

# Why Airplanes Look Like They Do

W. H. Mason



**Aerospace and  
Ocean Engineering**

collage from John McMasters



Technology advances?

A new capability someone might pay to have?

**Designer**

How to exploit technology for capability?

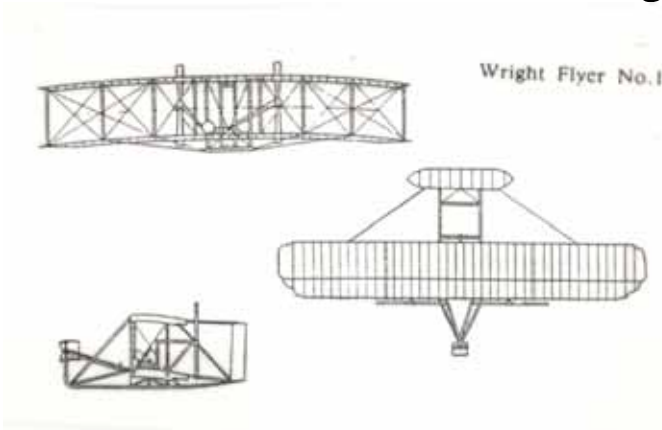
Configuration Concept

**Airplane Shapes Have Changed to Exploit Advances in Technology**



## Configuration Concept:

- Payload
- Lifting surface arrangement
- Control surface(s) location
- Propulsion system selection
- Landing Gear



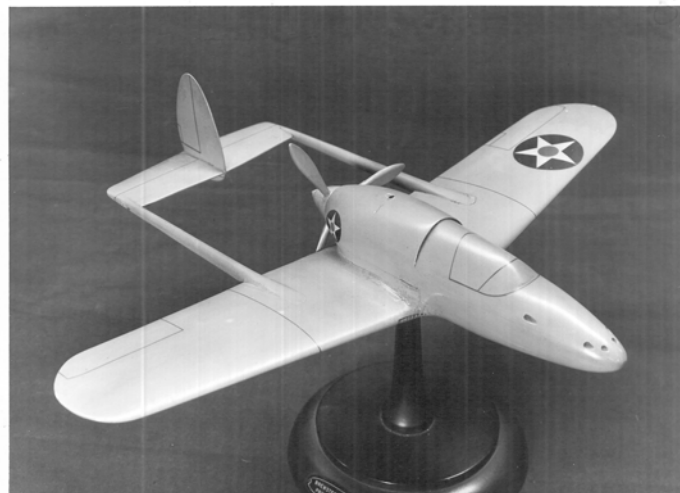
### Wright Brothers:

- Innovative control concept  
(more important than stability)
- “Light weight” propulsion
- Continual design evolution/refinement

## Basic Laws of Airplane Design

- ...
- Simplicity is the essence of true elegance—
  - it can also save weight and/or reduce cost.
- If you can't build it, you can't sell it.
- ... from John McMasters, Boeing

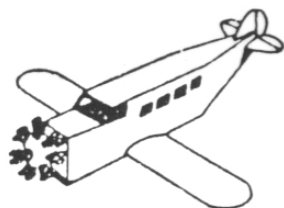
Brewster P-33A



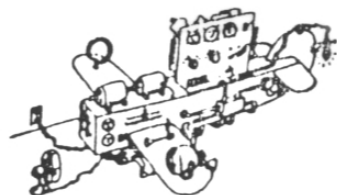
Example of an airplane management decided was to risky to build

