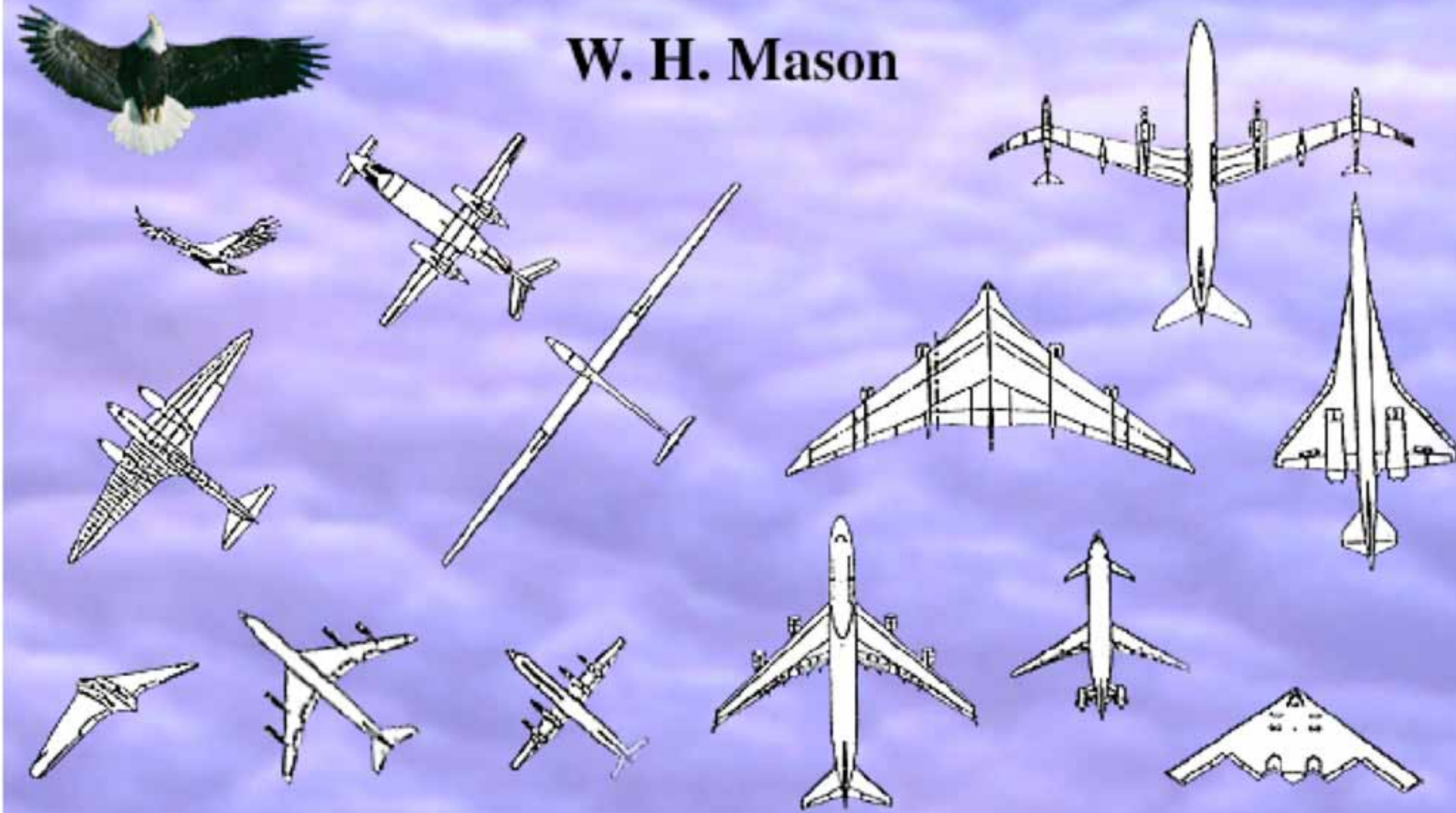
Why Airplanes Look Like They Do

W. H. Mason



Aerospace and
Ocean Engineering

collage from John McMasters

Technology advances?

Designer

A new capability someone might pay to have?

