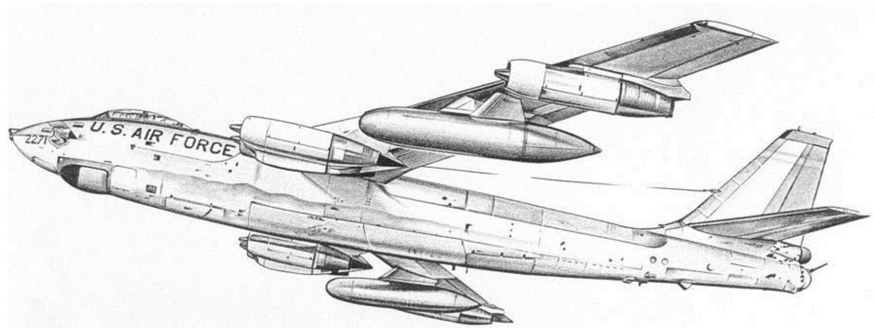
Evolution of the jet airliner shape

Boeing B-47 (1947) to Boeing 787 (2009)

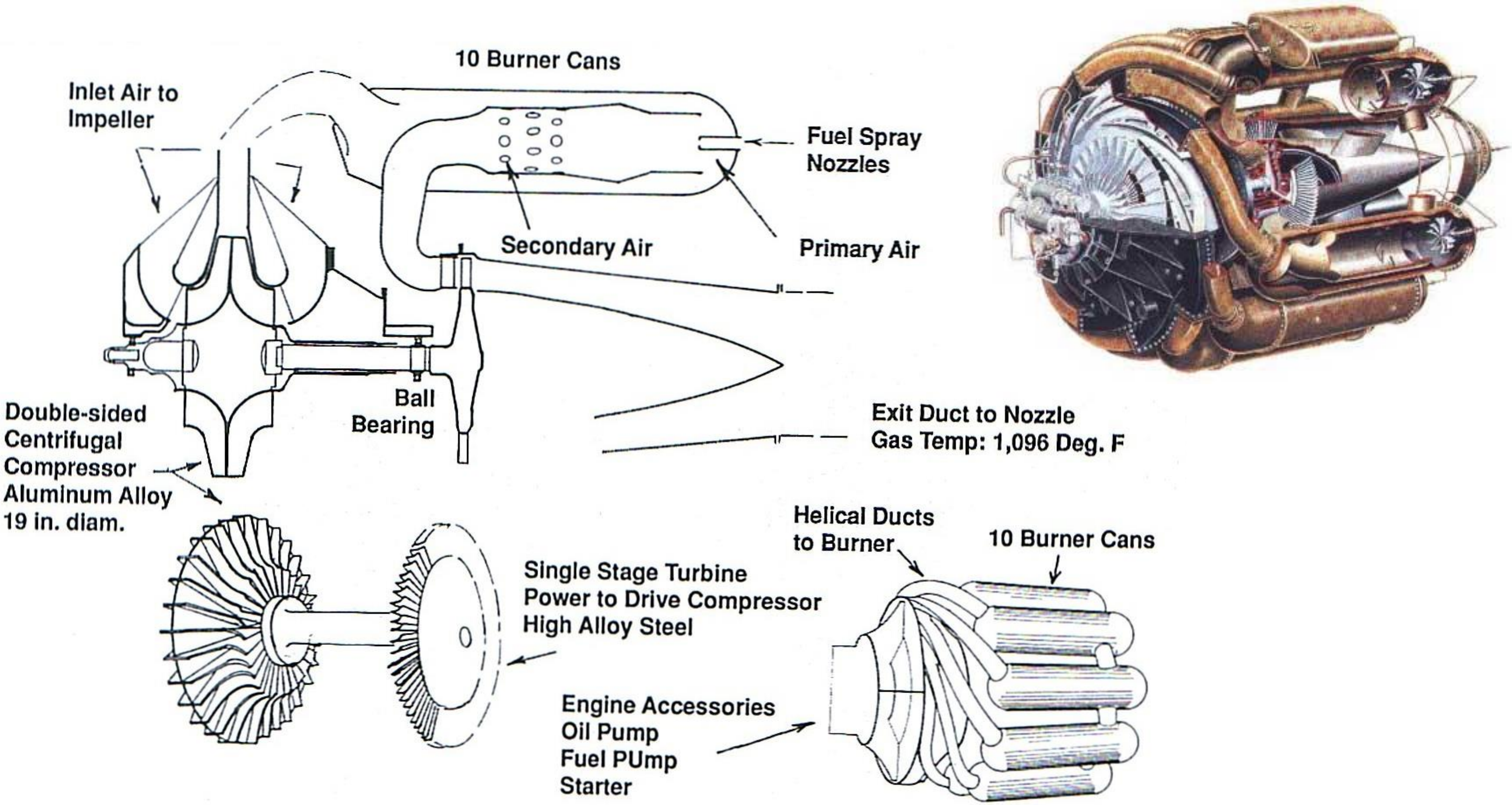


Ray Whitford
Cranfield University

Topics

- Jet Propulsion
- **Podded engines**
- **Swept wing**
- American medium bombers 1947
- Evolution of B-47
- De Havilland Comet & Tupolev Tu-104
- Development of Boeing 367-80 and 707
- Future configurations?

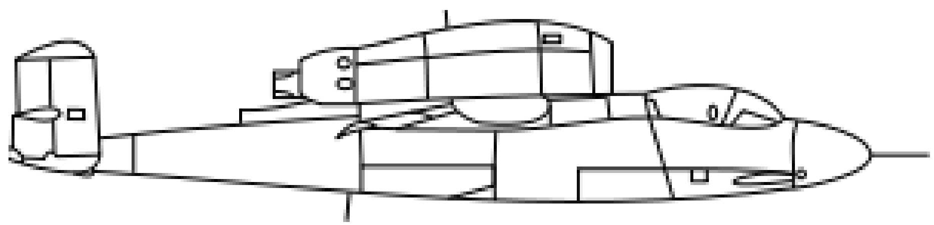
Whittle W-1 engine
(CENTRIFUGAL FLOW)