courtesy Dr. George Inger

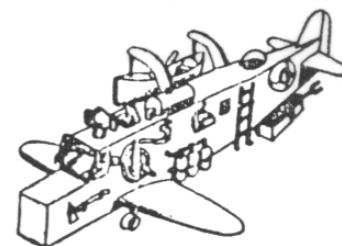
# Beauty is in the Eye of the Beholder



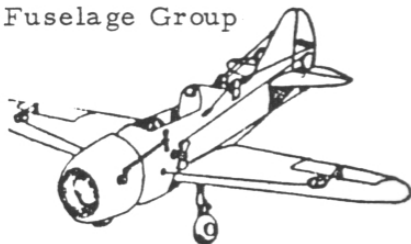
Fuselage Group



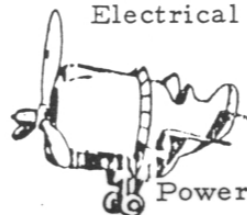
Electrical Group



Equipment Group



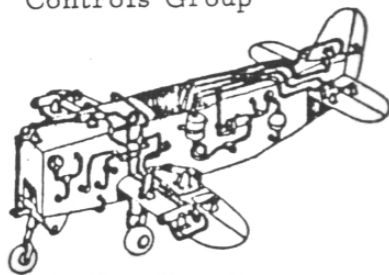
Controls Group



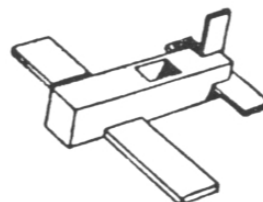
Power Plant Group



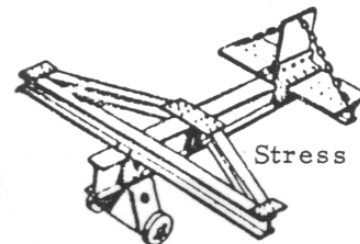
Aerodynamics Group



Hydraulics Group



Loft Group



Stress Group



Production Engineering Group



Aerospace and  
Ocean Engineering

“Dream Airplanes” by C.W. Miller,  
as shown in *Fundamentals of Aircraft Design*, by L.M. Nicolai

## Good Aircraft

- Aerodynamically efficient, including propulsion integration (streamlining!)
- Must balance near stability level for minimum drag
- Landing gear must be located relative to  $cg$  to allow rotation at TO
- Adequate control authority must be available throughout flight envelope
- Design to build easily (cheaply) and have low maintenance costs
- Today: quiet, low emissions

