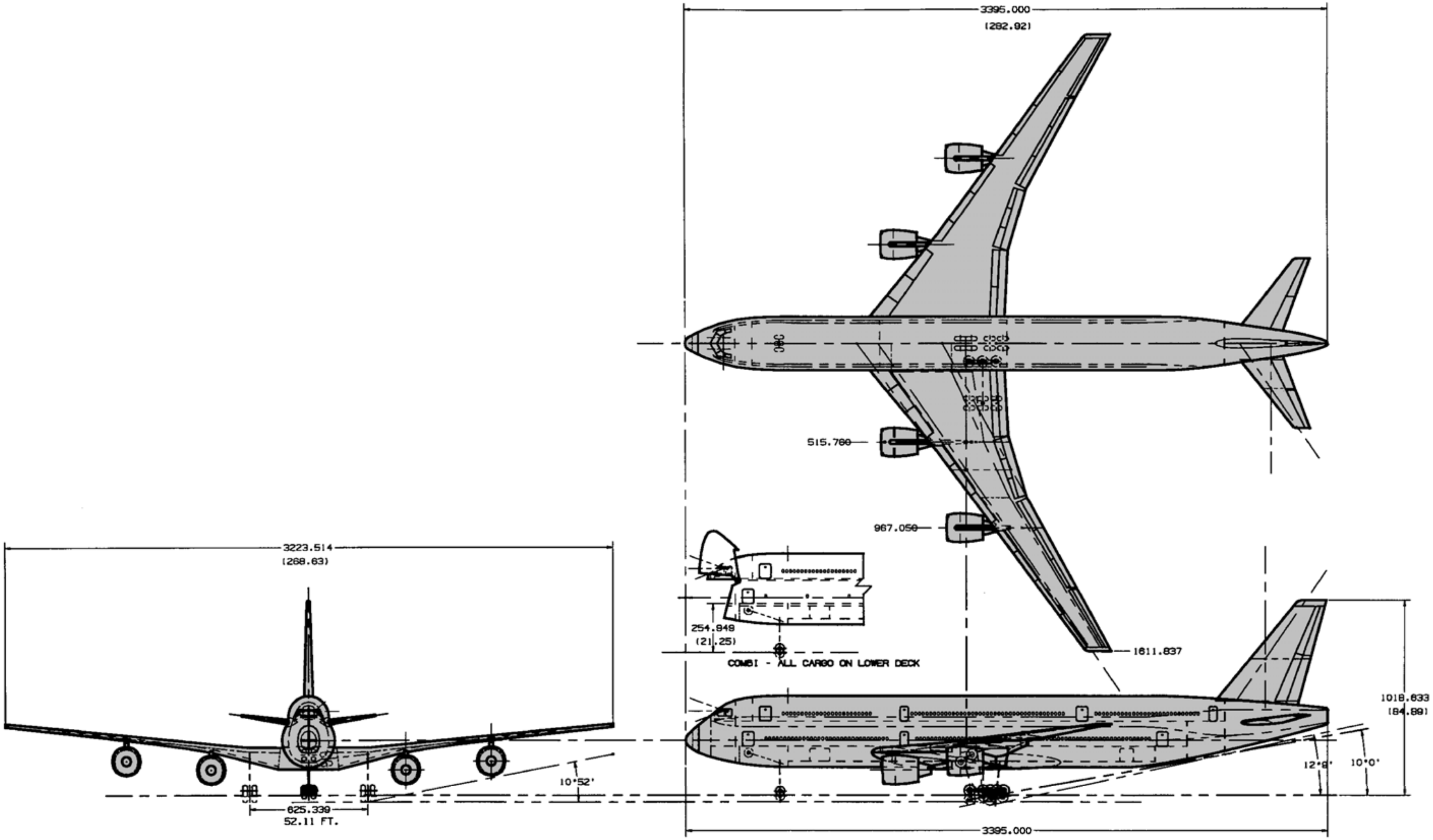
Second-Generation BWB
(NASA / Douglas Aircraft 1994-97)



Conventional Baseline
(NASA / Douglas Aircraft 1994-97)



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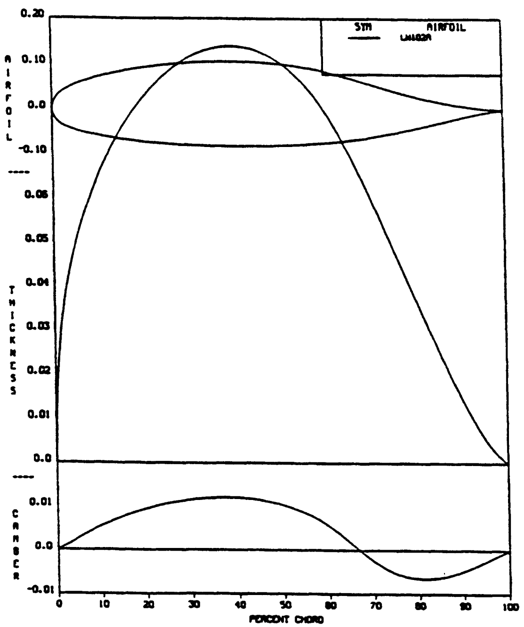
Performance Comparison
(NASA / Douglas Aircraft 1994-97)

Range	= 7,000 nmi	800 Pax in mixed class seating
TOGW	= 823,000 lbs	Double-deck cabin
WingArea	= 7,840 sq-ft	Stitched RFI Structure
Wingspan	= 280 ft	Simple high-lift system

BWB performance relative to a Conventional Configuration.

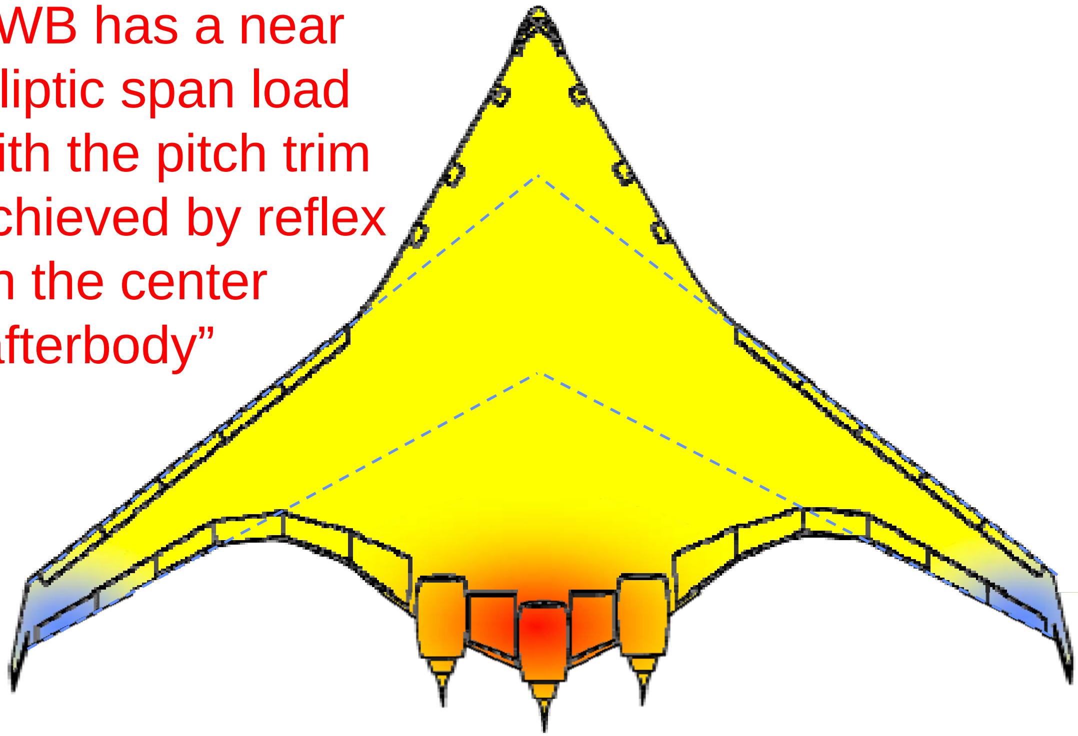
TOGW	- 15.2%
L/D	+ 20.6%
Fuel-Burn	- 27.5%
OEW	- 12.3%
Thrust	- 27%
DOC	- 13%