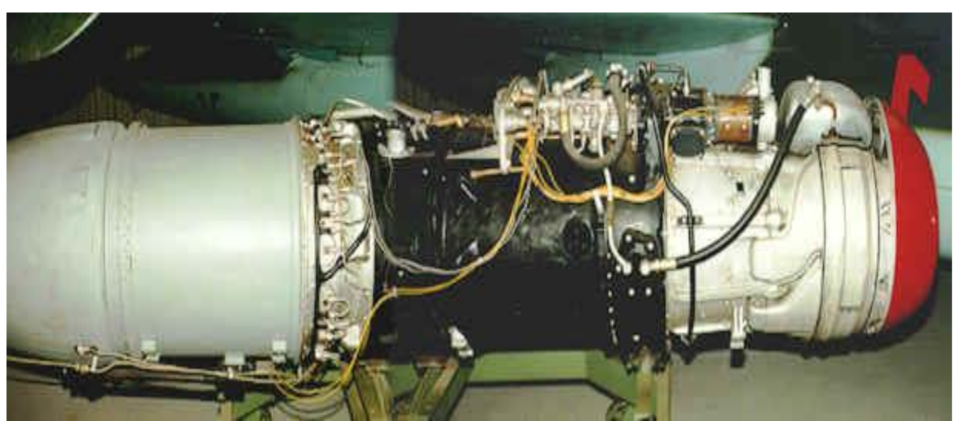


Podded engines

He162 with **AXIAL FLOW** BMW 003 turbojet

First flight Dec 1944

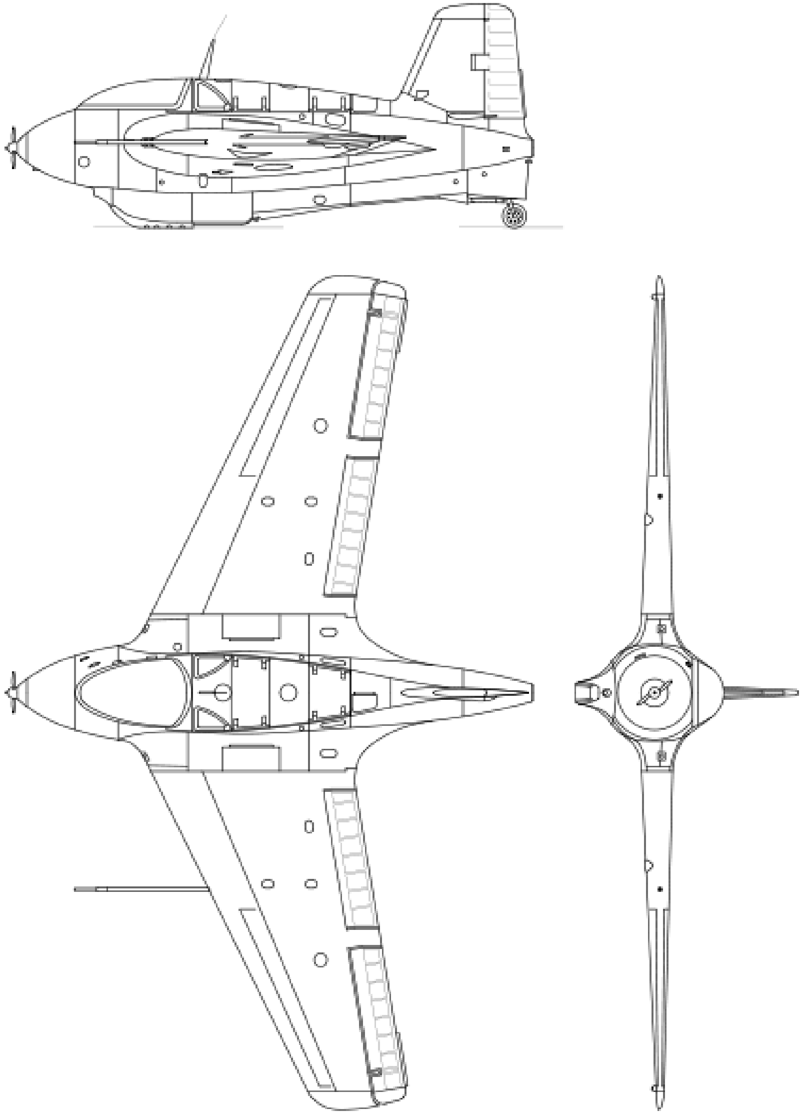




Me163

First flight Sept 1941

SWEEPBACK



Bundesarchiv, Bild 146-1972-058-62
Foto: o.Ang. | 1941

George Shairer (Boeing)
“Stop the bomber design”

In 1945, Schairer saw technical data at the captured German research Volkenrode centre **(in the area designated for occupation by Britain)**, showing the drag reduction offered by swept wings.

His letter to Boeing included a drawing of the swept wing and presented the key formulae: **wing weight need not be excessive.**

The B-47 design was changed using wings swept back 29 degrees (then 36 degrees). This proved crucial in efforts to win the design competition for the B-47 including using podded engines.

Schairer's letter

10 May 1945

G. S. SCHARER

Germany
5/10/45

Boeing Aircraft Co
Seattle Wash USA

Dear Ben,

It is hard to believe that I am in Germany within a few miles of the front line. Everything is very quiet and I am living very normally in the middle of a forest. We have excellent quarters including lights, hot water, electric razors etc.

We are seeing much of German aerodynamics. They are ahead of us in a few items which I will mention.

G. S. SCHARER

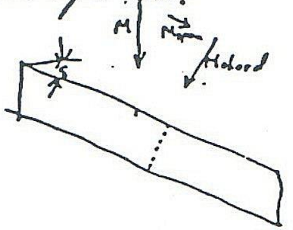
(2)

The Germans have been doing extensive work on high speed aerodynamics. This has led to one very important discovery. Sweepback or sweepforward has a very large effect on critical Mach No. This is quite reasonable on second thought. The flow parallel to the wing may not effect the critical Mach No and the component normal to the airfoil is the one of importance. Thus the critical M is determined by the

A very important discovery: Sweepback has a very large effect on critical Mach No.

(3) G. S. SCHARER

airfoil section normal to the wing and by the sweepback.



Mchord = M cos δ

For instance a 9% wing might have a critical M = .8 and an 18% wing M = .7. This is a ratio of .875 ∴ cos⁻¹ .875 = 29°. If the same span is retained the chord parallel to the wind will be constant and the thickness will increase not by 2:1 but by

(4) G. S. SCHARER

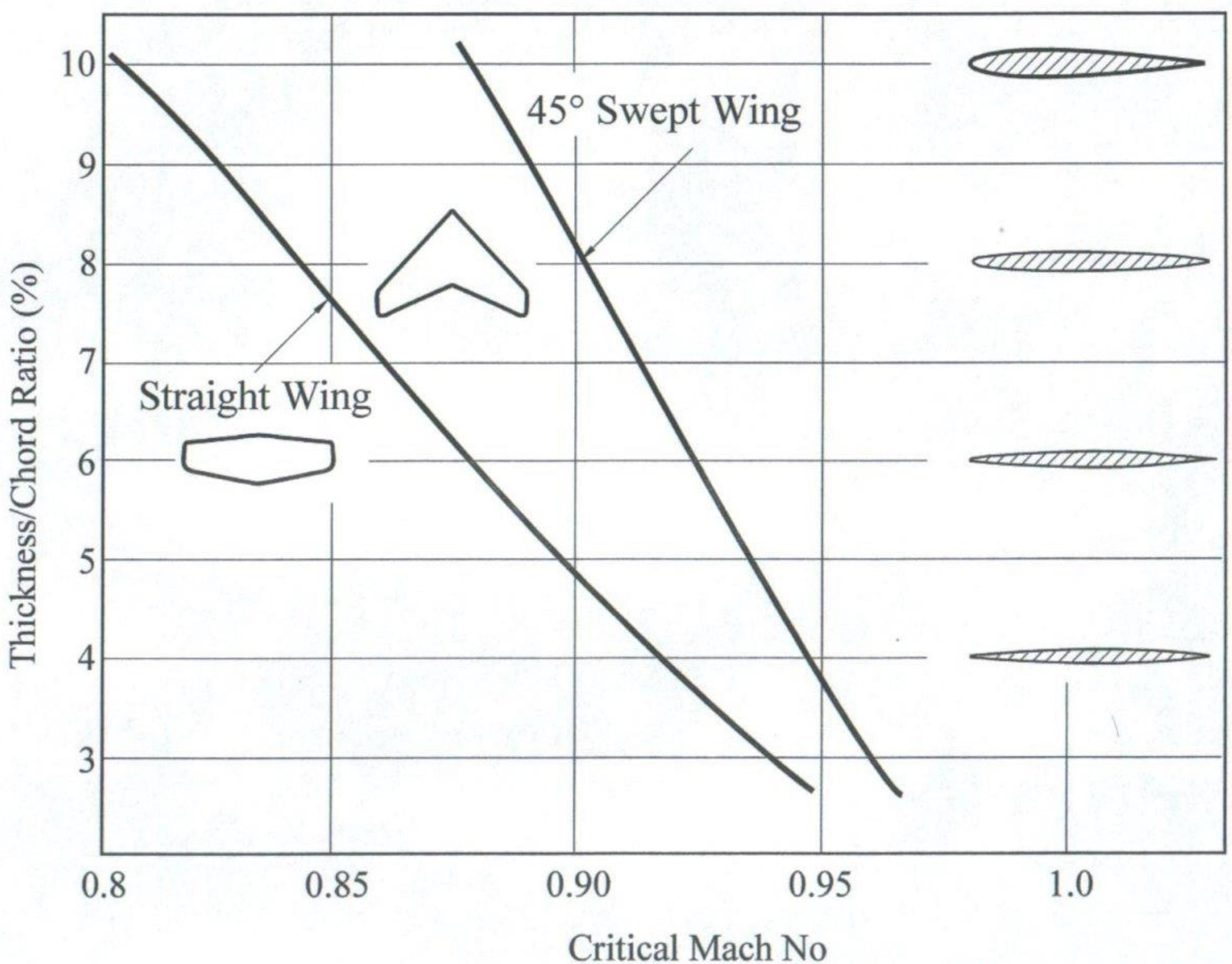
2 × .875 : 1 or 1.75 : 1. The length of the wing will be increased to $\frac{1}{.875}$ = 1.14. The material required at the root will then decrease to $\frac{1.14}{1.75}$ = .65. The wing bending material will decrease to .65 × 1.14 = .74. This is to keep constant Mcrit when changing from a chordwise section of 9% to one of .875 × 18 = 15.8% with the addition of 29° of sweep. If the wing weight is held constant a large increase in Mcrit will result.