## Themes in Design

- Efficient payload movement
- Speed/Maneuverability
- Field Performance



The NASA/Grumman Research Fighter Configuration

## Key Technologies

- Aerodynamics
- Propulsion
- Structures

*in the late 70s:*

- Flight controls

*in the 80s and early 90s:*

- Systems/avionics/observables & Manufacturing

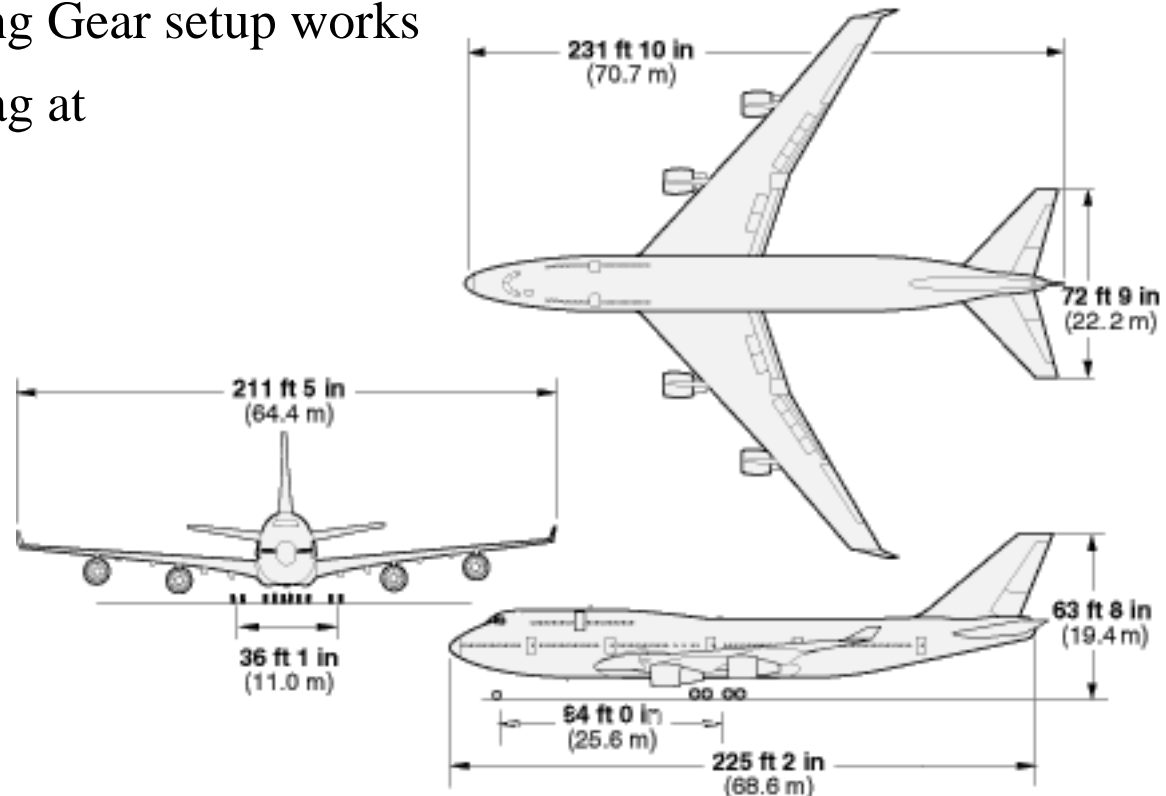
*today:*

- **the design *process* - (includes MDO)**

Amazingly Tricky to Integrate Advances in Each Technology

## Conventional Subsonic - A Baseline

- Payload distributed around  $c_g$
- Longitudinal control power from tail (with moment arm)
- Vertical Tail for directional stability, rudder for control
- Wing/Fuselage/Landing Gear setup works
- Minimum trimmed drag at near neutral stability



## Configuration Options

- Where do you put
  - the wings?
  - the engines (in fact, what kind?)
- Where do you put the control surfaces?
  - what options are available?
- Do you have room for the landing gear?
- Possible innovative designs?

## Why Sweep the Wing?

*Subsonic (usually small)*

- Adjust wing aero center relative to  $cg$
- On flying wing, get moment arm length for control

*Transonic (significant,  $30^\circ$ - $35^\circ$ )*

- Delay drag rise Mach (compressibility effect)
  - definition of the drag divergence Mach no.?

*Supersonic (large,  $45^\circ$ - $70^\circ$ )*

- Wing concept changes,
  - must distribute load longitudinally as well as laterally
- reduce cross-sectional area and area variation

Wing sweep increases wing weight for fixed span

## The classic large airplane: The Boeing 747



## Why Sweep the Wing Forward?

- For transonic maneuver, strong shock is close to trailing edge, highly swept TE (shock) reduces drag.
  - forward swept wing allows highly swept TE
  - equivalent structural  $AR$  less than aft swept wing
- Synergistic with canard
- Good high angle of attack (root stall, ailerons keep working)
- But:
  - must be balanced at least 30% unstable
  - not stealthy
  - poor supersonic volumetric wave drag

Example: X-29

*Note: some would also say for laminar flow and for less twist in wing.*

## the X-29



NASA Dryden Flight Research Center Photo Collection  
<http://www.dfrc.nasa.gov/Gallery/Photo/index.html>  
NASA Photo: EC87-0182-14 Date: July 24, 1987 Photo By: NASA