Planform Trim



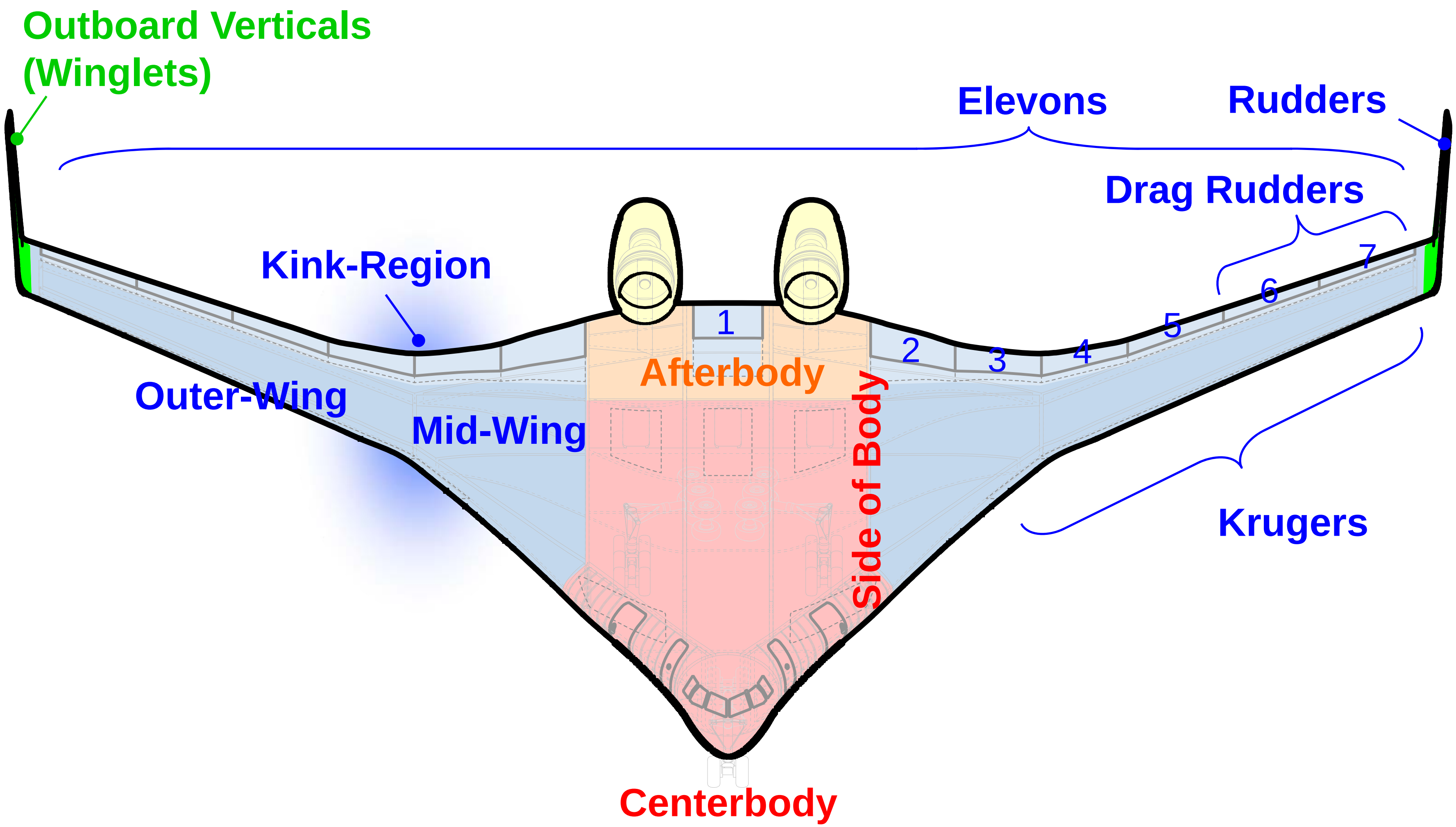
Original Inboard Airfoil Section

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



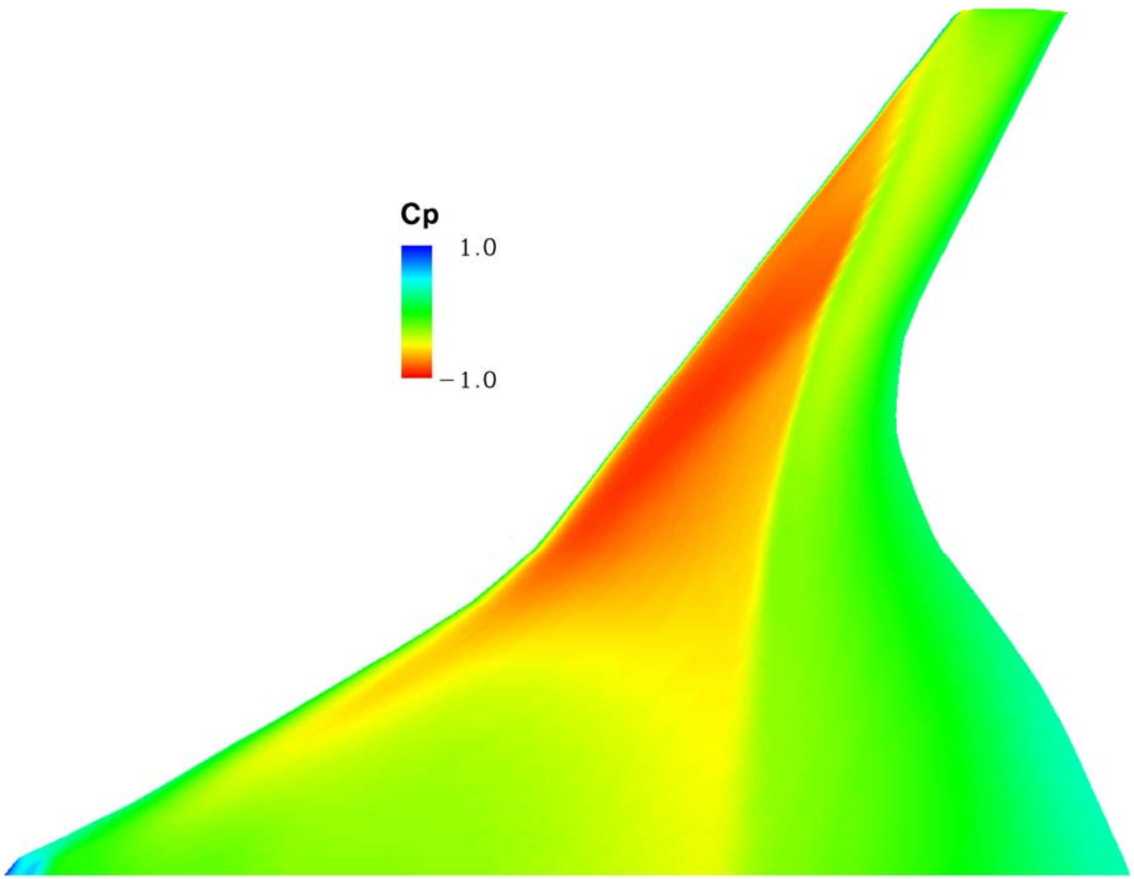
Traditionally flying wings down load the wing tips for pitch trim

Architecture



Upper Surface Pressure Distribution

Navier-Stokes



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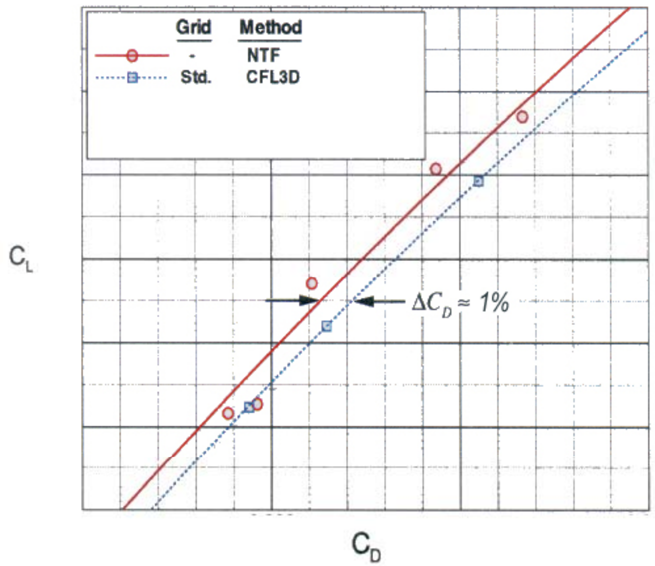
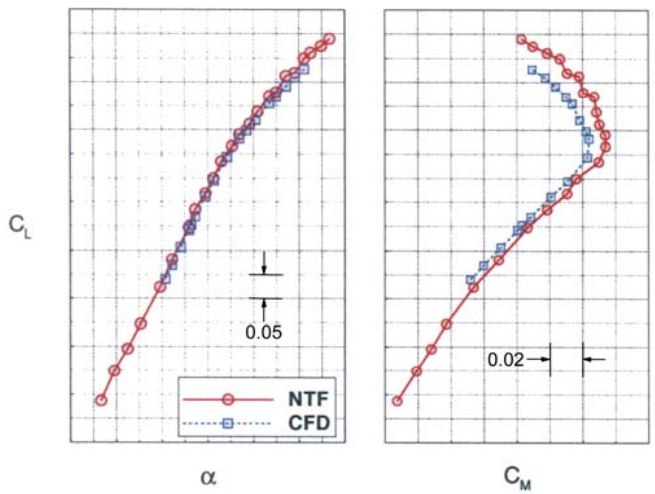
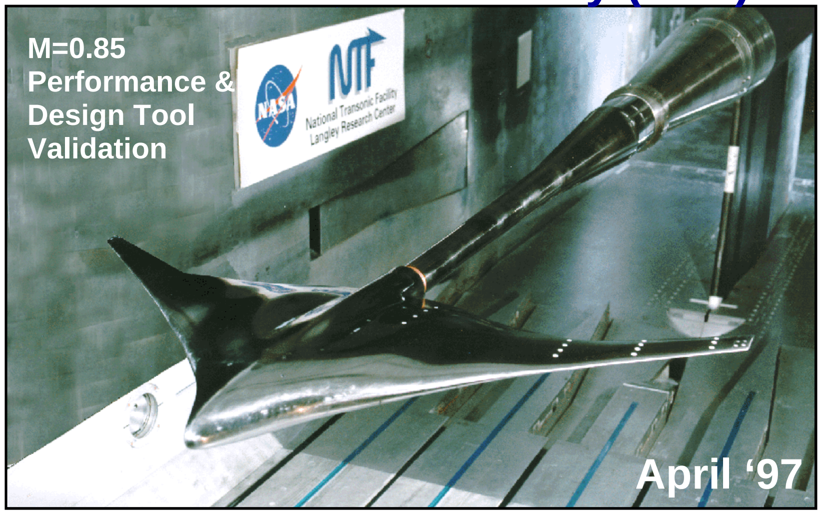
BWB Wind Tunnel Testing



Comparison of CFD Predictions with NTF Results

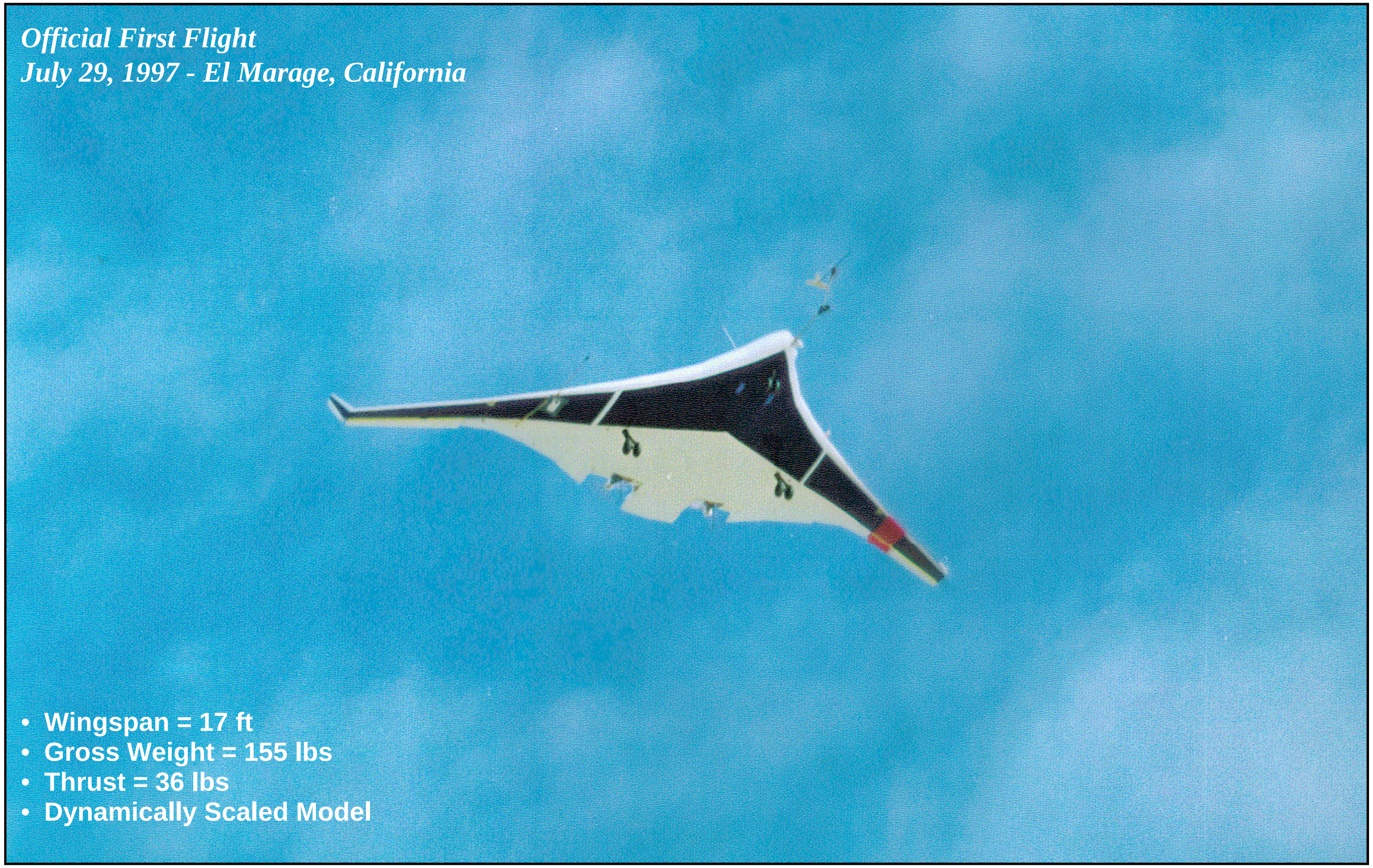


National Transonic Facility (NTF)