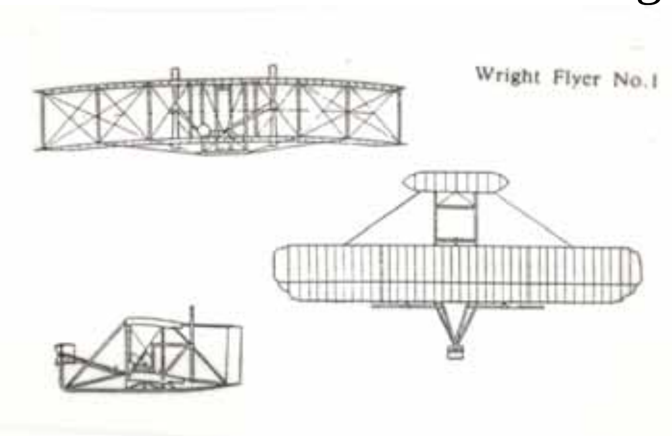
How to exploit technology for capability?

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

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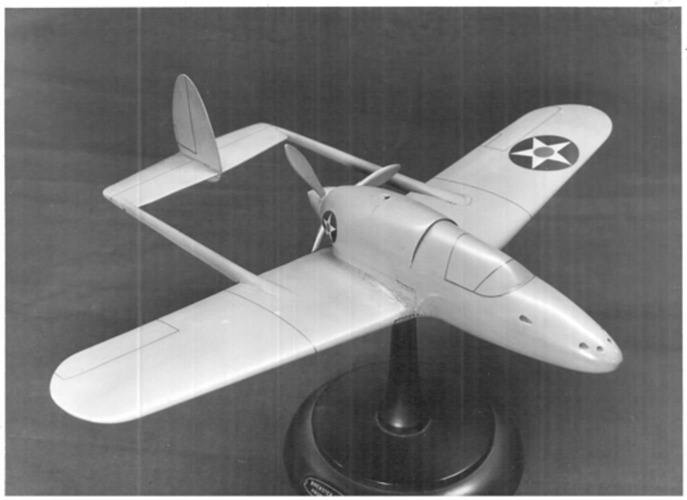
Basic Laws of Airplane Design

- …
- 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



courtesy Dr. George Inger

Example of an airplane management decided was to risky to build

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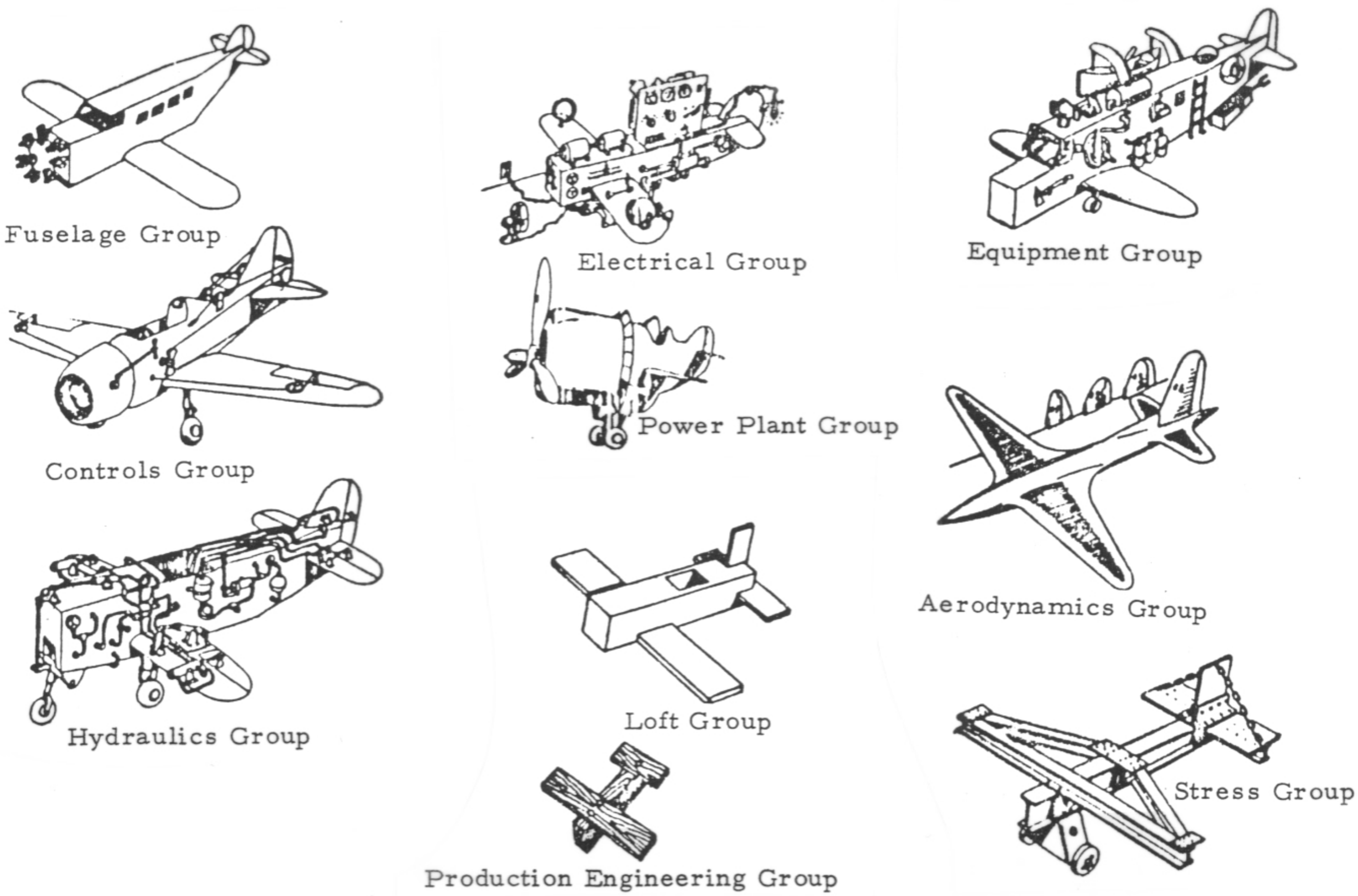
Beauty is in the Eye of the Beholder