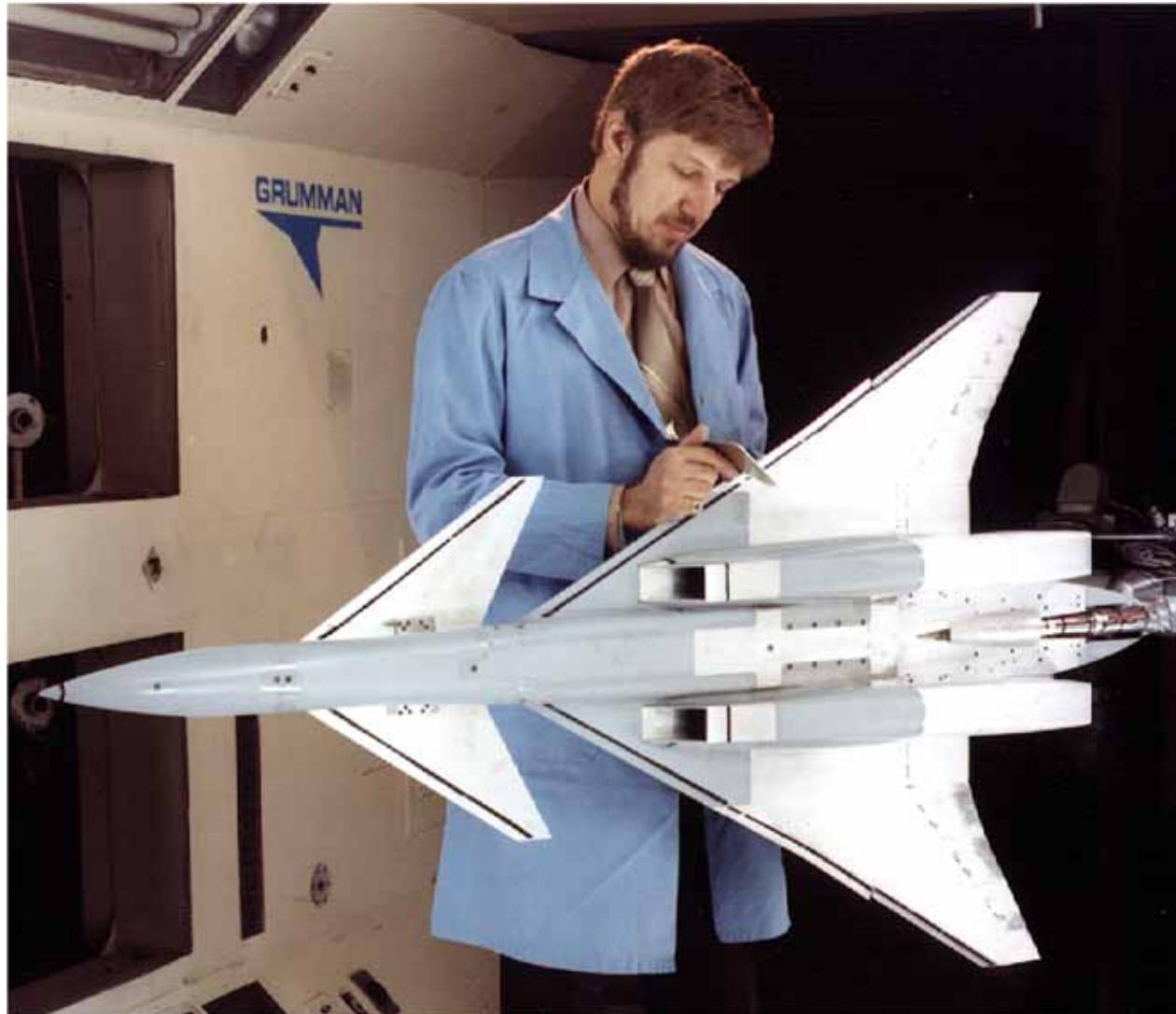
X-29 in Banked Flight

Mason worked on this before it was called the X-29,  
one of about 3 or 4 engineers working on it.

## Why Canards?

- trim surface carries positive load for positive  $g$  maneuvers
- reduces subsonic-supersonic  $ac$  shift
- drawback: downwash from canard unloads wing  
(for forward swept wing this is good)
- if balanced stable,  $C_L$  on canard is much higher than the wing
- balanced unstable, control system design very expensive
- acceptable high angle of attack lateral/directional characteristics hard to obtain
- When to use?
  - severe supersonic cruise/transonic maneuver requirement
- Not Stealthy

## The Grumman Research Fighter



Aerospace and  
Ocean Engineering

designed by Nathan Kirschbaum, Ron Hendrickson in pix

slide 16

9/4/09

## Why a Flying Wing?

- removing fuselage must improve aero efficiency
  - But, payload volume distribution is still an issue
- synergistic effect with relaxed static stability
- military: stealth
- commercial: distribute load, reduce weight
- but, limited *cg* range