NASA LaRC 14x22-foot Tunnel

Flight Control Testbed Built by Stanford University

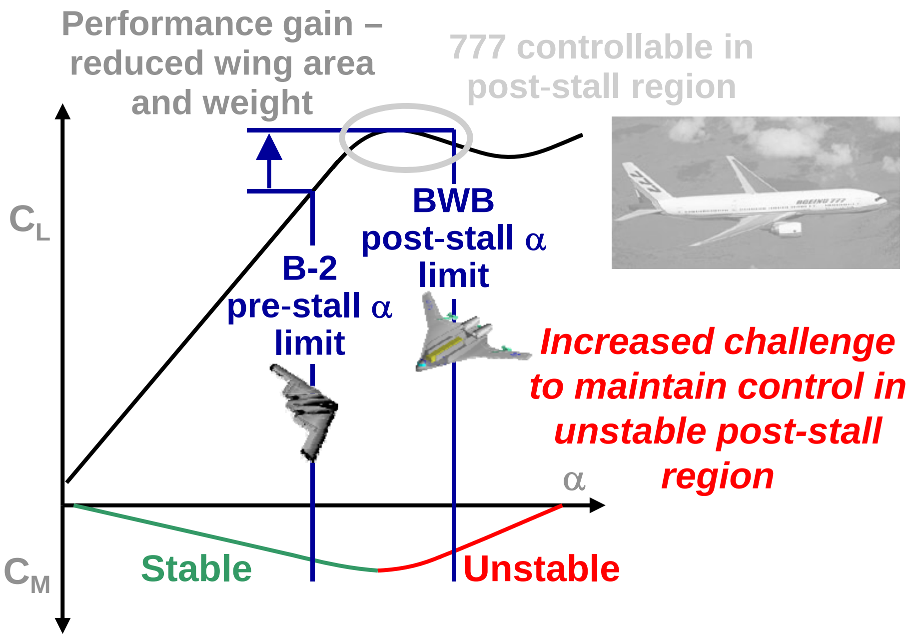


July '97

Current BWB-Baseline in the NTF Tunnel

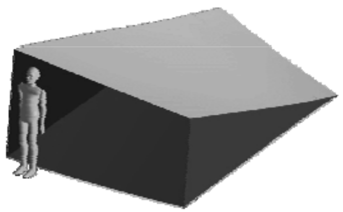
Technical Focus Areas

Flight Mechanics



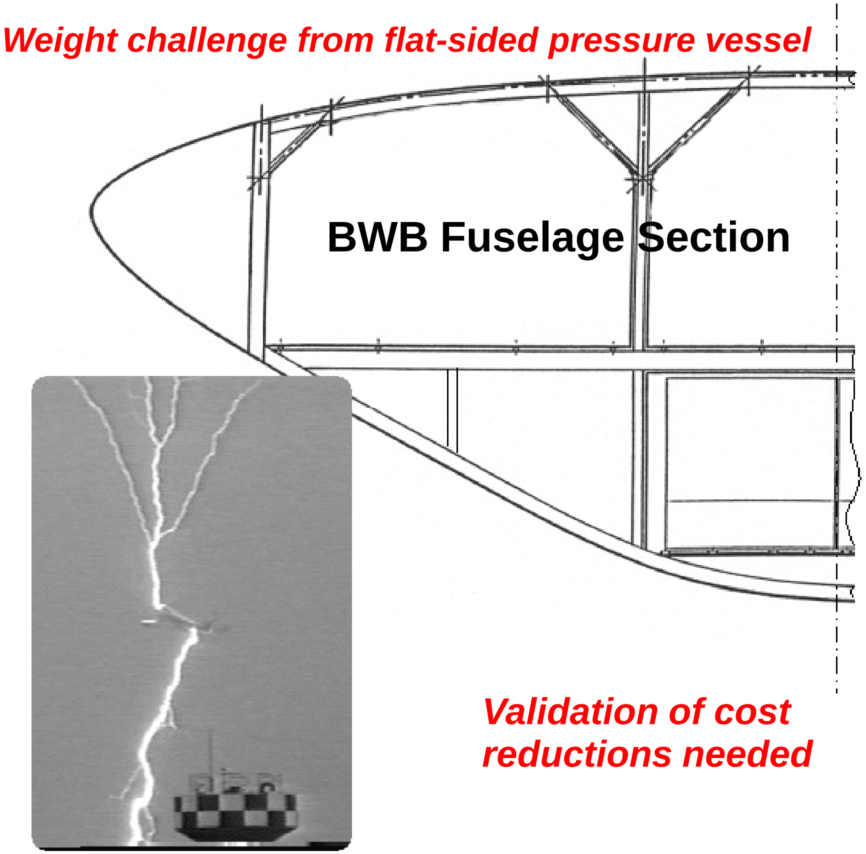
BWB Spin Tunnel Test

BWB Control Surface



Composite Structures

Weight challenge from flat-sided pressure vessel



Validation of cost reductions needed

Practical composite issues: lightning protection, thermal compatibility, fuel compatibility

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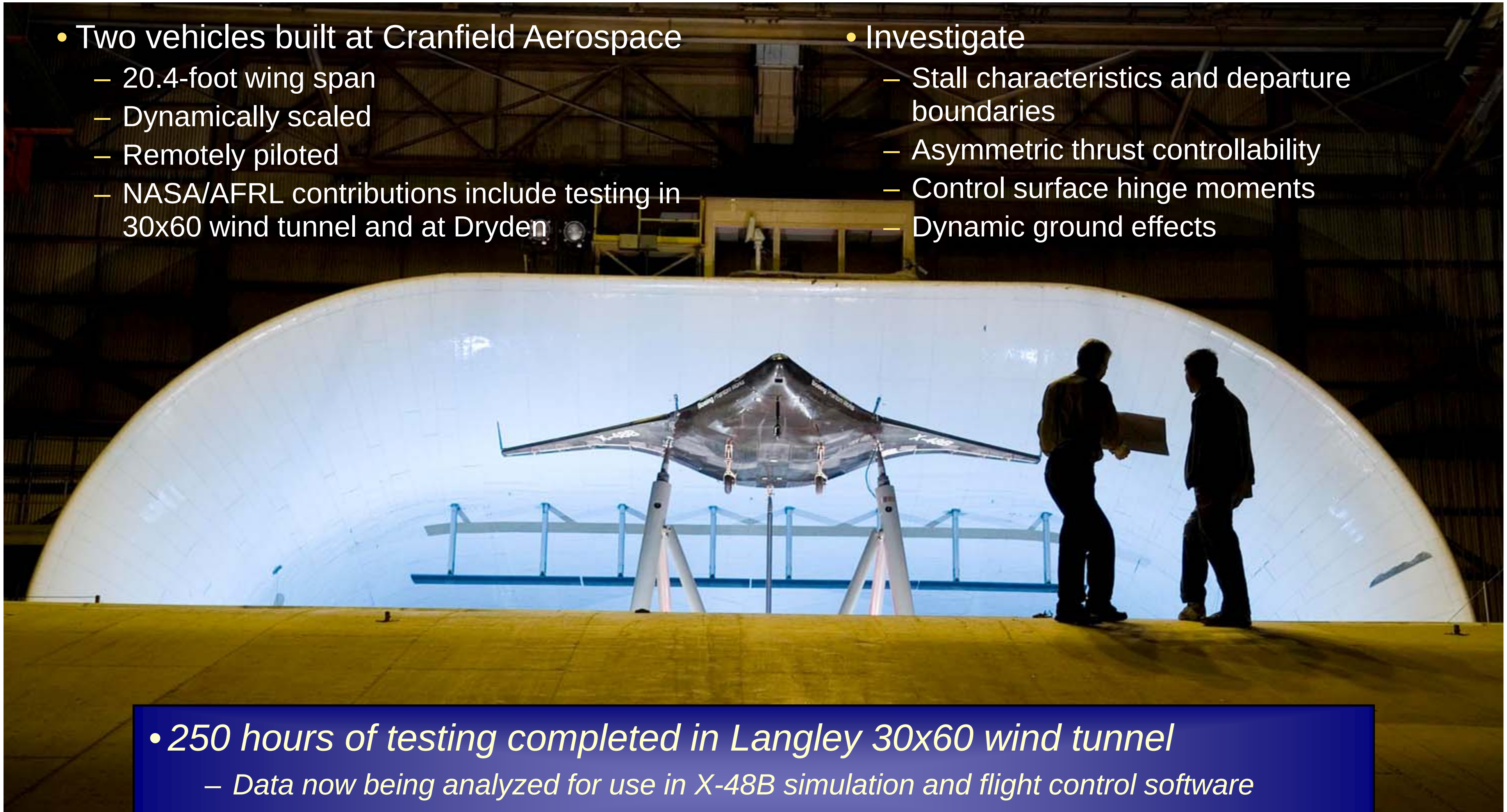
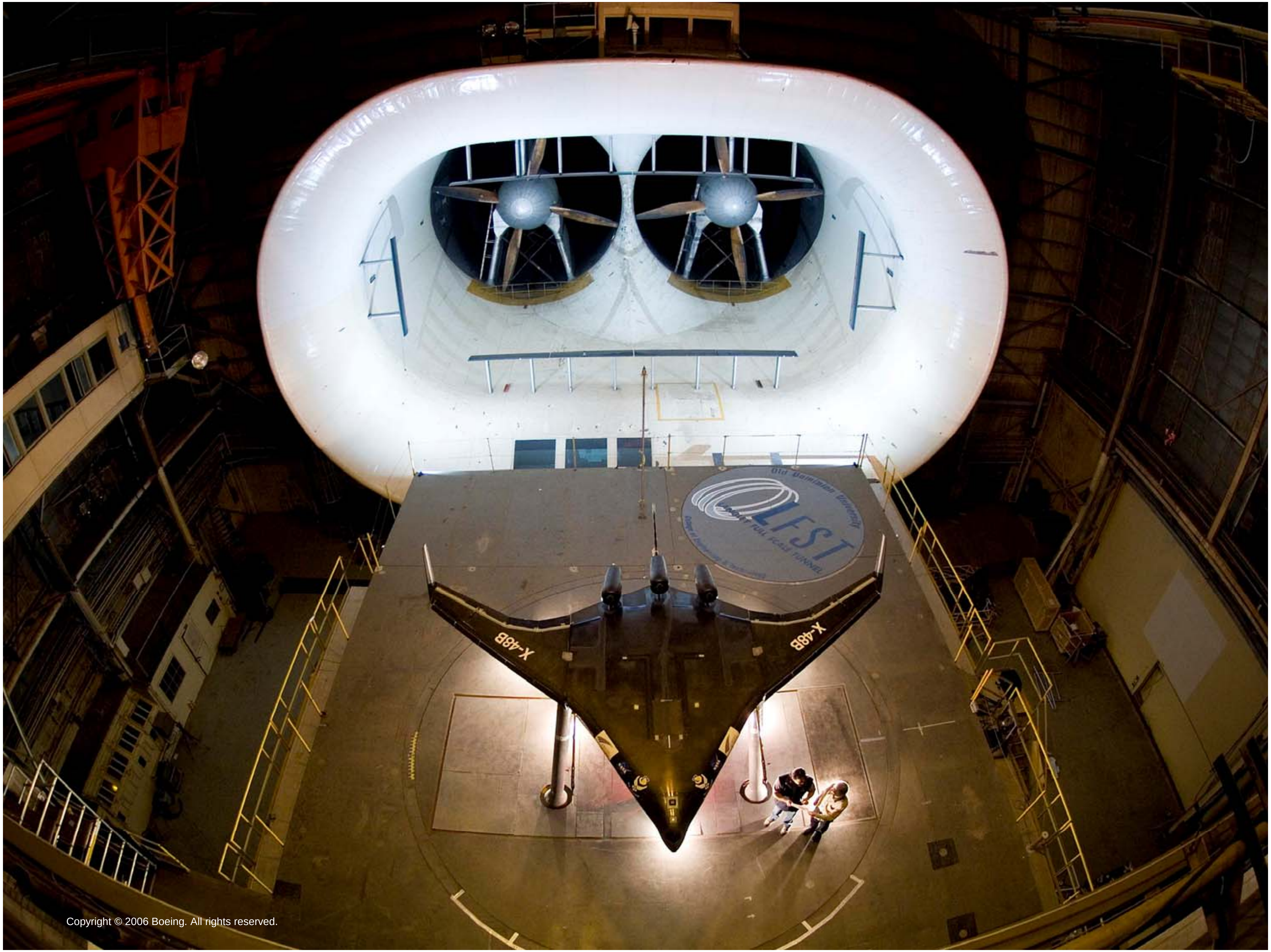
BWB X-48B



- 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

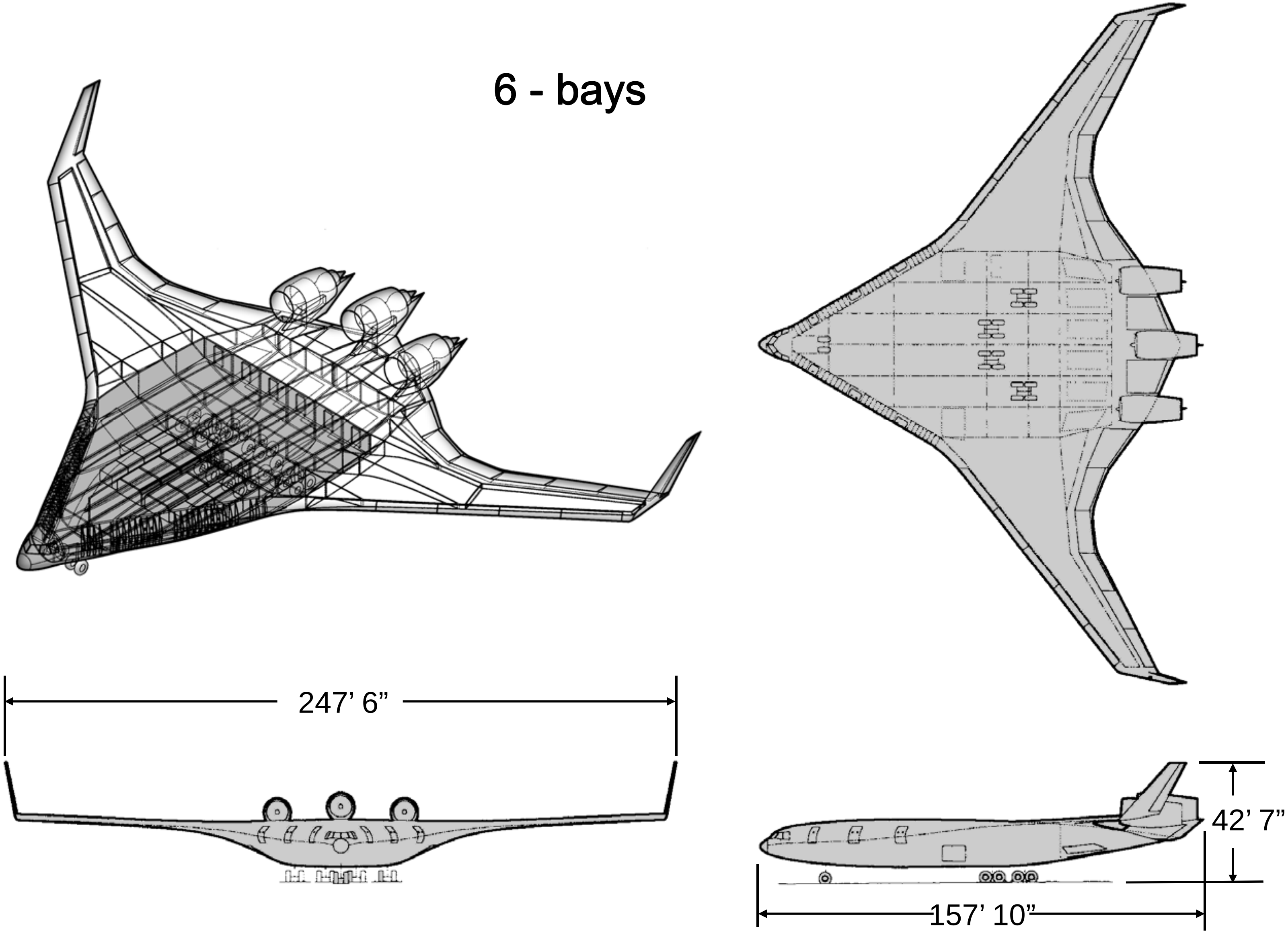
- *250 hours of testing completed in Langley 30x60 wind tunnel*
  - *Data now being analyzed for use in X-48B simulation and flight control software*
- *First flight planned for 4Q ’06 at Dryden*