29° wing sweep suggested

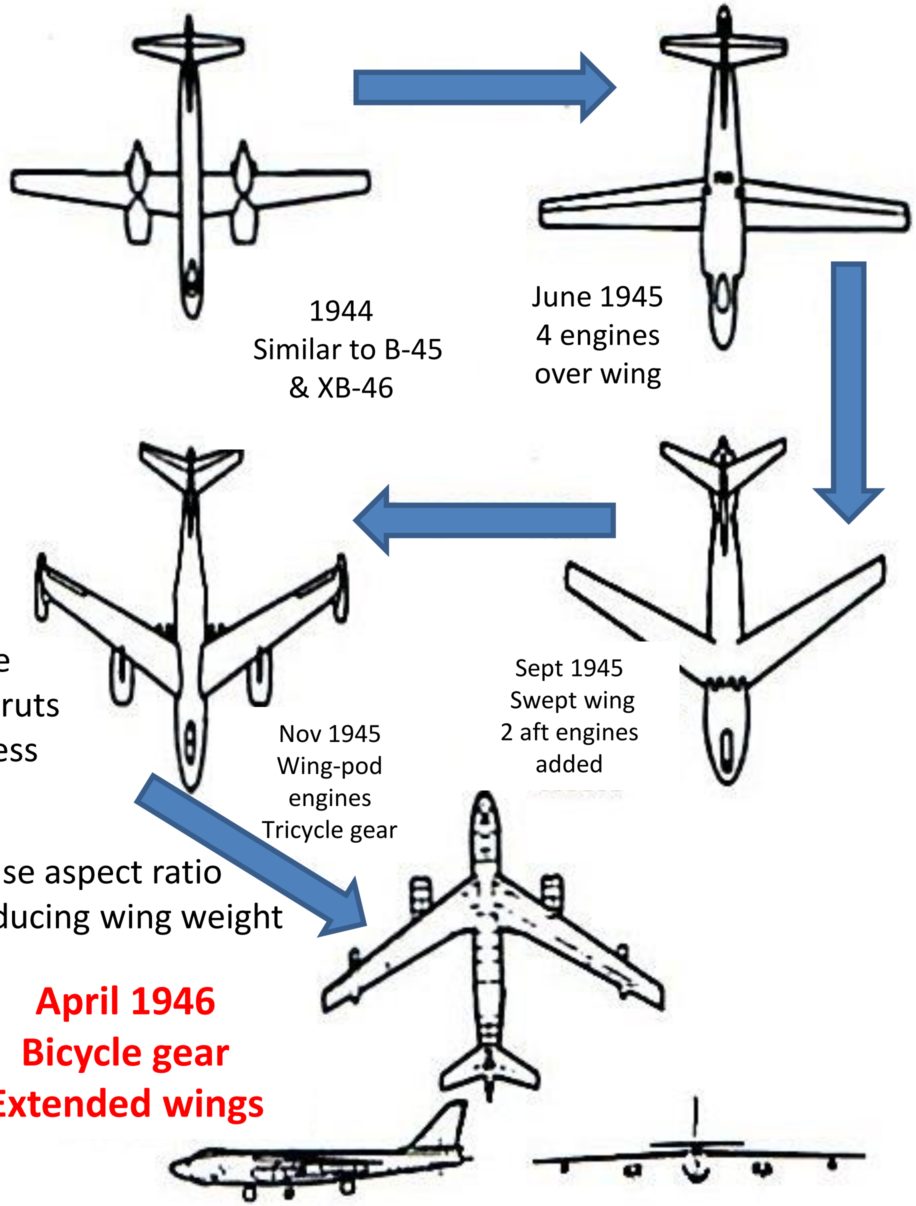
Swept versus straight wing at M<1

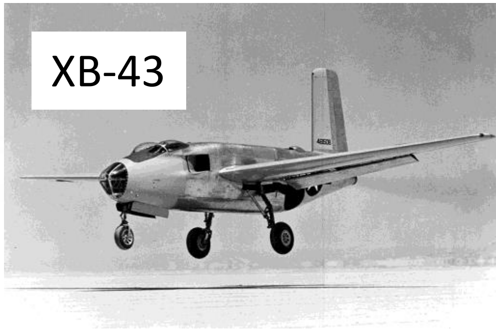
Busemann (1935): sweep for M>1 flight

Betz (1939): sweep for transonic flight



Evolution of Boeing B-47





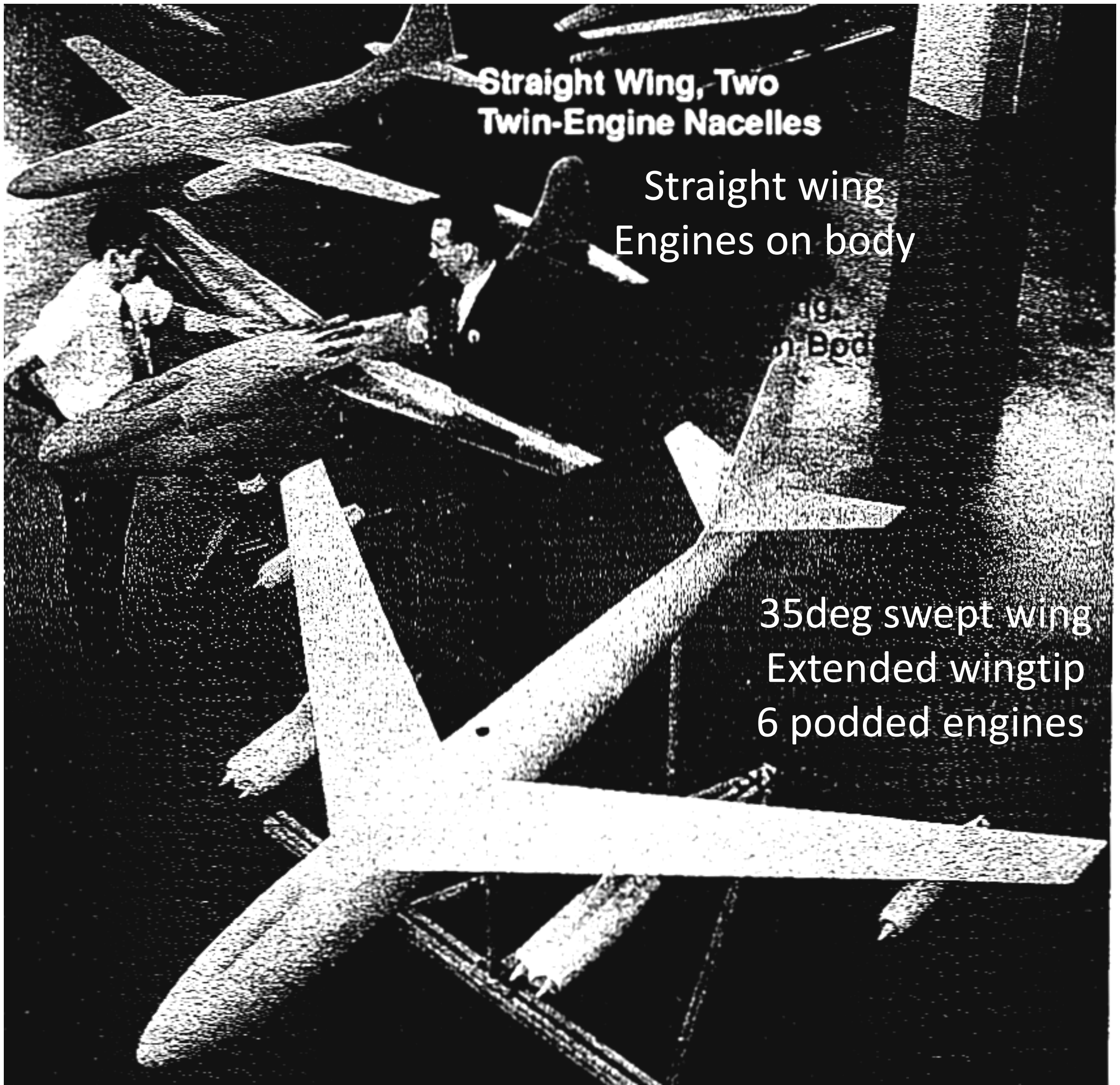
Fuselage engines rejected by USAF due to fire risk: WWII experience

Slimmer fuselage
Even with pods & struts
wetted area was less

Wing span increased to raise aspect ratio
Allowed by engine position reducing wing weight

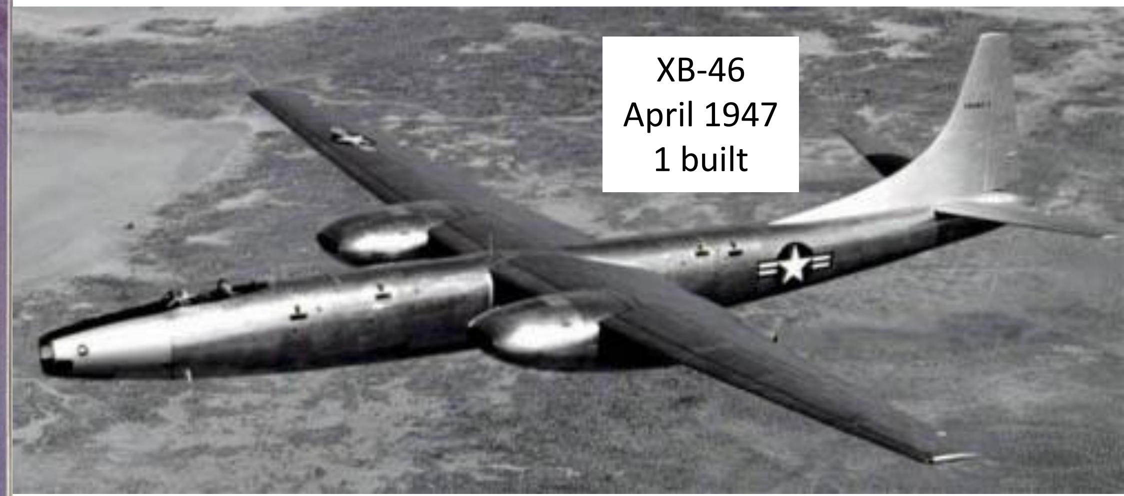
April 1946
Bicycle gear
Extended wings

B-47 models 1944- May 1946



Post-war USAF medium jet bombers

B-45
March 1947
143 built



XB-46
April 1947
1 built

XB-48
June 1947
2 built

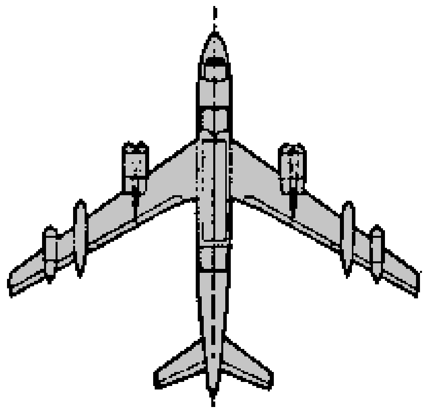
B-47
Dec 1947
2032 built

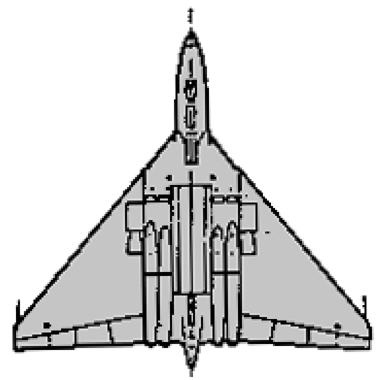
Little consensus on 'best' configuration