"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

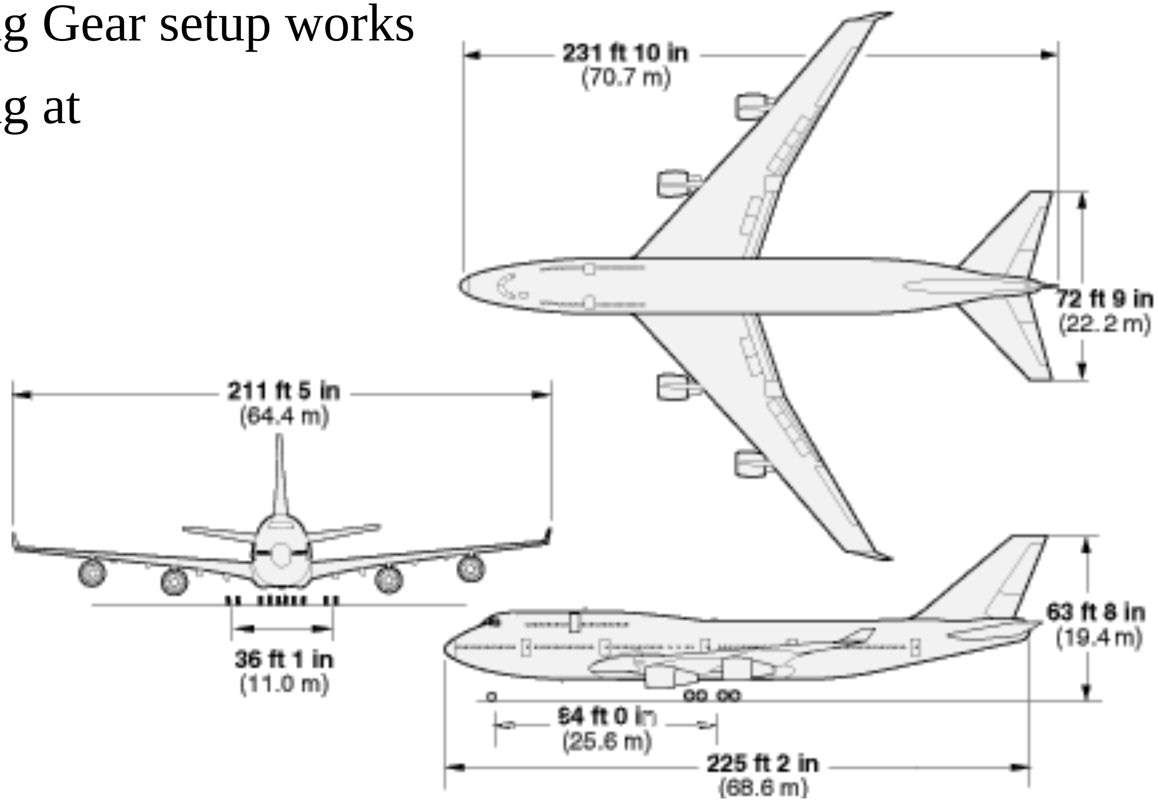
today:

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

Amazingly Tricky to Integrate Advances in Each Technology

Conventional Subsonic - A Baseline

- Payload distributed around *cg*
- 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



Boeing 747-400, source: www.boeing.com

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°-35°)

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

Supersonic (large, 45°-70°)

- 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

source: www.boeing.com

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

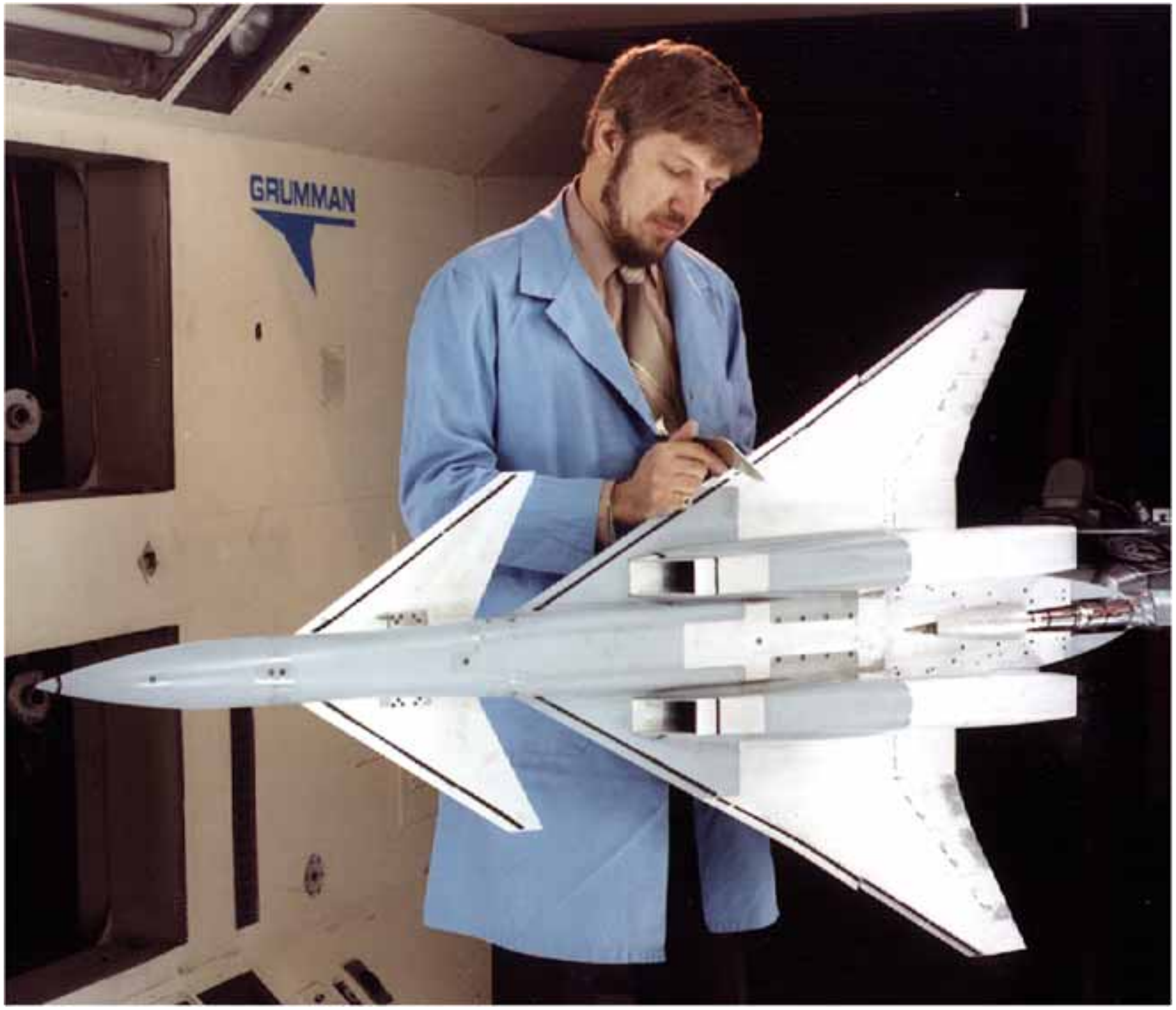
X-29 in Banked Flight

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



designed by Nathan Kirschbaum, Ron Hendrickson in pix

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

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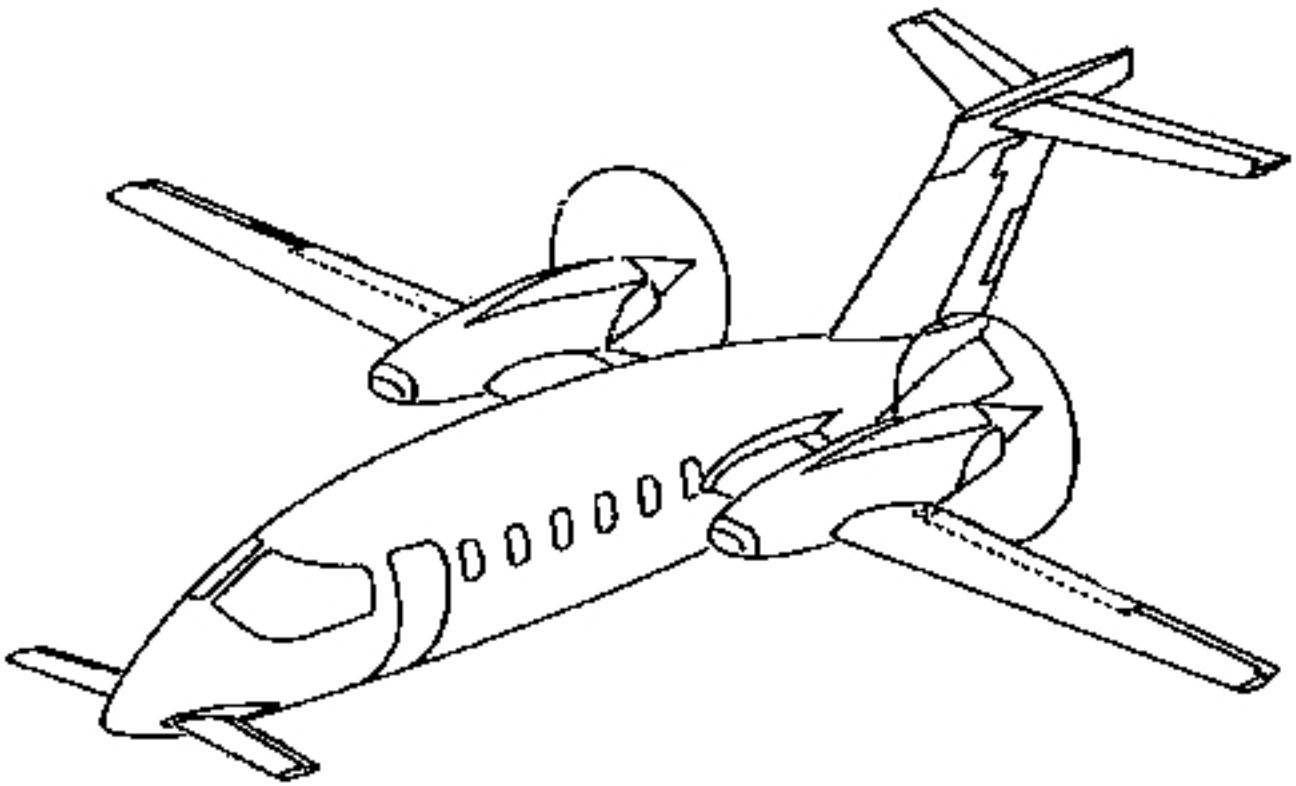
Why Three-Surfaces?