X-48B
X-48B
COLLEGE OF ENGINEERING AND


X-48B
X-48B


X-48B
X-48B

Current Boeing BWB-Baseline



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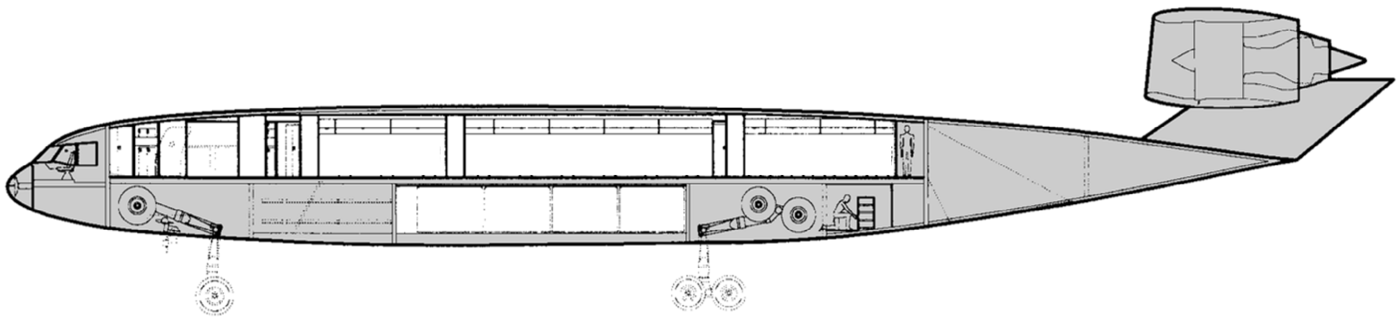
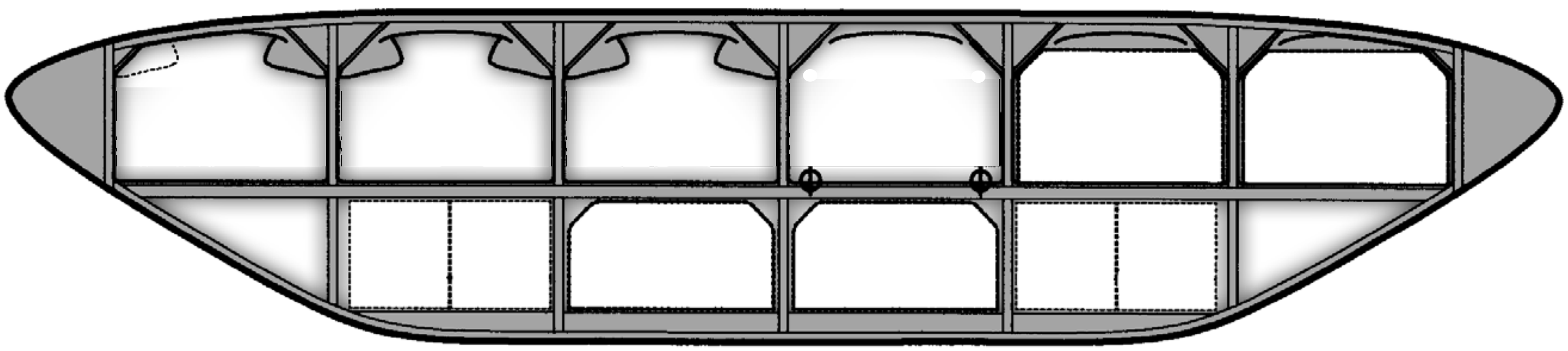
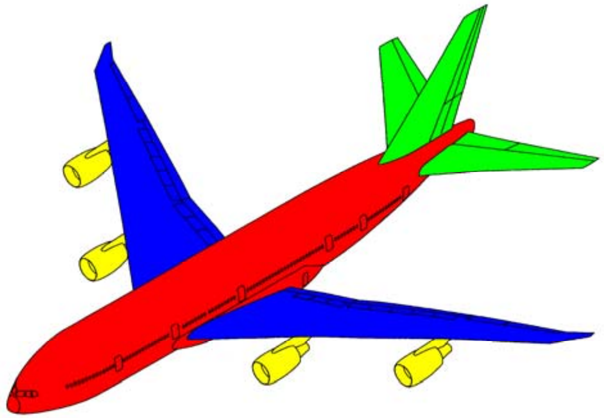
Centerbody Interior Cross-Sections



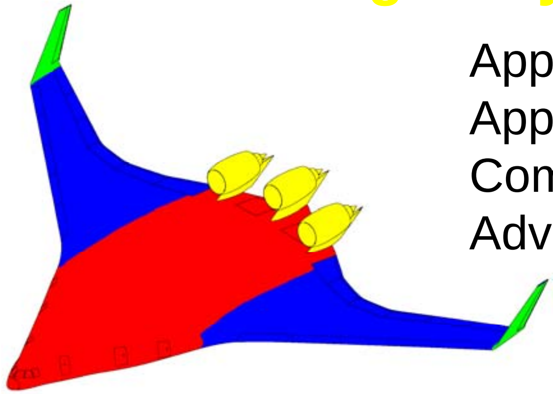


Structural Weight Fractions

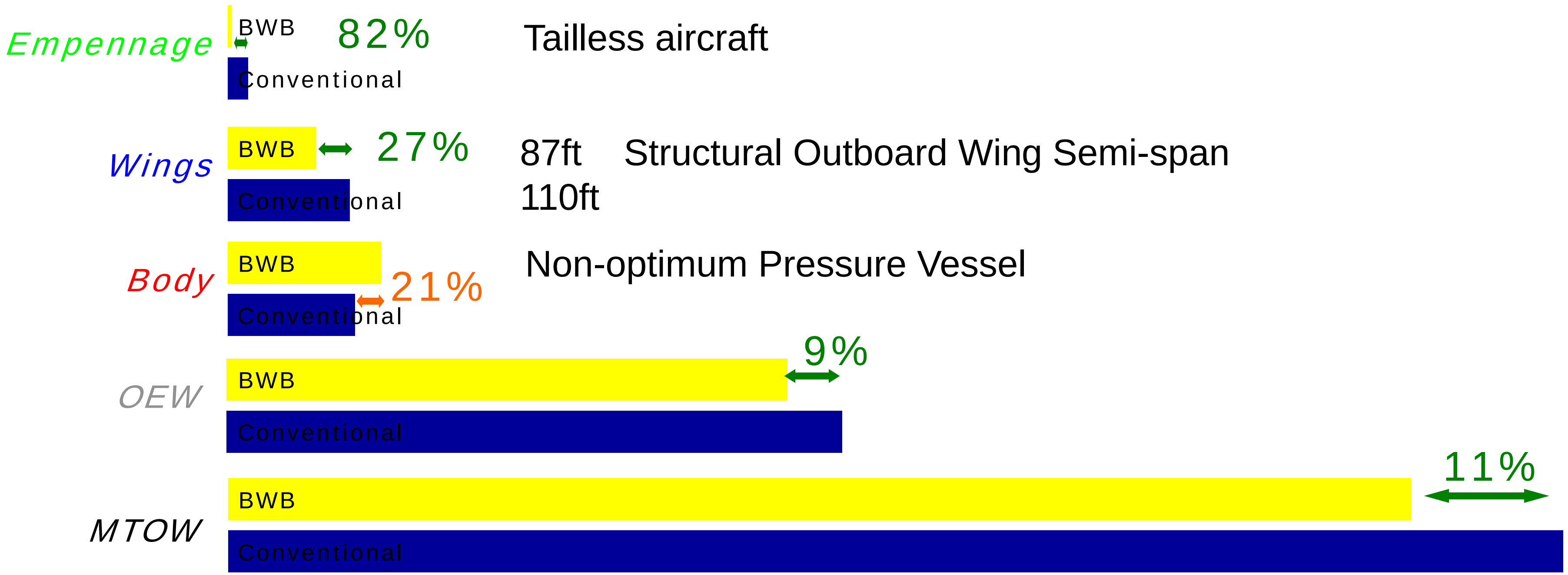
Conventional Aircraft



Blended Wing-Body



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



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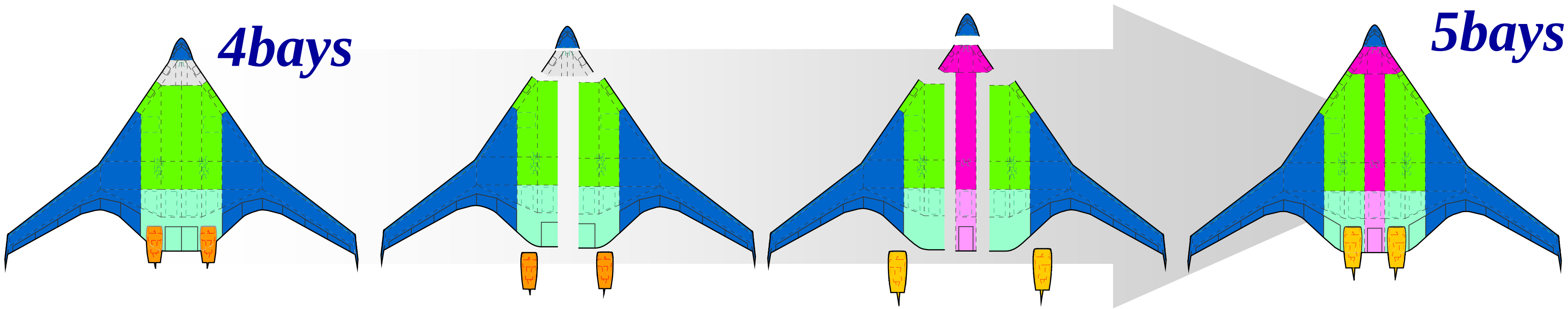
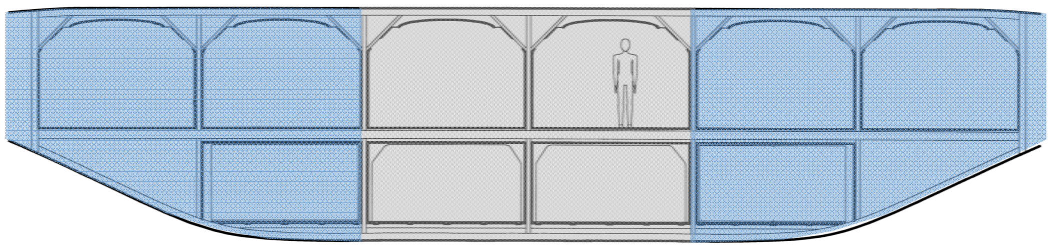
Growing a Highly-Common Family