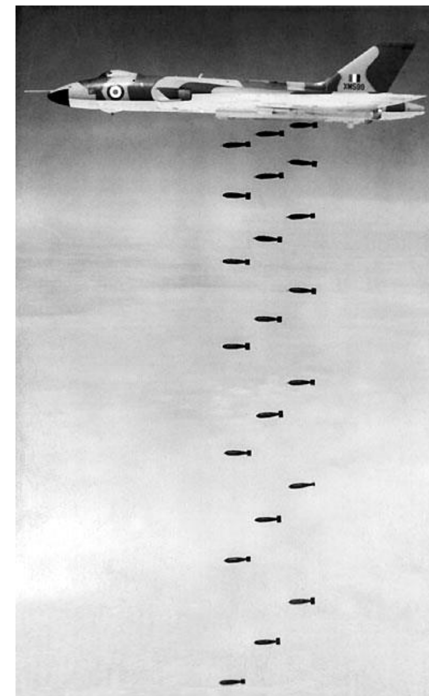
Design Philosophy Affects Results

(Or there's more than one way to skin a cat)

20,000lb bombload over 3000miles



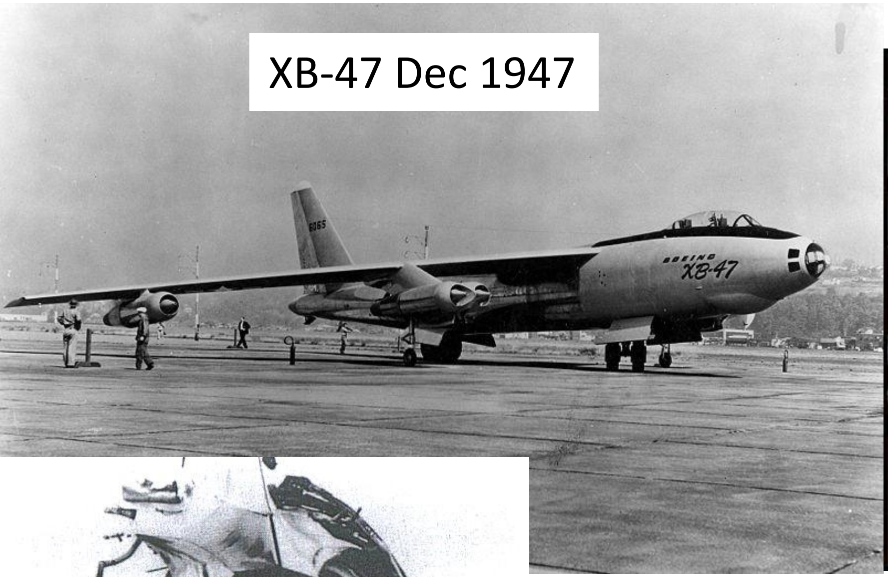


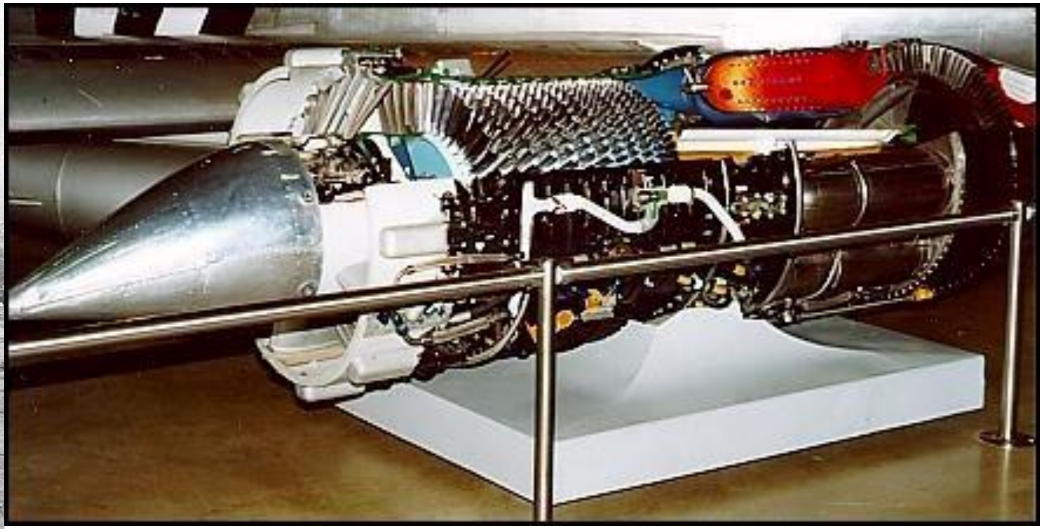


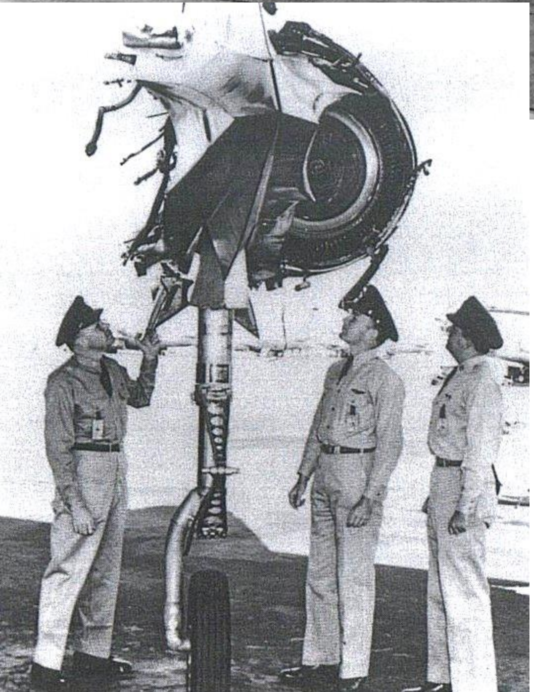
	BOEING B-47		AVRO Vulcan B.1	
WING AREA, FT^2	1,430		3,446	
SPAN, FT	116		99	
ASPECT RATIO	9.43		2.84	
MAX W/S, LB/FT^2	140		43.5	
MAX W/b, LB/FT	1,750		1,520	
WETTED AREA, FT^2	11,300		9,500	
$(L/D)_{max}$ C_L (opt)	17.3	0.68	17.0	0.26

But out of the B-47, came the B-52, 707, 737, 747, etc (i.e. $$$)

General Electric TG180/J35 turbojet
(Only 4000lb thrust so B-47 needed six engines)