Example: XB-35, YB-49, B-2

## The B-2 Stealth Bomber

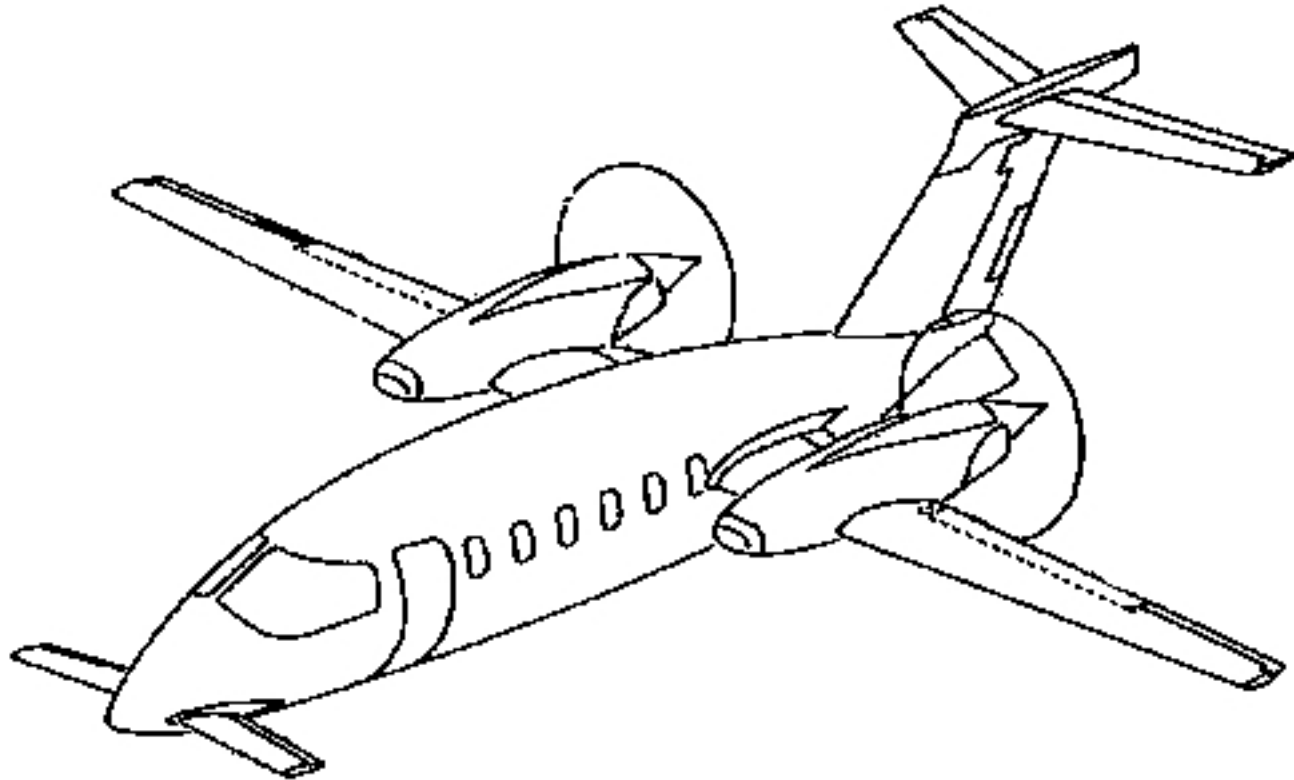


## Why Three-Surfaces?

- Can trim with near minimum drag over wide  $cg$  range
- But: If you can make a design with two surfaces, why use three?  
Adds cost, weight, wetted area
- Sometimes, efficient component integration leads to three-surfaces to save weight

Example: Piaggio Avanti

# Piaggio Avanti



courtesy Piaggio

## Why Winglets?

- Nearly equivalent to span extension *w/o* increased root bending moment
- Used where span limitations are important
- Good wingtip flow crucial to low drag
- The local flowfield is extremely nonuniform, to work:

*Requires advanced computational aerodynamics methods to design*

# Winglet Example



At the Roanoke, VA airport

## Why Variable Sweep?

- Swept back: low supersonic drag, good “on-the-deck” ride quality
- Unswept position: low landing speed (carrier suit.), *efficient loiter*
- Optimum sweep back available over transonic speed range
- But: adds weight/complexity, currently unfashionable

Example: F-14 Tomcat

# The F-14 Tomcat



NASA Dryden Flight Research Center Photo Collection  
<http://www.dfrc.nasa.gov/gallery/photo/index.html>  
NASA Photo: ECN-33403-2 Date: 1986

F-14 VSTFE

## Why Put Engines in Pods on Wing?

- load relief on wing: weight savings
- access to work on engines (maybe)
- safety
- can be low drag

Original idea by the British – in wing!



De Havilland Comet, Airliner Tech Series, Vol 7.