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

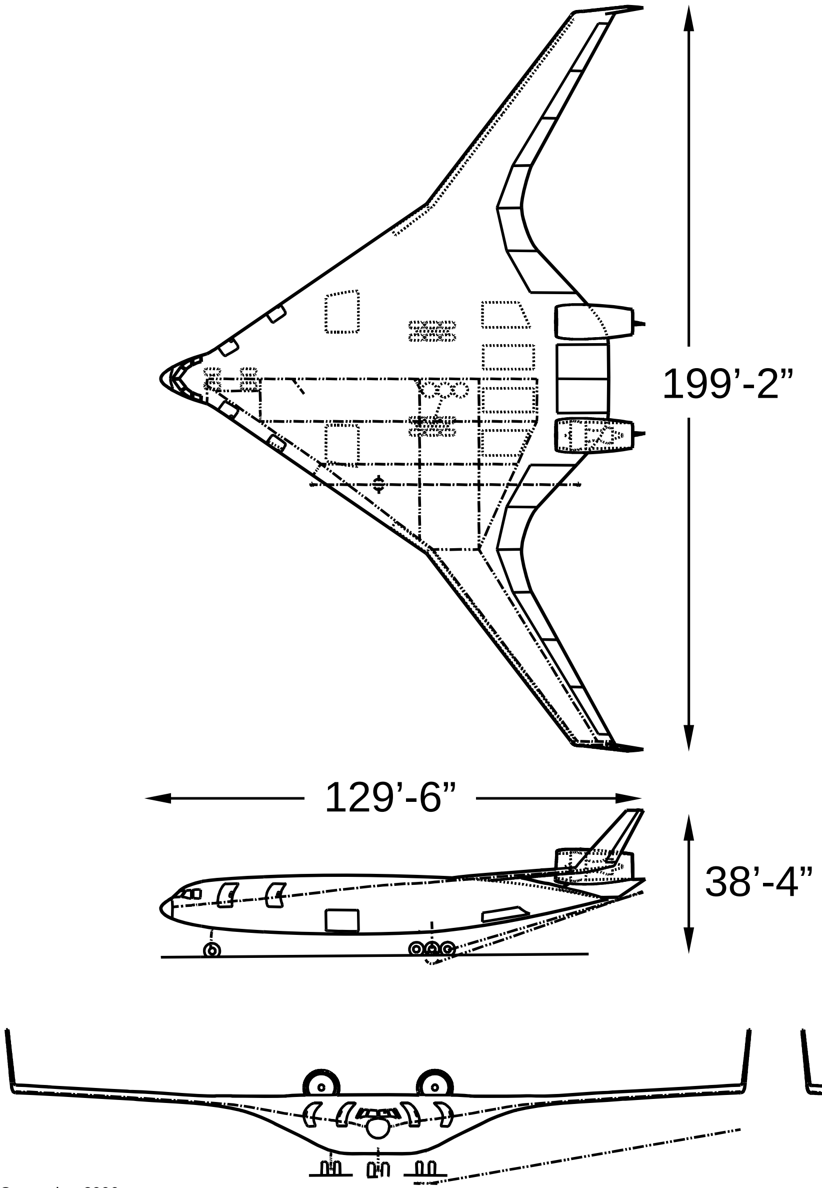
- Each bay in the BWB is an identical "cross-section" and thus lends itself to high part/weight commonality amongst the family members
- The BWB 6-bay retains 97% of the BWB 4-bay's furnishings weight