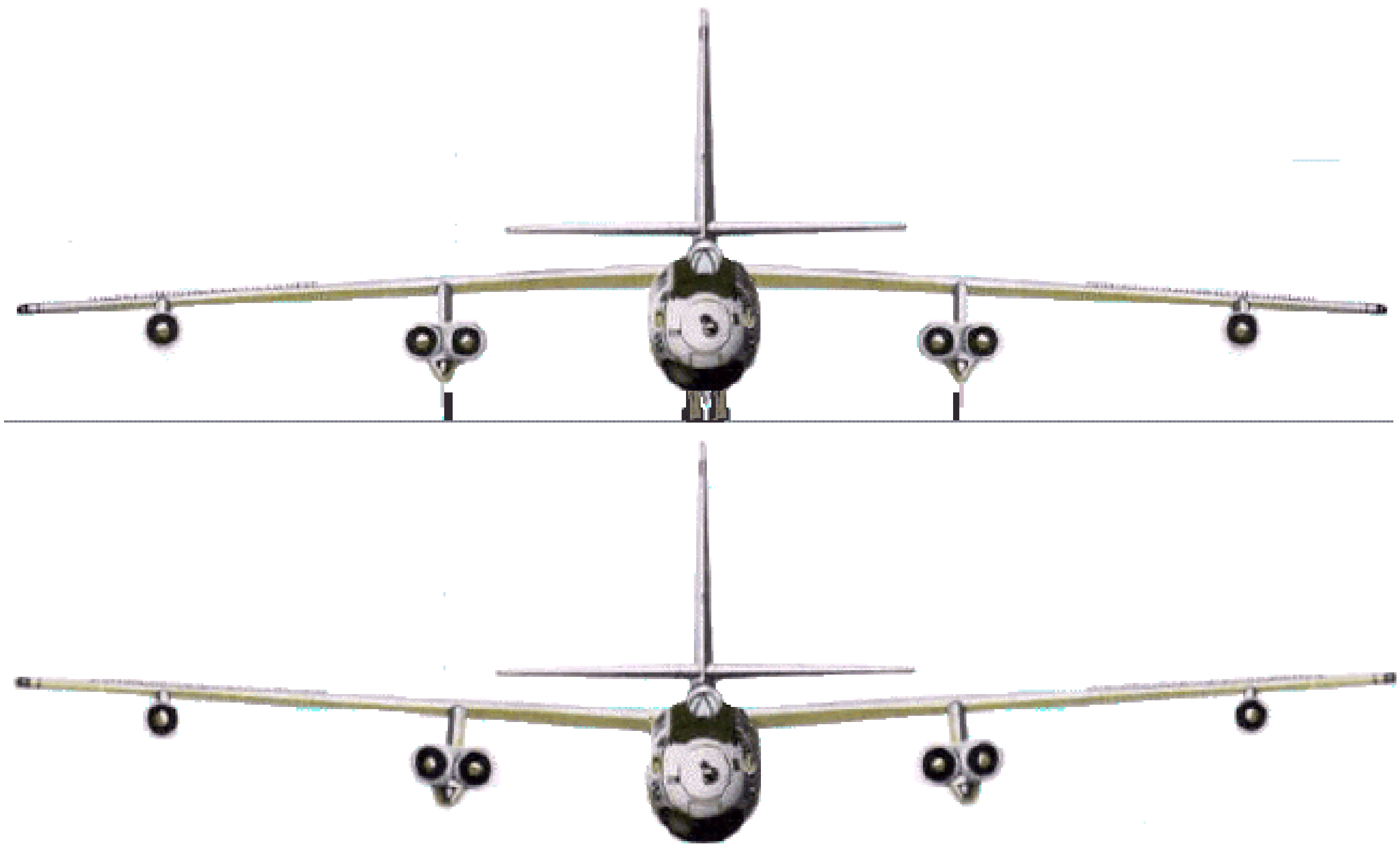

XB-47 Dec 1947





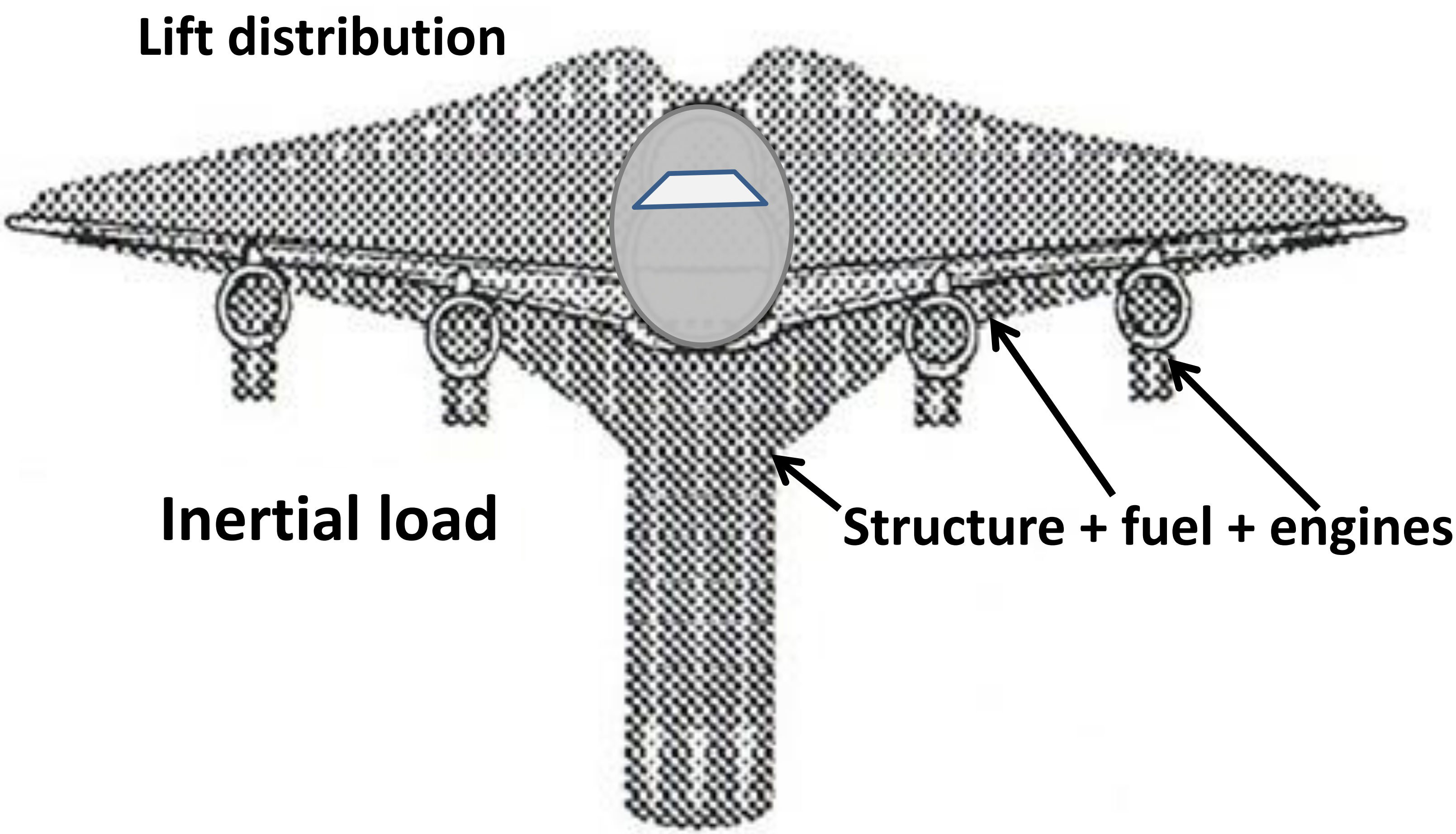
Overhaul life for the J47 ranged from 15 hours (in 1948) to a predicted 1,200 hours (625 hours achieved in practice) in 1956.

B-47 wing bending
(Distributing engines across wing saves weight)



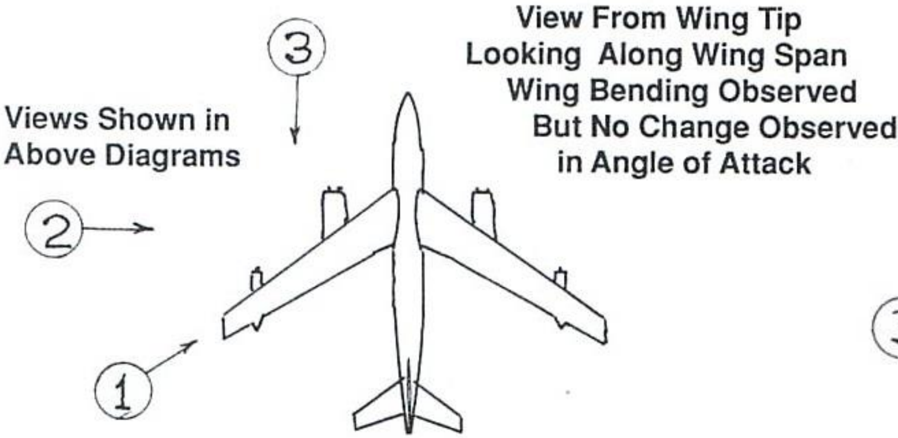
Wing inertia relief

(Engines + fuel + structure)