If it's small, can't put them below wing



At the Tech airport

### Boeing Made Wing Mounted Engines Work



The Dash-80, at the Udvar-Hazy, Dulles Airport

## The Aspect Ratio Trap

$$D = qSC_D = qS \left( C_{D0} + \frac{C_L^2}{\pi ARE} \right)$$

$$L = W = qSC_L$$

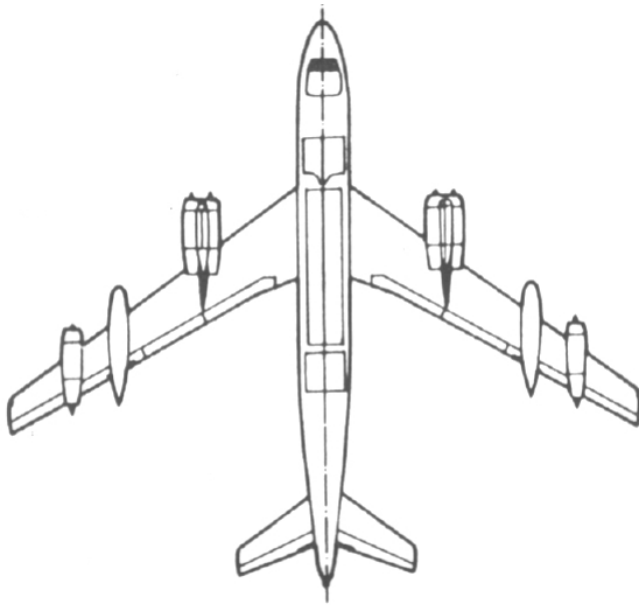
$$\text{or: } C_L = \frac{W}{qS}$$

$$\Rightarrow D = qSC_{D0} + \frac{1}{\pi E q} \left( \frac{W}{b} \right)^2$$

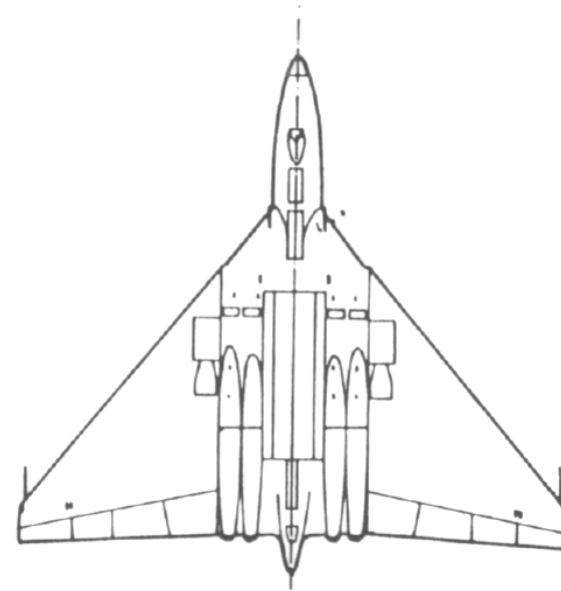
Span plays a bigger role than aspect ratio

## Classic Example: B-47 vs Avro Vulcan B-1

- traditional idea: higher  $AR$  gives higher  $L/D$
- low  $AR$  all wing with less wetted area competes with high  $AR$



B-47



Vulcan

## Similar $L/D$ max Achieved Both Ways

*from Nicolai, design notes, 1982*

	<u>B-47</u>	<u>Vulcan</u>
Gross wing area (sq ft)	1430	3446
Total wetted area (sq ft)	11,300	9500
Span (ft)	116	99
Max Wing Loading (W/S)	140	43.5
Max Span Loading (W/b)	1750	1520
Aspect Ratio	9.43	2.84
CD0 (est)	0.0198	0.0069
<b>L/D max/CL opt</b>	<b>17.25 /0.682</b>	<b>17.0 /0.235</b>
CD0 S	28.3	25.8
CL (max cruise)	0.48	0.167