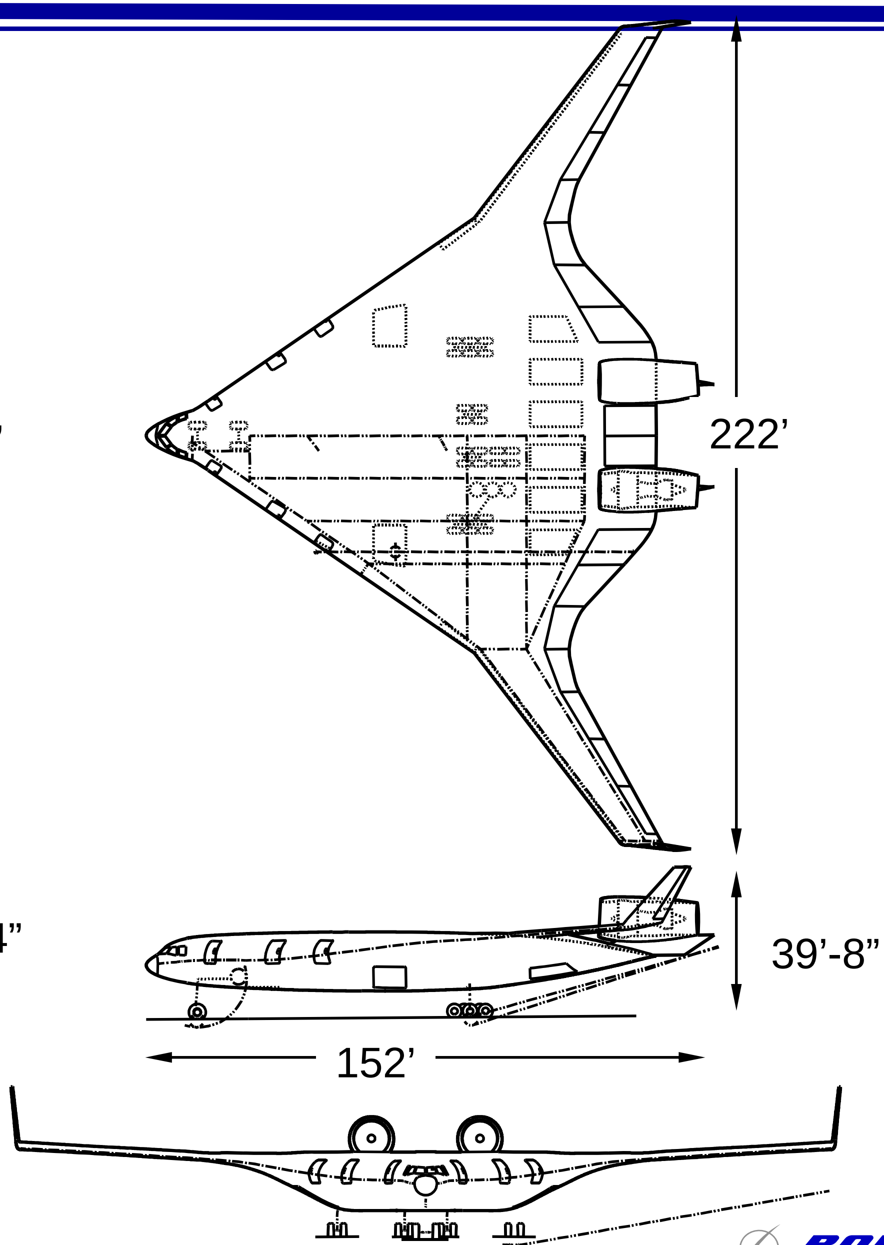
Patent No. 6,568,632

BOEING

BWB 4-bay

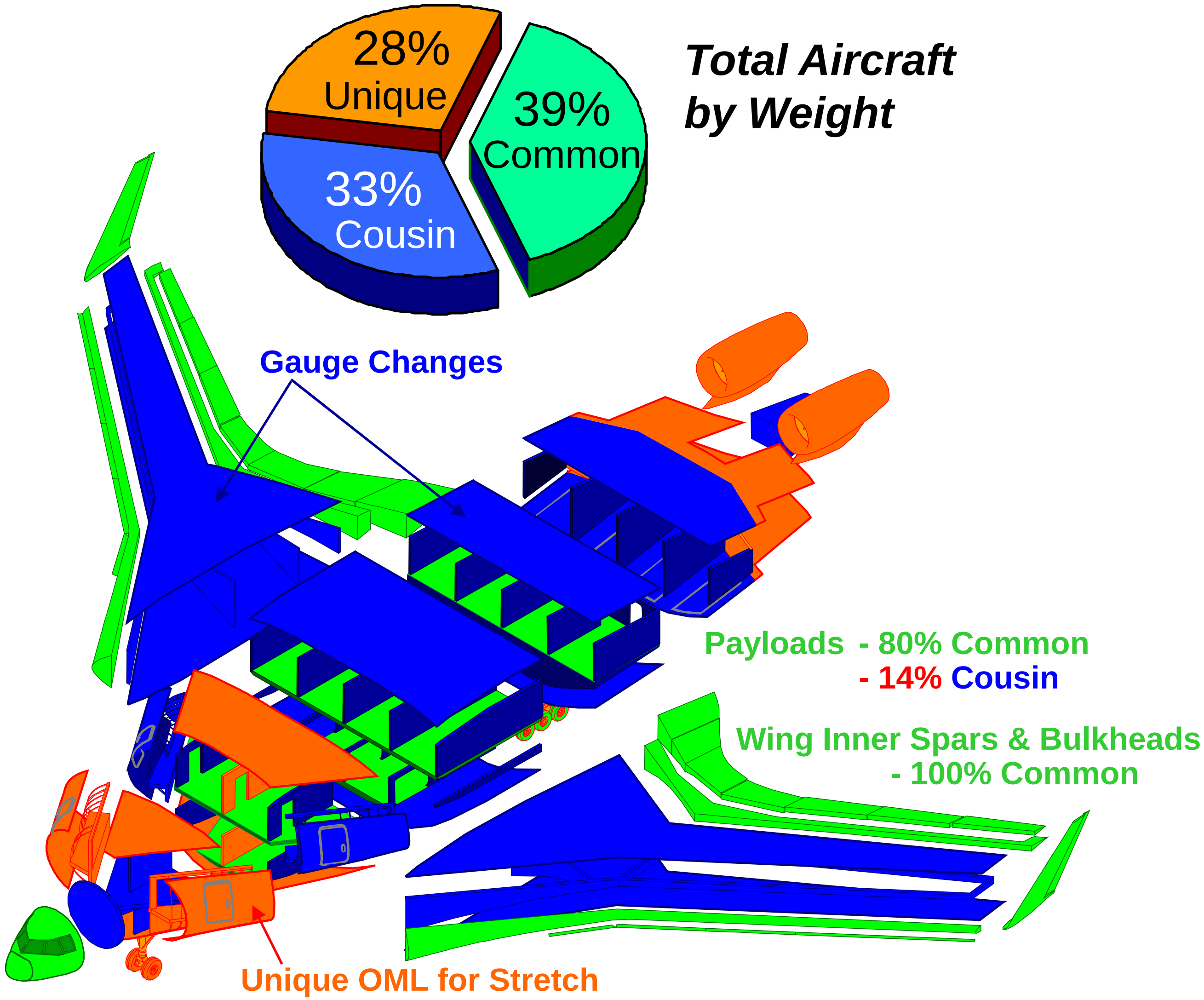


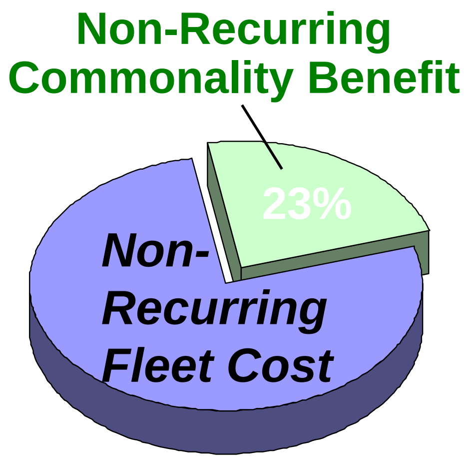
BWB 6-bay

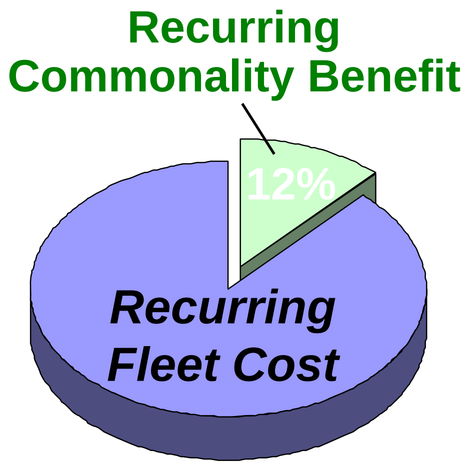


Definition of Common/Cousin Parts

Between BWB 4-bay and 6-bay

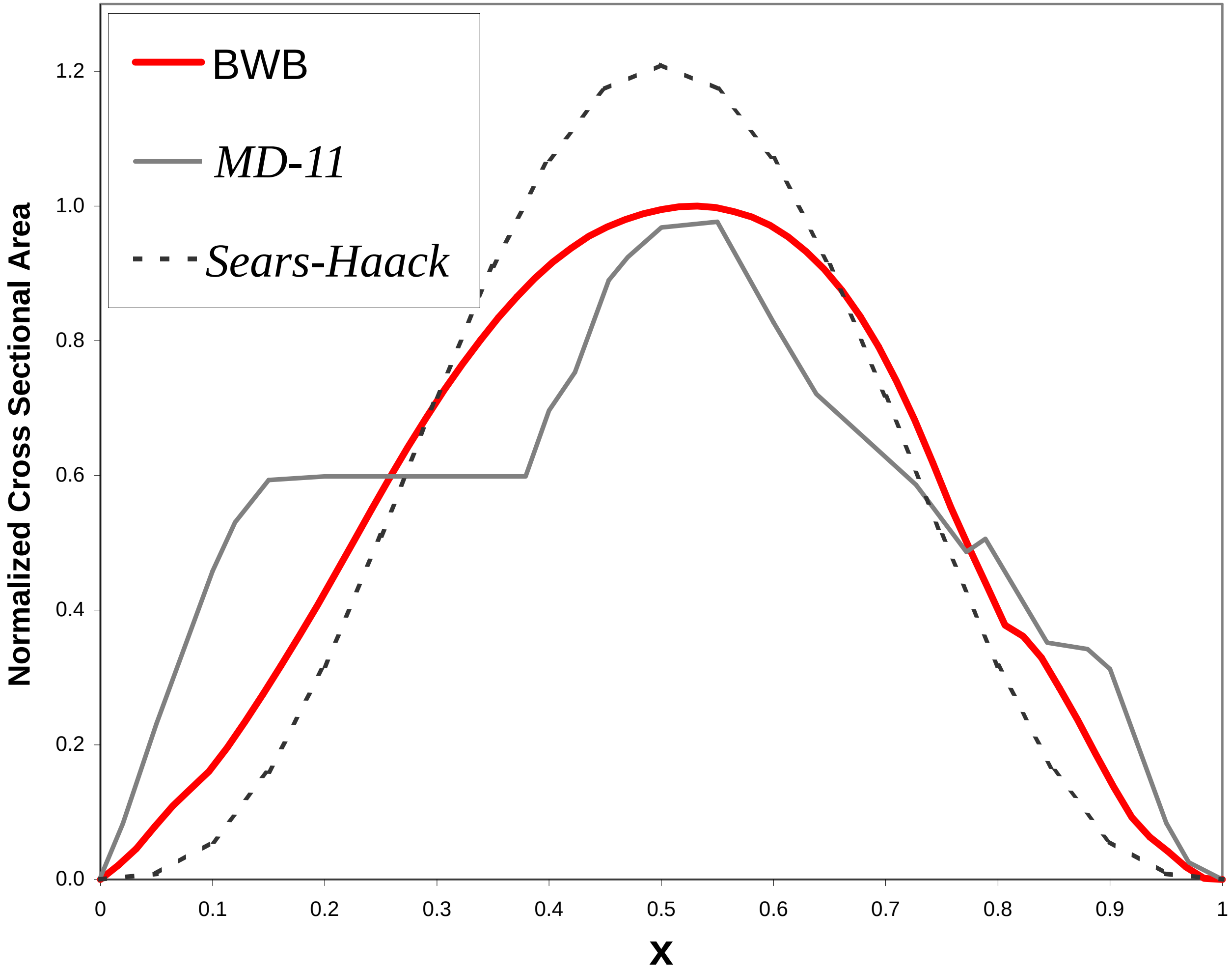






Area Distribution

$$\frac{D}{q_0} \approx \frac{1}{2\pi} \int_0^1 \int_0^1 S''(x) S''(\xi) \log \frac{1}{|x - \xi|} dx\, d\xi$$



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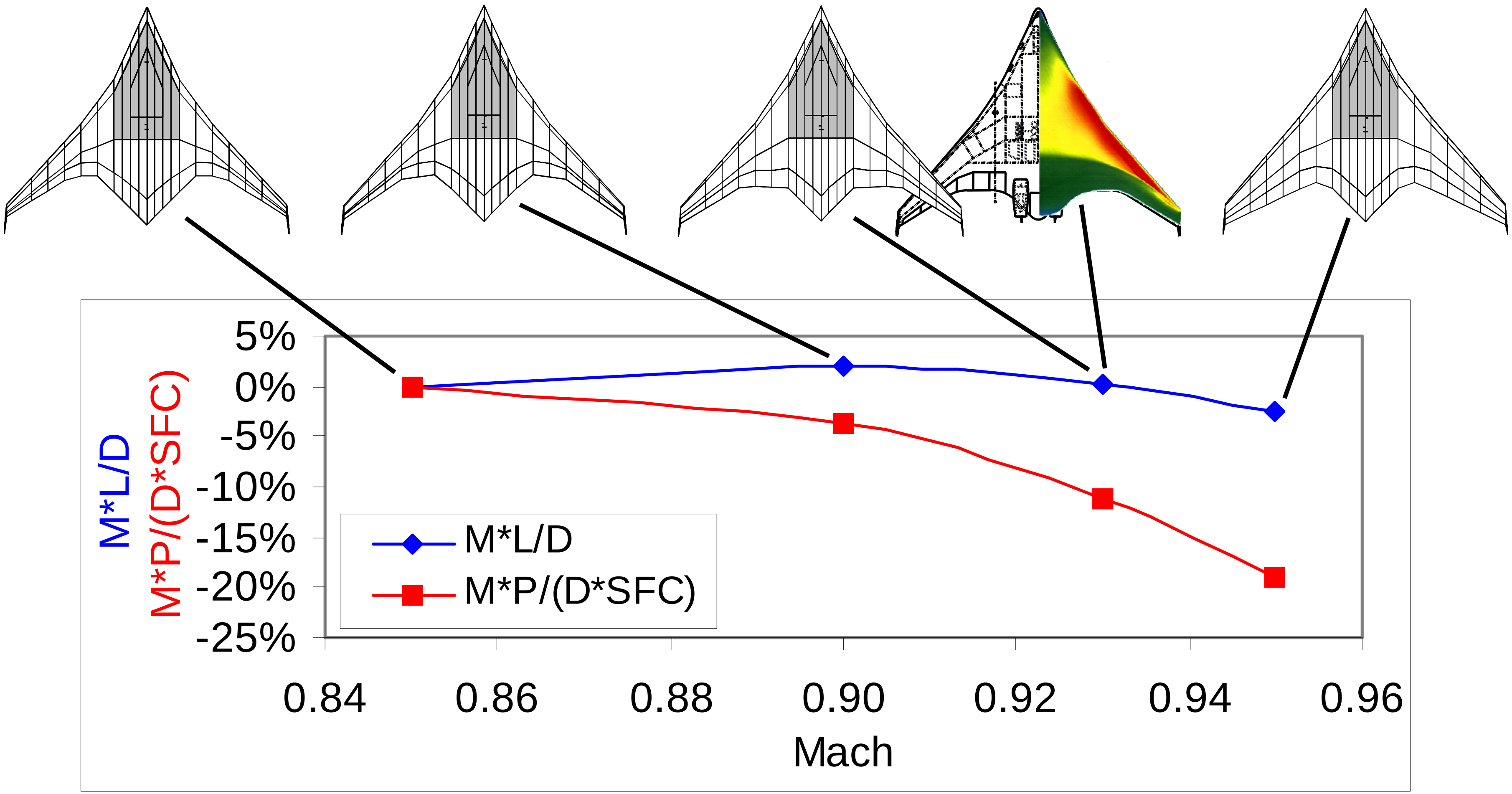
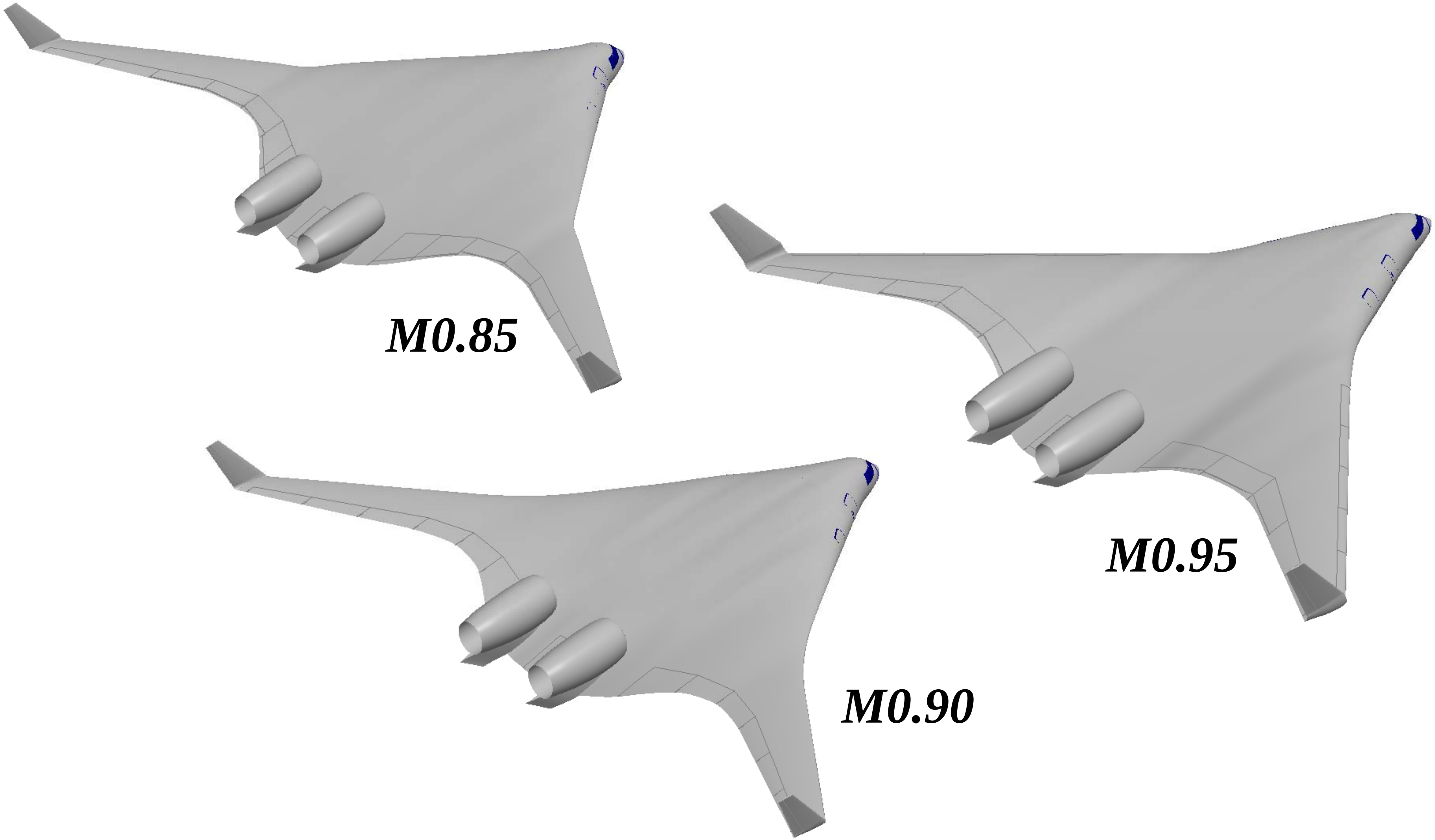
ML/D and MP/D Trends with Mach Number