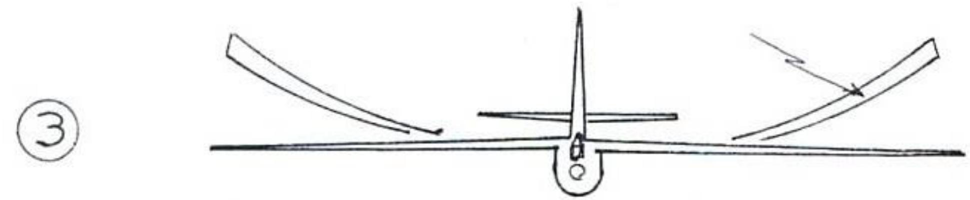
Wing bending

Boeing B-47

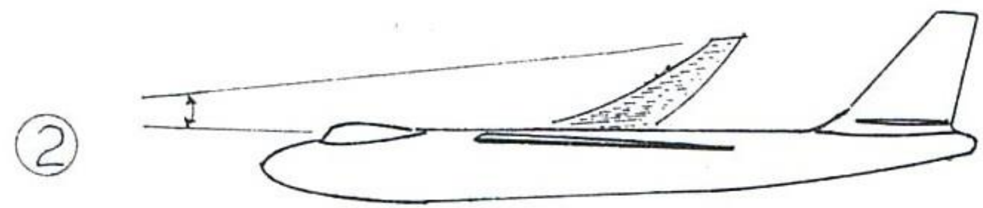


A Rough Air Shock Absorber

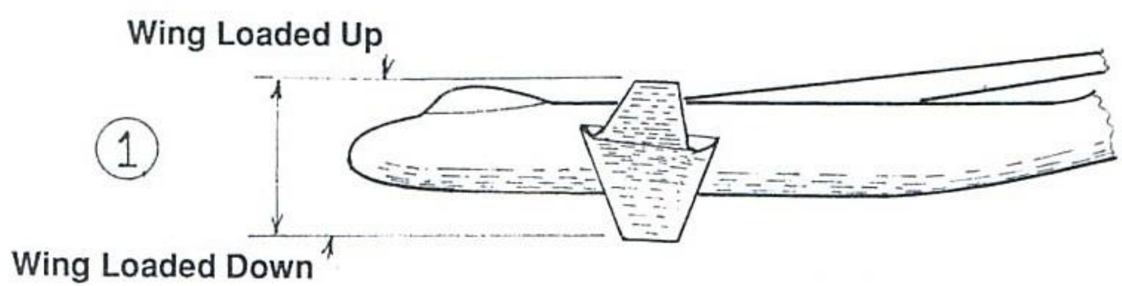
Wasn't realised that when swept wing bent it would also twist (thin 12% t/c wing)



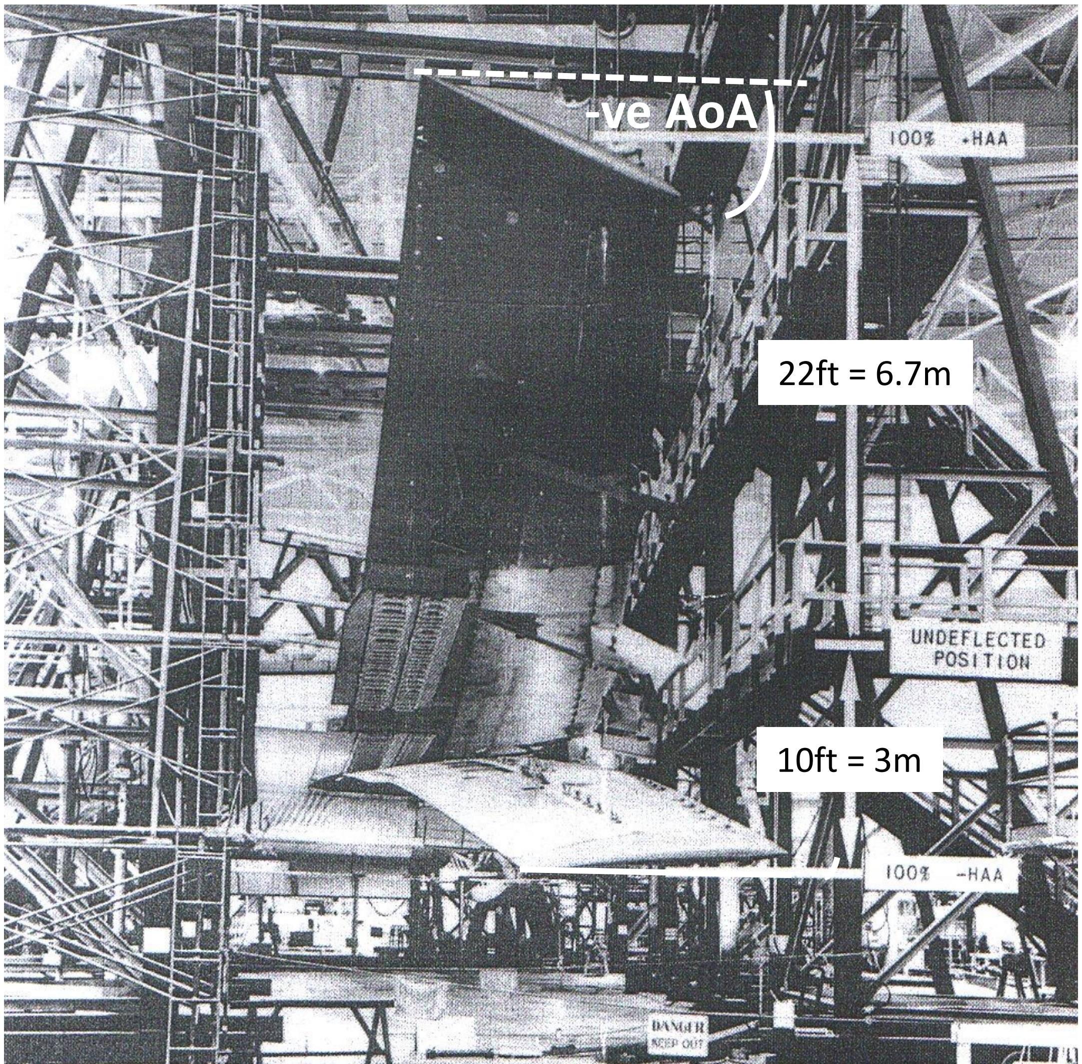
Front View With Max Bending Deflection
Upper Surface of Wing Observed