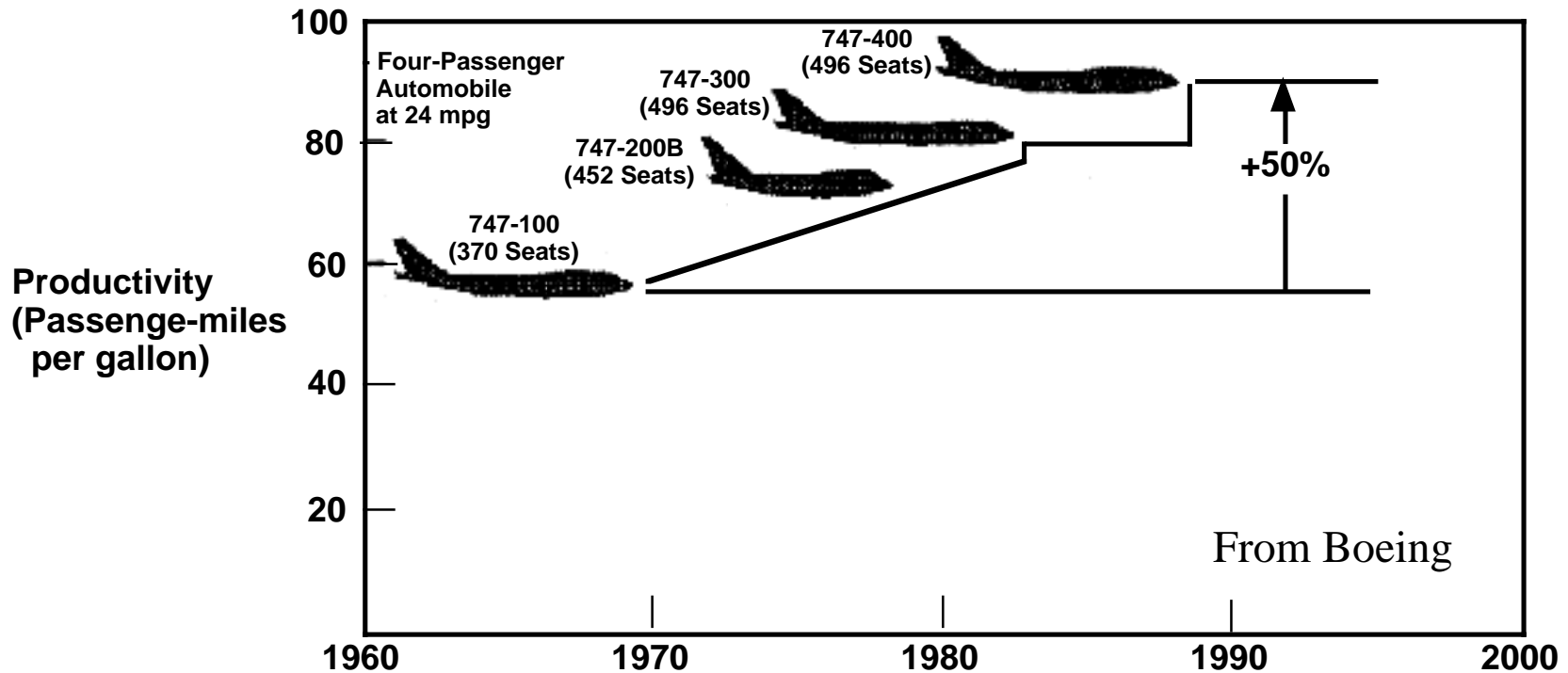
$$\text{recall : } \frac{L}{D} \Big|_{\text{max}} = \frac{1}{2} \sqrt{\frac{\pi A R E}{C_{D0}}}, \quad C_{L/L/D \text{ max}} = \sqrt{\pi A R E C_{D0}}$$



## The Wing Size Dilemma

- Efficient cruise implies  $C_L$  close to  $C_L$  for  $L/D_{max}$   
(if drag rise were not an issue,  $C_L$  for max range would be much less than  $C_L$  for  $L/D_{max}$ )
- Wings sized for efficient cruise require very high max lift coefficient, or long runway to land.

## So Where Have We Come So Far? 747 Productivity improvement



## Another consideration: Propulsion for lift/control

- Aero-Propulsion integration also needs to be considered
- Thrust vectoring for control.
- Powered lift for VTOL/STOL



## A Few Novel Concepts



### • Blended Wing-Body Concept

- Concept from Bob Liebeck (Douglas A/C)
- Less wetted area (no fuselage as such)
- Possibly more efficient structure
- This is now the X-48 series of planes

### • Oblique Wing Supersonic Transport

- concept by R.T. Jones
- fore-aft symmetry of lift and also better area distribution
- possibly only “practical” SST
- flying wing version also



AD-1, Circa 1980

## Another Novel Concept: SpaceShipOne



The White Knight

Pictures from the  
Scaled Composites web site

Burt Rutan: Still imagineering!

SpaceShipOne



## Our Current Favorite: the Strut Braced Wing

See AIAA Paper 2005-4667

- Werner Pfenninger's strut-braced wing concept from 1954
- We need MDO to make it work



- The strut allows a thinner wing without a weight penalty
- Also a higher aspect ratio (span), less induced drag
- Reduced  $t/c$  allows less sweep without a wave drag penalty
- Reduced sweep leads to *even lower* wing weight
- Reduced sweep allows for some natural laminar flow
  - reduced skin friction drag

**We are again working on this for NASA**

## Lockheed, Virginia Tech, NASA Team



*Compared to a conventional cantilever design:*

- 12-15% less takeoff weight
- 20-29% less fuel
- less noise and emissions

See AIAA Paper 2009-7114

# Today



## And Hope for Low-Sonic Boom Noise Flight

A modified F-5E demonstrated a low-noise boom on Aug. 27, 2003

So-called “boom shaping” can be used to reduce the part of the boom that hits the ground.