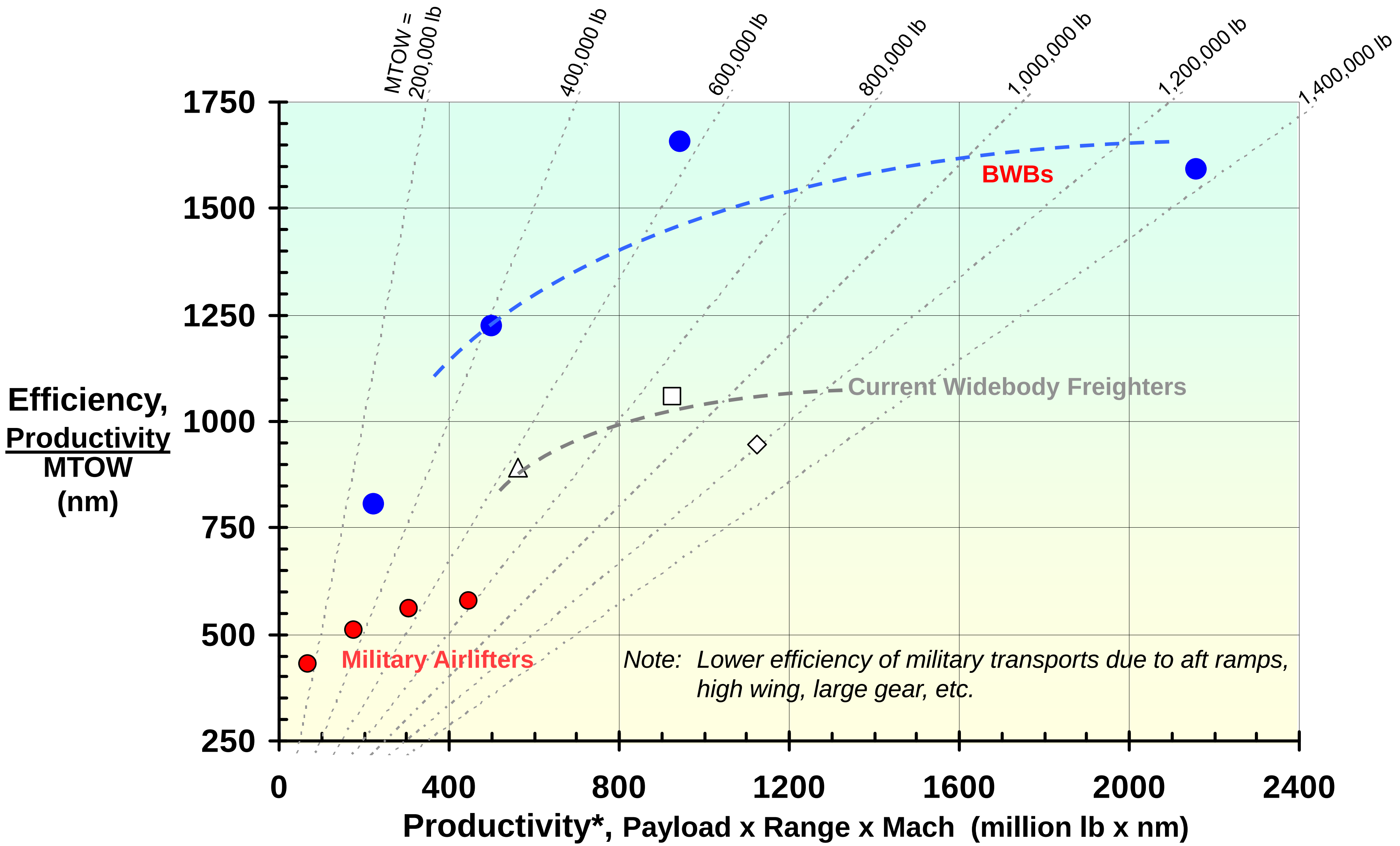


Effect of Mach Number

BWB 4-bay



Airplane Efficiency



*Using Maximum Payload, Range at Maximum Payload, and Cruise Mach Number

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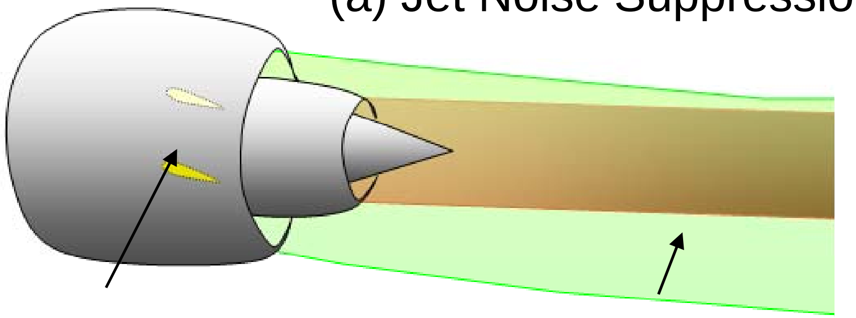
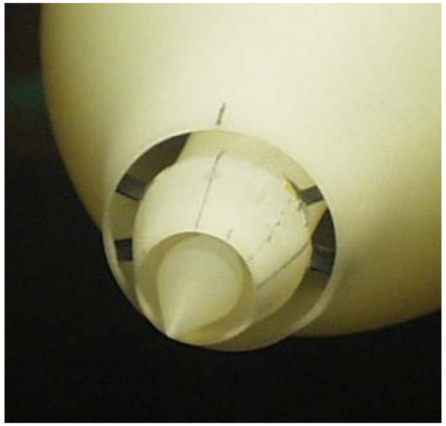
Fan Flow Deflection (FFD*)

(a) Jet Noise Suppression



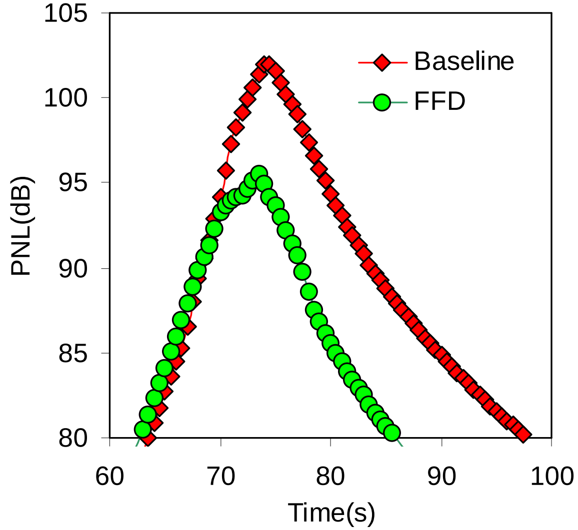
Deflector vanes internal to fan duct tilt bypass plume downward and sideward relative to core plume

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



UCI nozzle

- 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%.

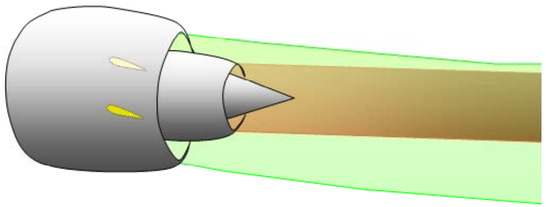


Example of flyover perceived noise level (PNL) history

*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.

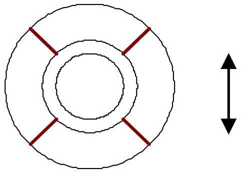
Fan Flow Deflection (FFD*)

(b)Thrust vectoring for aerodynamic control



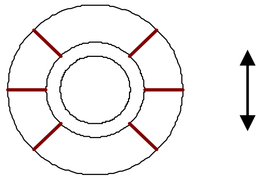
The FFD method offers the potential for thrust vectoring (longitudinal and/or lateral). Below are preliminary analytical estimates of side force and thrust loss for a BPR=8 configuration at 0.2 flight Mach number.

Example with 2 pairs of vanes



Vane angle of attack (deg)	Side force/ Total thrust	Thrust loss (entire engine)
0	0%	0.2%
5	3%	0.3%
10	6%	0.6%
15	9%	1.0%

Example with 3 pairs of vanes



Vane angle of attack (deg)	Side force/ Total thrust	Thrust loss (entire engine)
0	0%	0.3%
5	5%	0.5%
10	10%	1.0%
15	14%	1.8%

*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

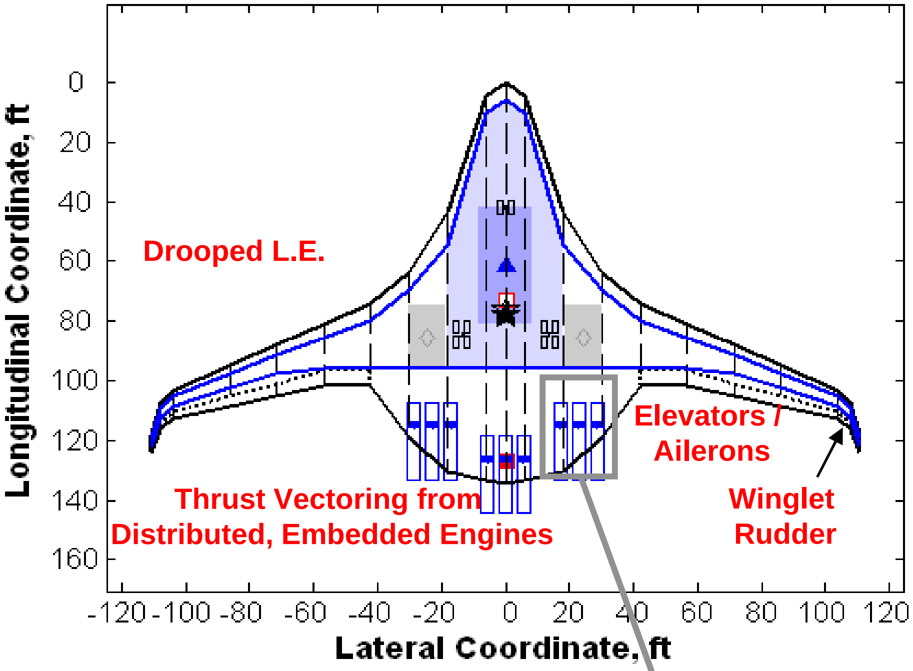
Current aircraft appears capable of sub **63 dBA** on takeoff and approach.

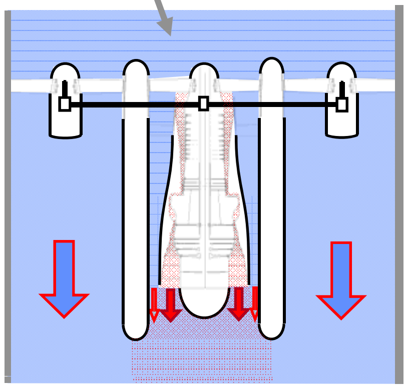
Estimated fuel burn of **124 passenger miles per gallon**.

Blended-Wing-Body type airframe.

Distributed, embedded propulsion system.

Each engine cluster has one core driving three fans.