Side View With Max Bending Deflection
Reduced Angle of Attack at Tip

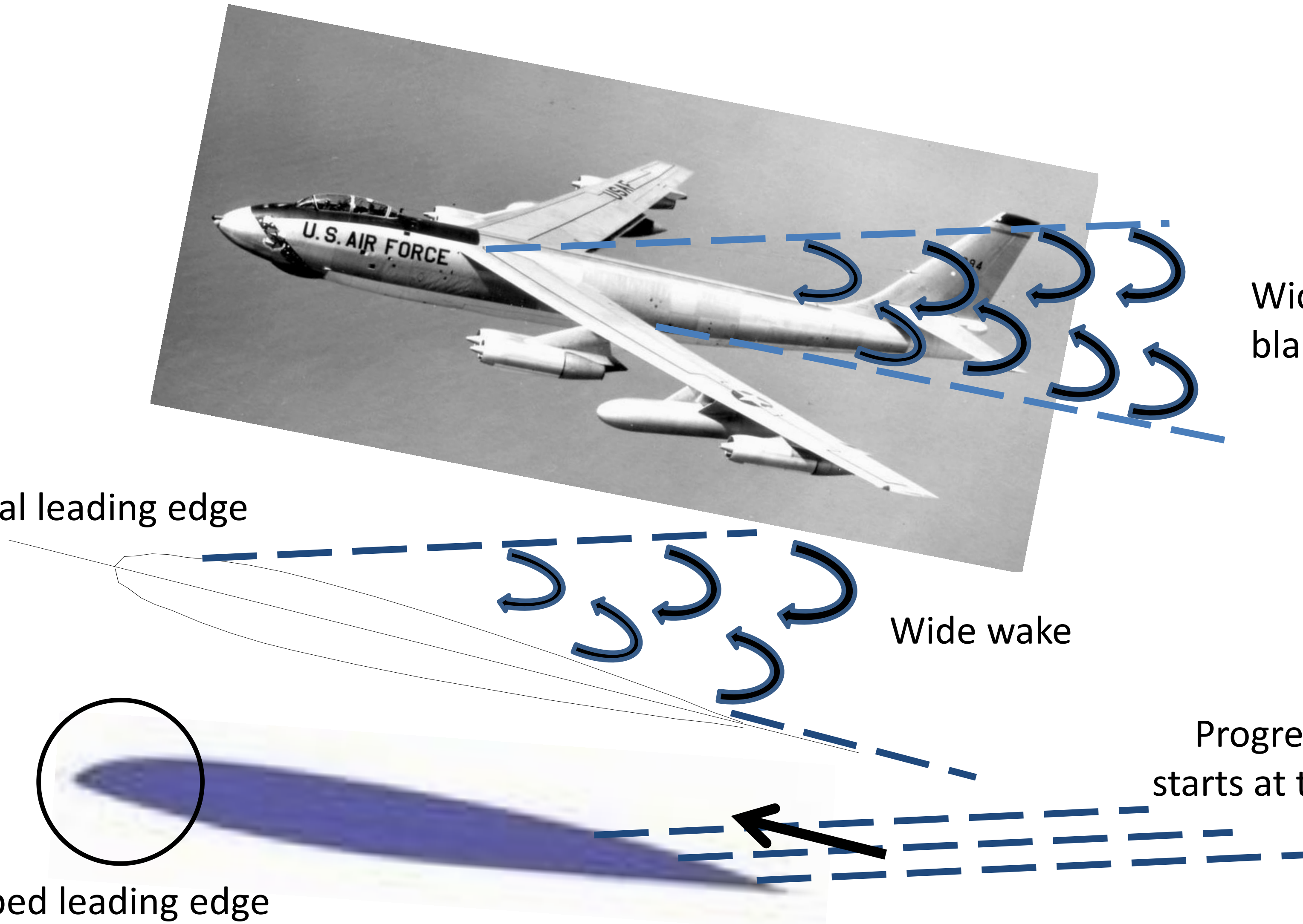


Wing deflection
B-52 limit loads



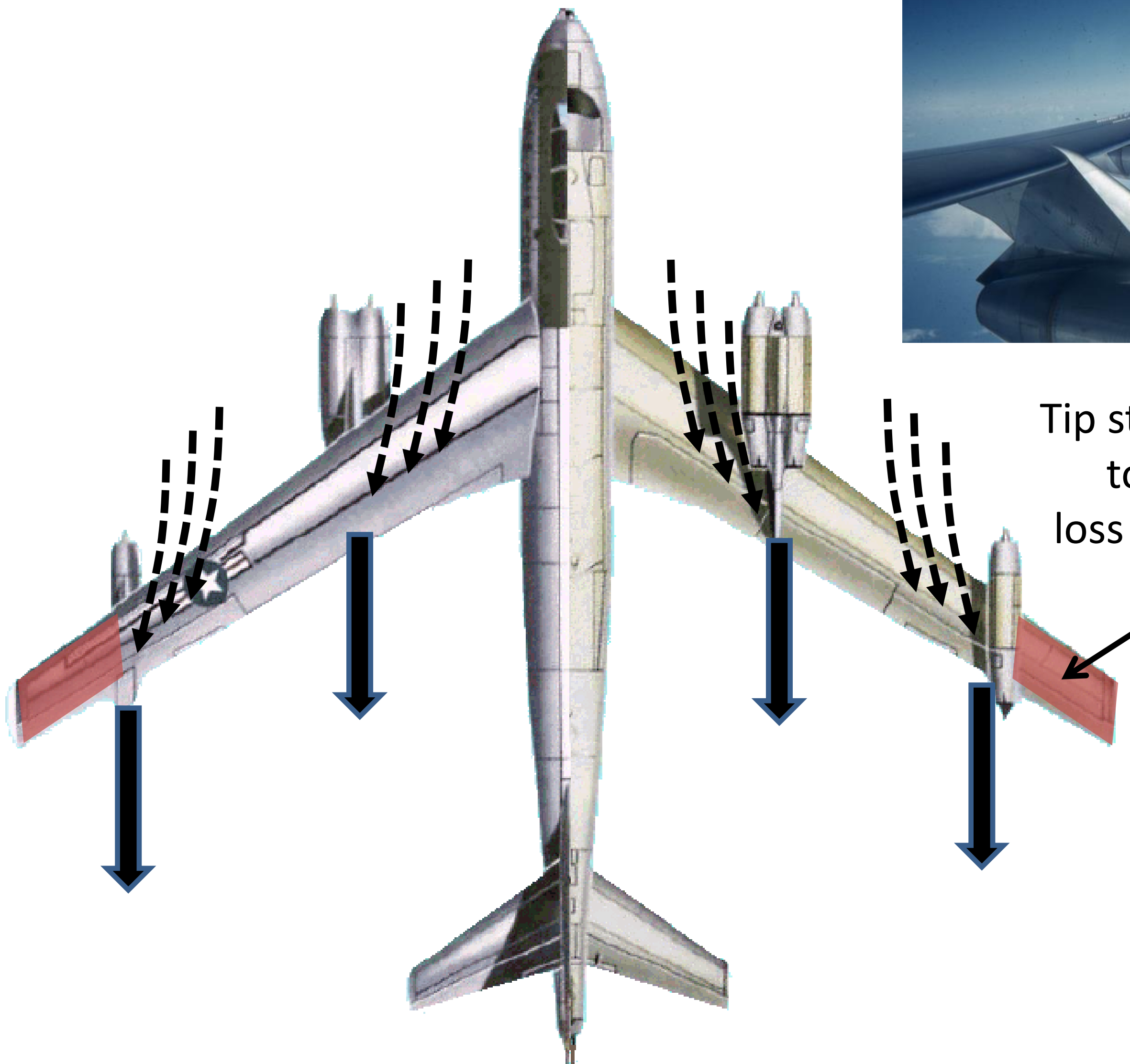
Fix 1 for pitch-up at stall

Drooped leading edge

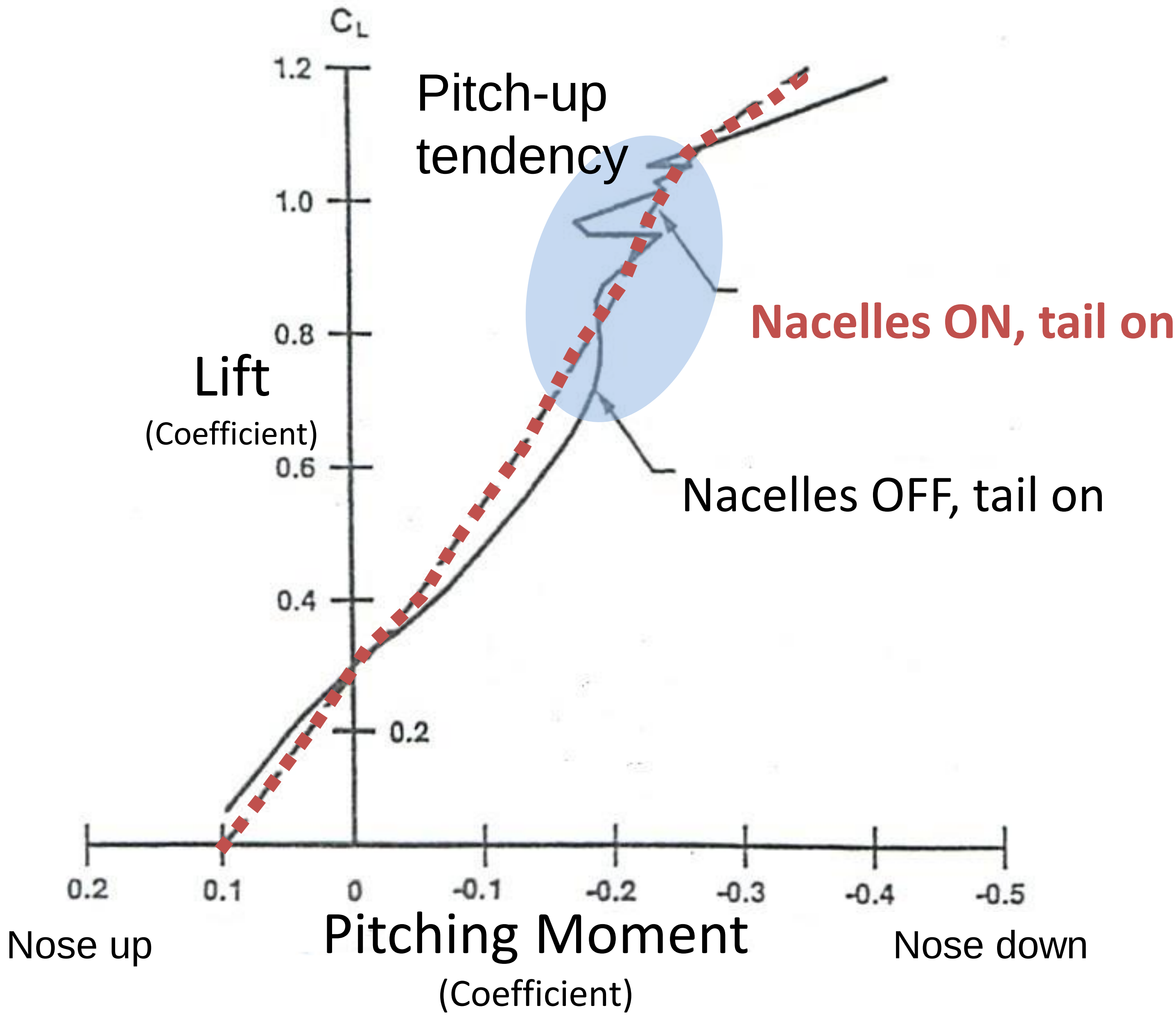


Fix 2 for pitch-up at stall