- 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

$$D = qSC_D = qS\left(C_{D_0} + \frac{C_L^2}{\pi ARE}\right)$$

$$L = W = qSC_L$$

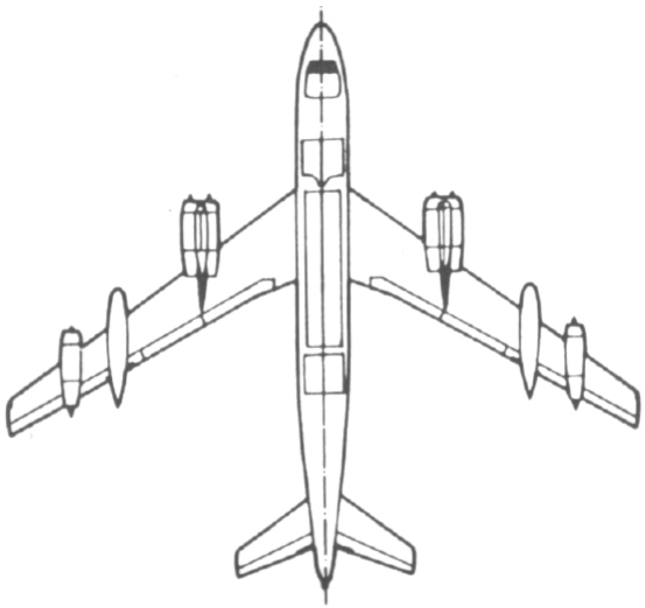
$$\text{or}: \quad C_L = \frac{W}{qS}$$

$$\Rightarrow \quad D = qSC_{D_0} + \frac{1}{\pi Eq}\left(\frac{W}{b}\right)^2$$

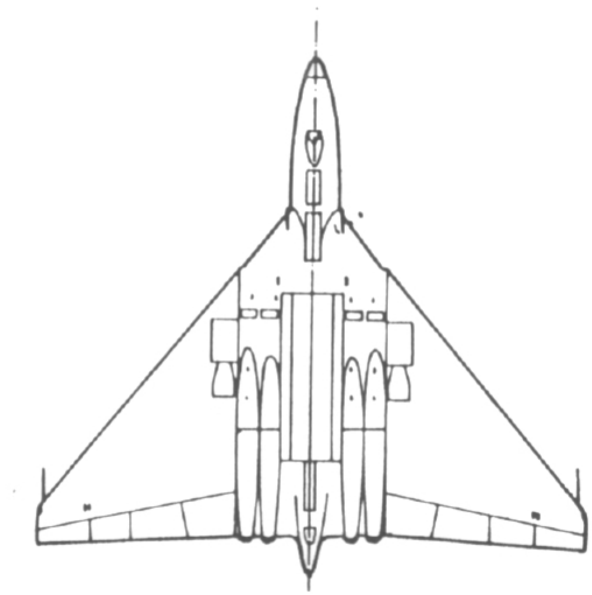
Span plays a bigger role than aspect ratio

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

	B-47	Vulcan
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
L/D max/CL opt	**17.25** /0.682	**17.0** /0.235
CD0 S	28.3	25.8
CL (max cruise)	0.48	0.167

$$\text{recall}: \left.\frac{L}{D}\right|_{\max} = \frac{1}{2}\sqrt{\frac{\pi ARE}{C_{D_0}}}, \quad C_{L_{L/D\max}} = \sqrt{\pi ARE C_{D_0}}$$