Range: 5,000 nm

Pax: 215

Intial Cruise Alt: 40,000 ft

Cruise Mach: 0.8

Cruise ML/D: 20.1

Span: 207.4 ft

Gross Area: 8,998 ft^2

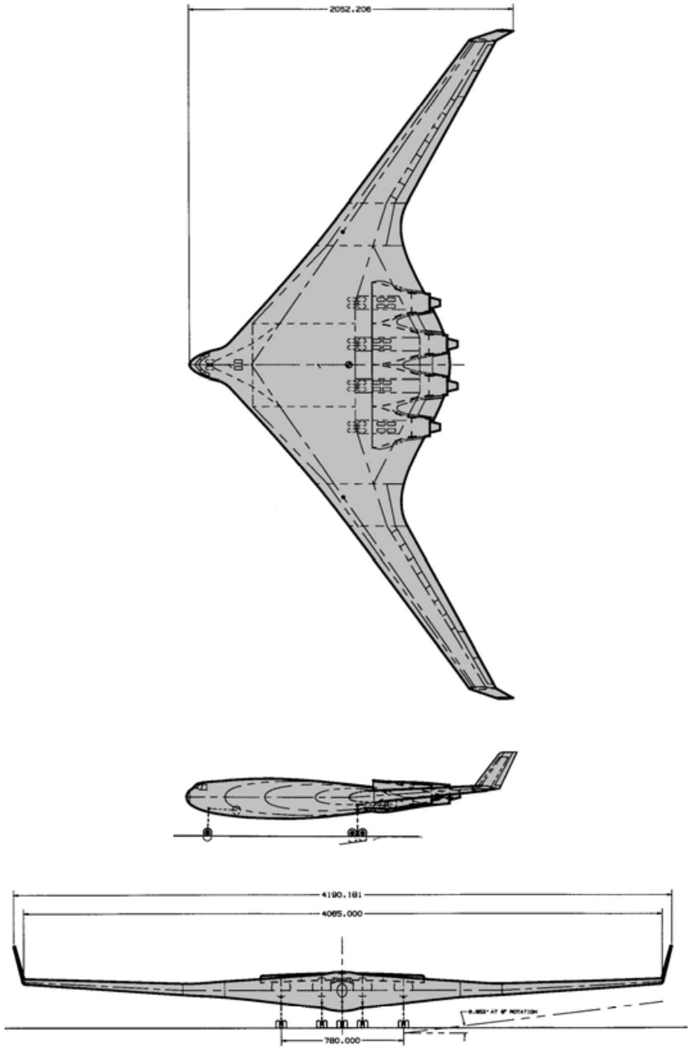
OEW: 207,660 lbs

Payload: 51,600 lbs

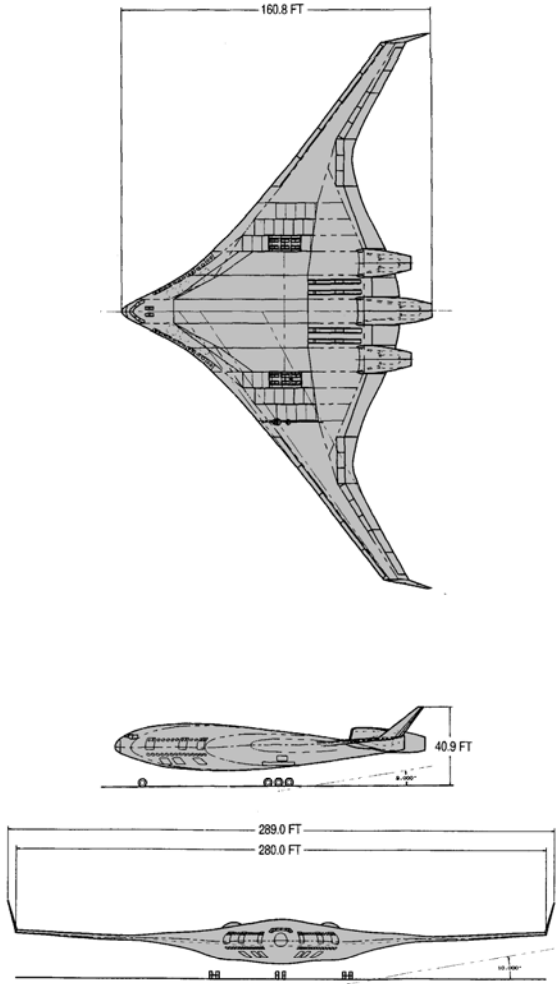
Fuel: 73,310 lbs

MTOW: 332,560 lbs

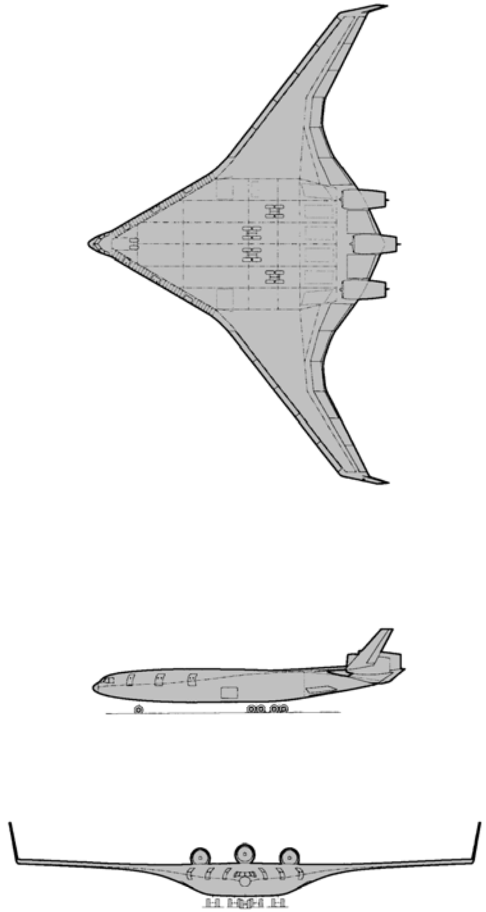
Three Generation Comparison



First-Generation



Second-Generation



Current BWB Baseline

Issues and Areas of Risk

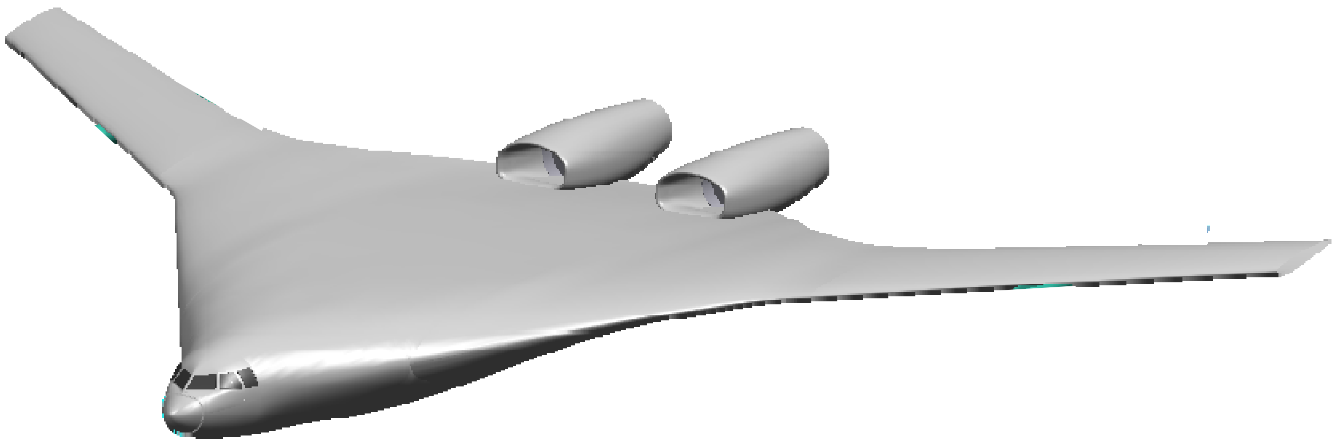
- Complex flight control architecture & allocation, with severe hydraulic requirements
- Large auxiliary power requirements
- New class of engine installation
- Flight behavior beyond stall
- High floor angle on take off & approach to landing
- Acceptance by the customer
- Performance at long range
-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

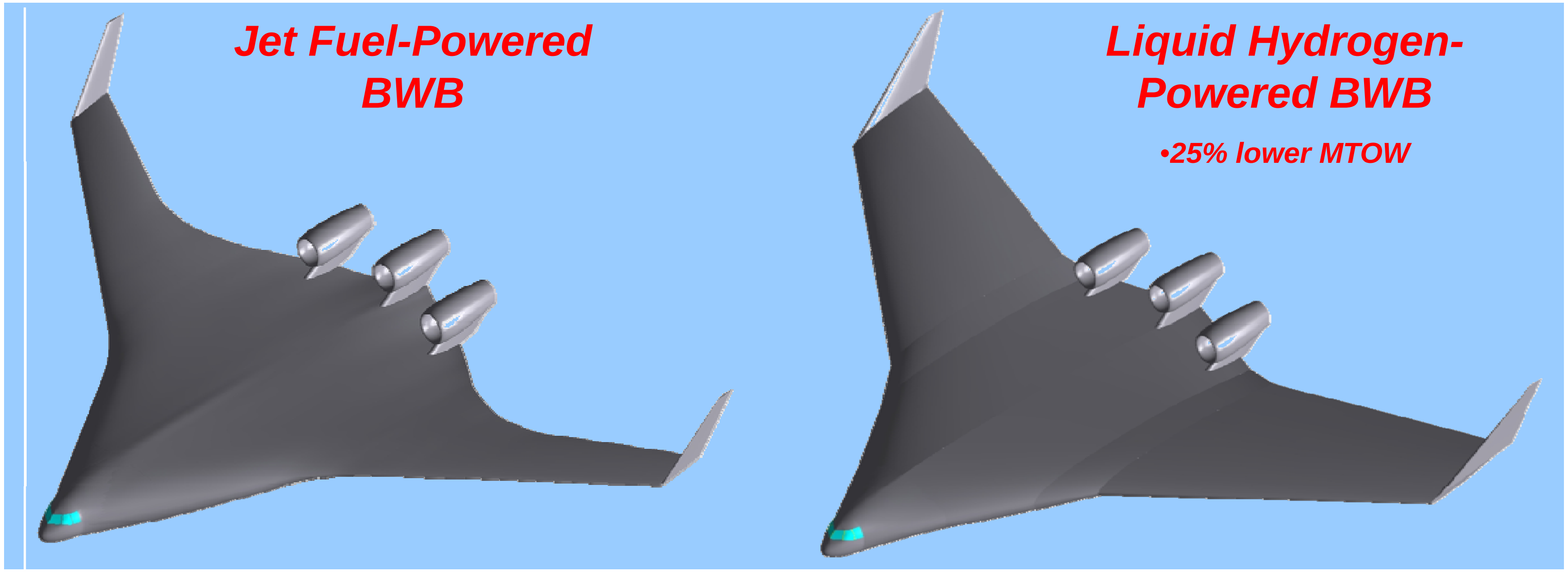
Advanced BWB Configuration



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 LH_2 version is less than required for the tube & wing airplane.
- Wing chord and thickness increased to maintain payload/range for a LH_2-powered BWB (< 3X net fuel volume compared to >4X for tube & wing).
- Aerodynamic, structural weight and fuel volume penalties for containing LH_2 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).

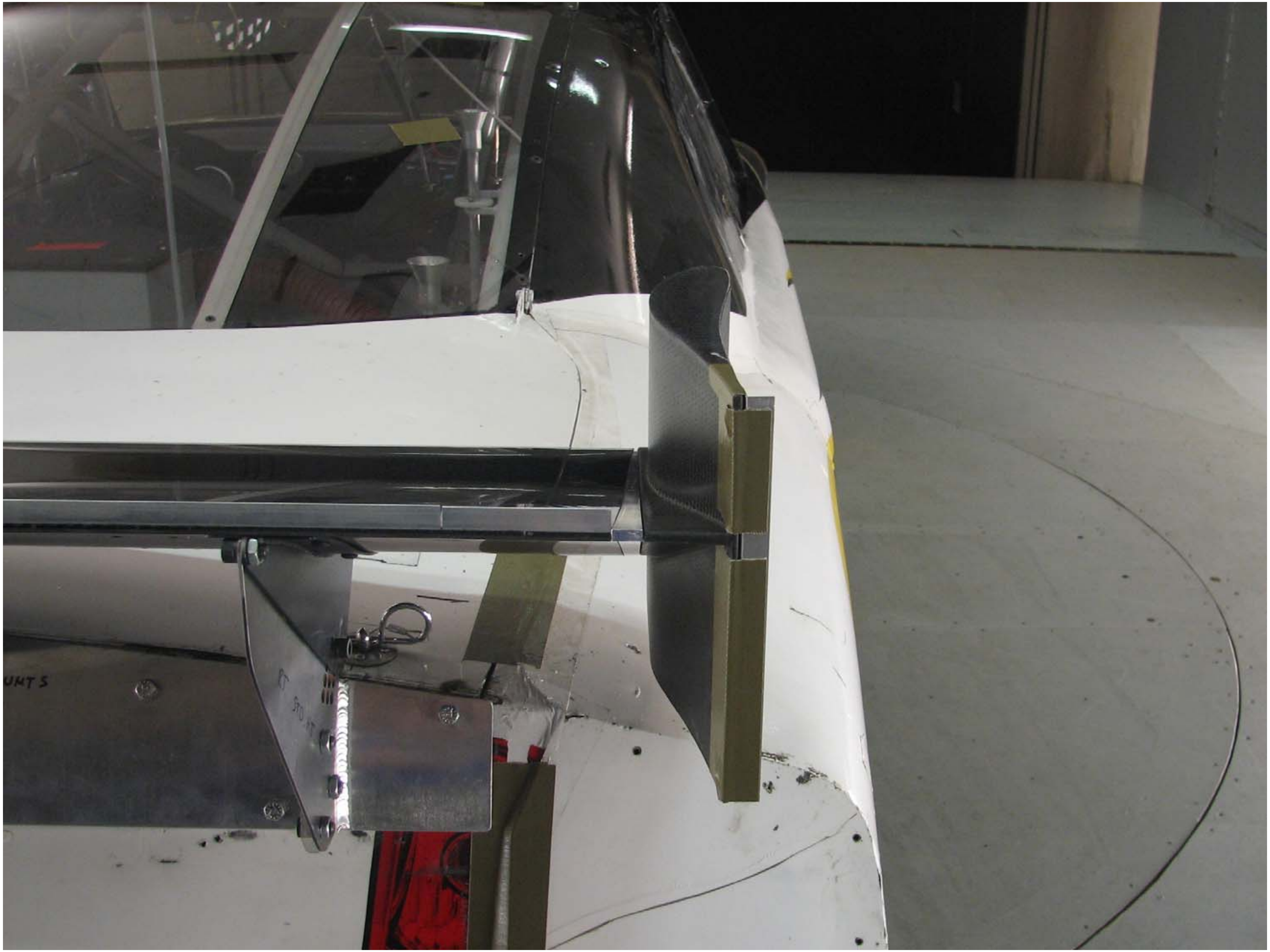
Initial Result: BWB that offered reduced fuel burn via a very high Lift/Drag ratio and large wingspan.

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.


MAY 1, 2006
COT P II BODY
RUN #3



Thank You

Boeing X-48B