NASA Press Release,  
Sept. 4, 2003



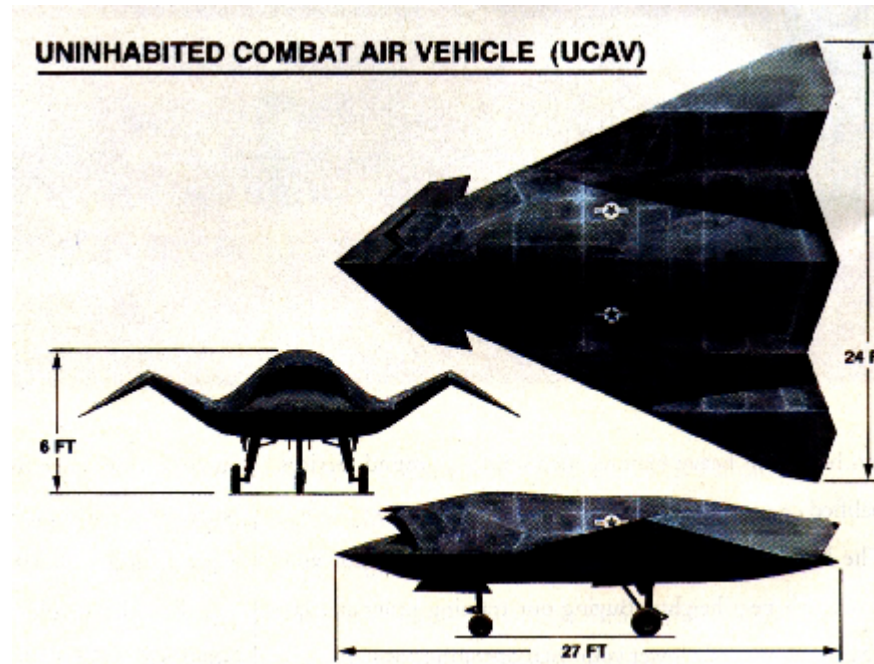
NASA Dryden Flight Research Center Photo Collection  
<http://www.dfrc.nasa.gov/Gallery/Photo/index.html>

NASA Photo: EC03-0210-1 Date: August 2, 2003 Photo By: Carla Thomas

Northrop-Grumman Corporation's modified U.S. Navy F-5E Shaped Sonic Boom Demonstration (SSBD) aircraft.

# The Latest:UCAVs

This one is based on  
Nastasi/Kirschbaum/Burhans Patent 5,542,625



Northrop Grumman Corporation, reprinted by *Aviation Week*, June 16, 1997

The vertical tail is eliminated for stealth, directional control comes from specially coordinated trailing edge deflections

## And finally, Micro AVs!

### *Black Widow*

### *AeroVironment, Inc.*

- 6-inch span fixed-wing aircraft
- Live video downlink
- Portable launch/control box
- Pneumatic launcher
- 60 gram mass
- 22-minute endurance
- Estimated 10 km range
- Electric propulsion



### *Achievements*

- World MAV endurance record of 22 minutes
- Smallest video camera ever flown on a UAV: 2 grams
- Smallest live video downlink ever flown on a UAV
- World's smallest, lightest multi-function, fully proportional radio control system: 3 grams
- First aircraft to be flown "heads-down" indoors

**Joel Grasmeyer, MS VT 1998 - team member!**

## To Learn More, Read These:

*The Anatomy of the Airplane*, by Darrol Stinton. Few equations and deceptively simple, but it's not. Lots of good information.

*Design for Air Combat* by Ray Whitford. Takes a deeper look at the details, again without equations and with lots of good graphics showing typical data to use deciding on design options. I continue to contend that the title suggests a much narrower focus than the book has.

*Aircraft Design: A Conceptual Approach*, by Daniel Raymer. Chapter 8, "Special Considerations in Configuration Layout" and Chapter 22, "Design of Unique Aircraft Concepts" is good once you've read the first two references.

*Airplane Design, Pt. II Preliminary Configuration Design etc.*, by Jan Roskam. Chapter 3, and 3.3 "Unusual Configurations", in particular.

## Still Room for Dreamers

We don't yet know what the ultimate airplane concept is.  
**and concerning the comments on configurations given above,  
remember:**

*there is a time and place for everything*

Next Time: How do we know how big to make the plane? **Sizing**