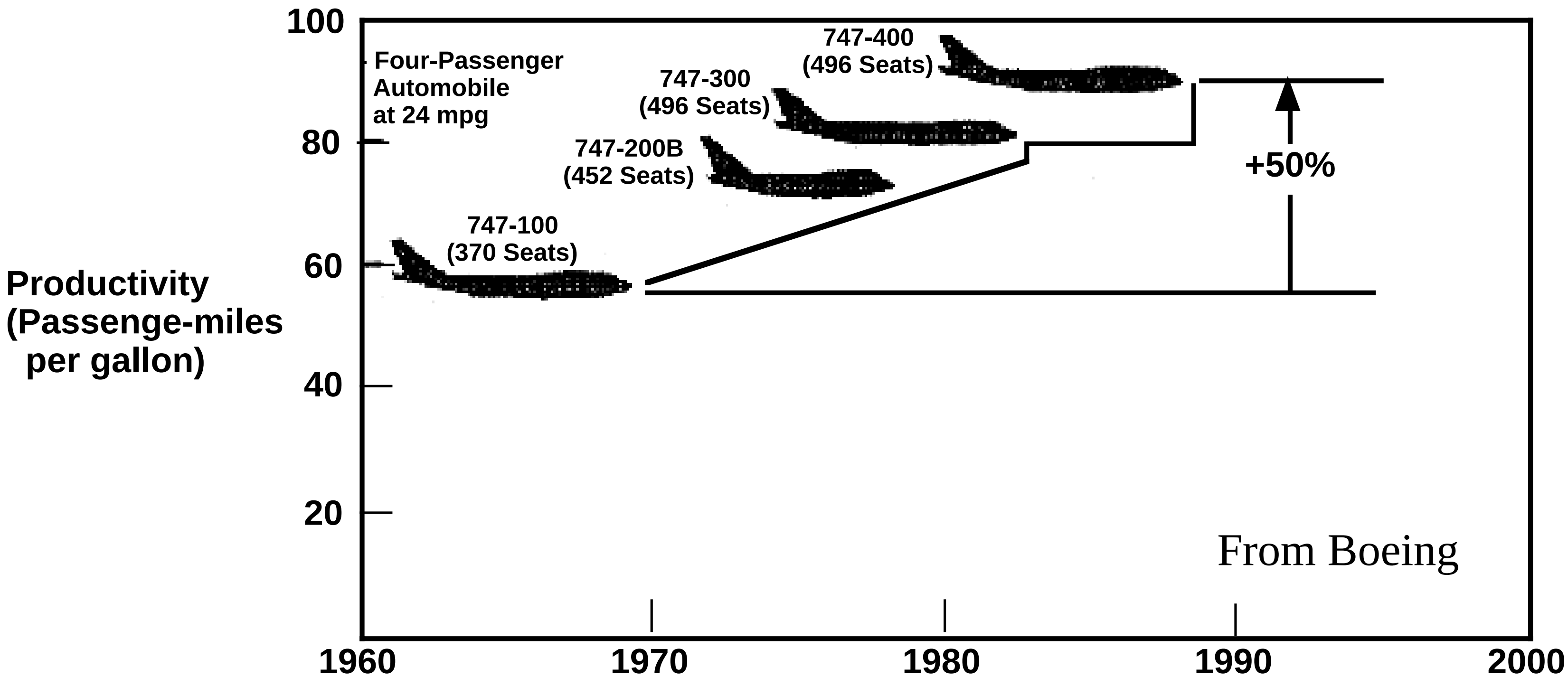
The Wing Size Dilemma

- 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

Burt Rutan: Still imagineering!

SpaceShipOne

Pictures from the
Scaled Composites web site

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

Courtesy Ohad Gur

And Hope for Low-Sonic Boom Noise Flight

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

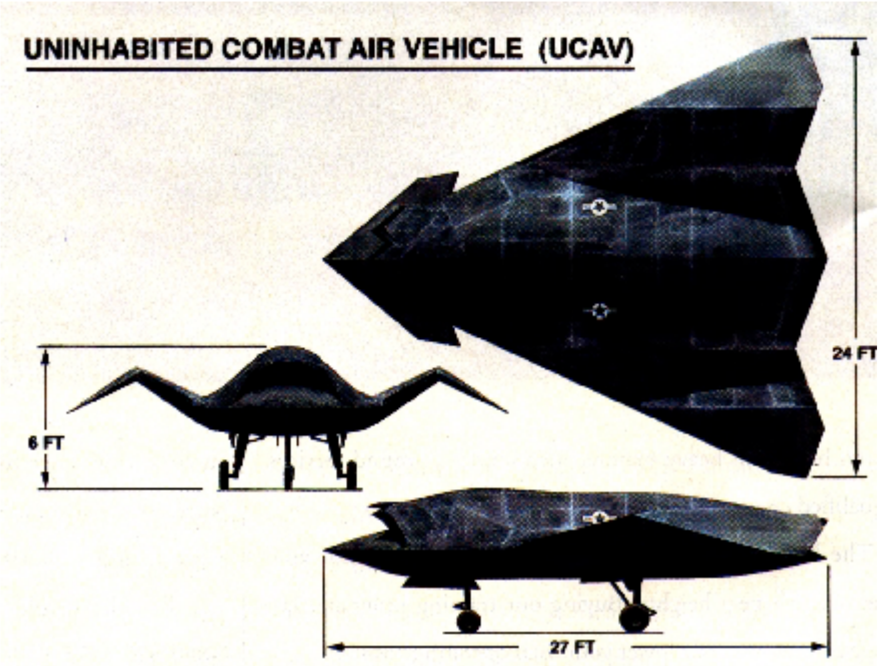
So-called “boom shaping” can be used to reduce the part of the boom that hits the ground.

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 Configurarion 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**