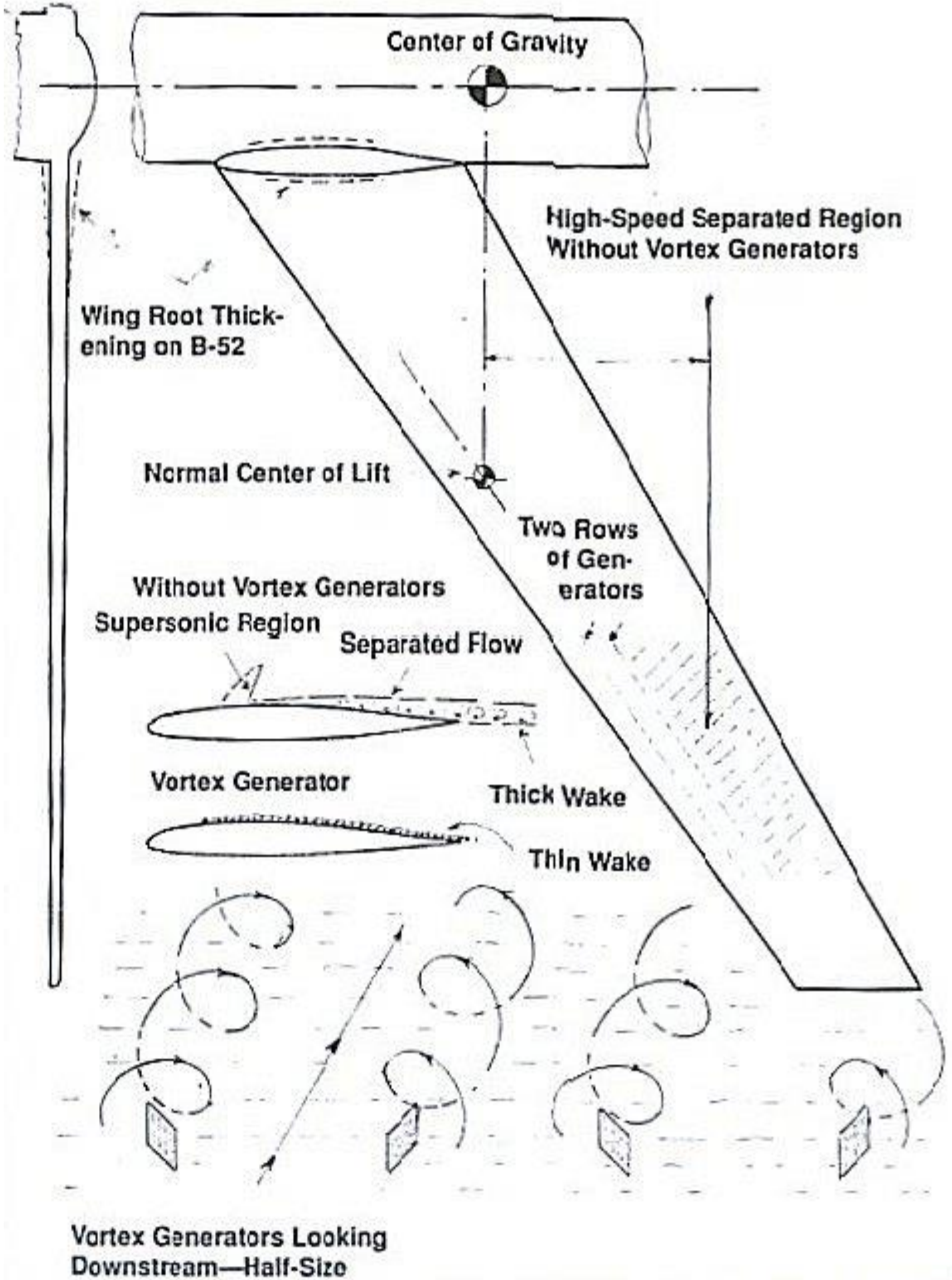
Engine pylons straightened airflow and avoided pitch-up

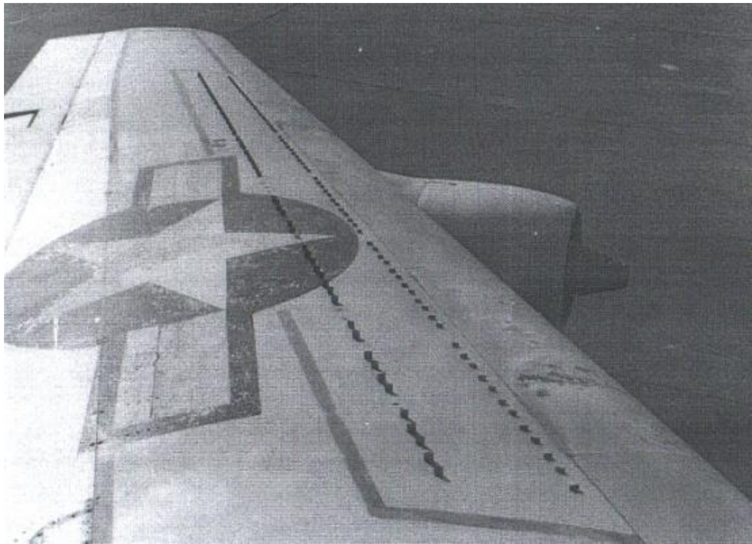


Effect of engine pylons – B-47

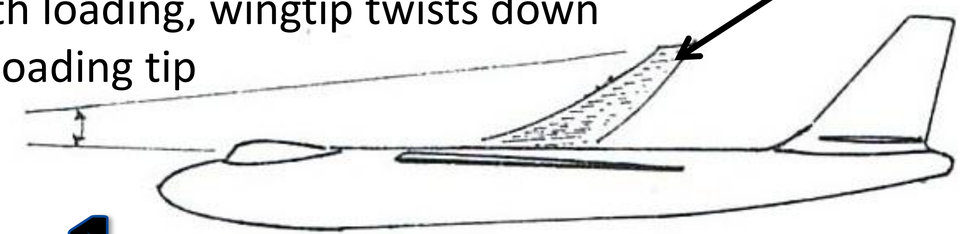


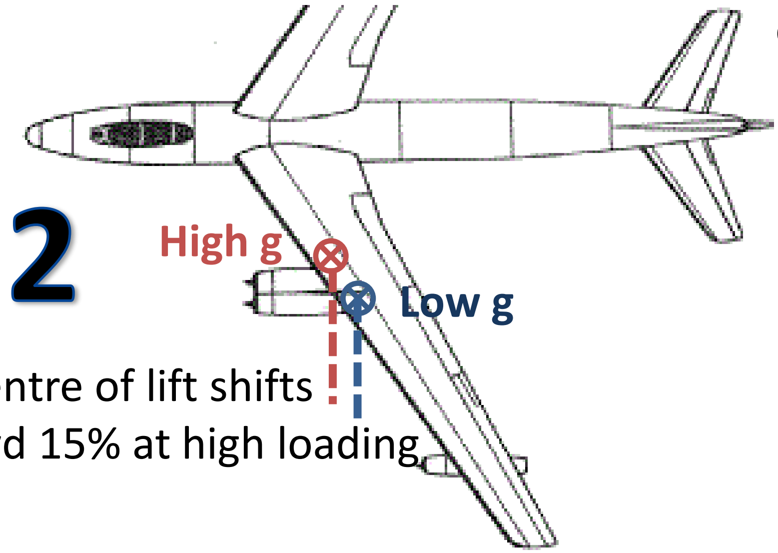
Vortex generators

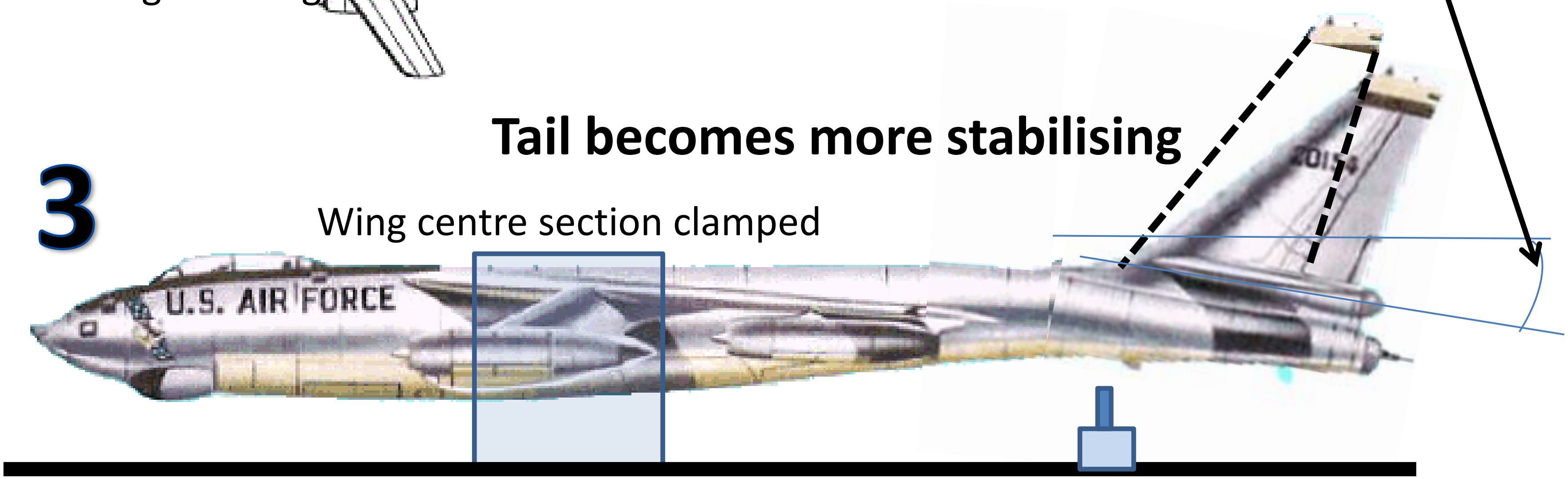




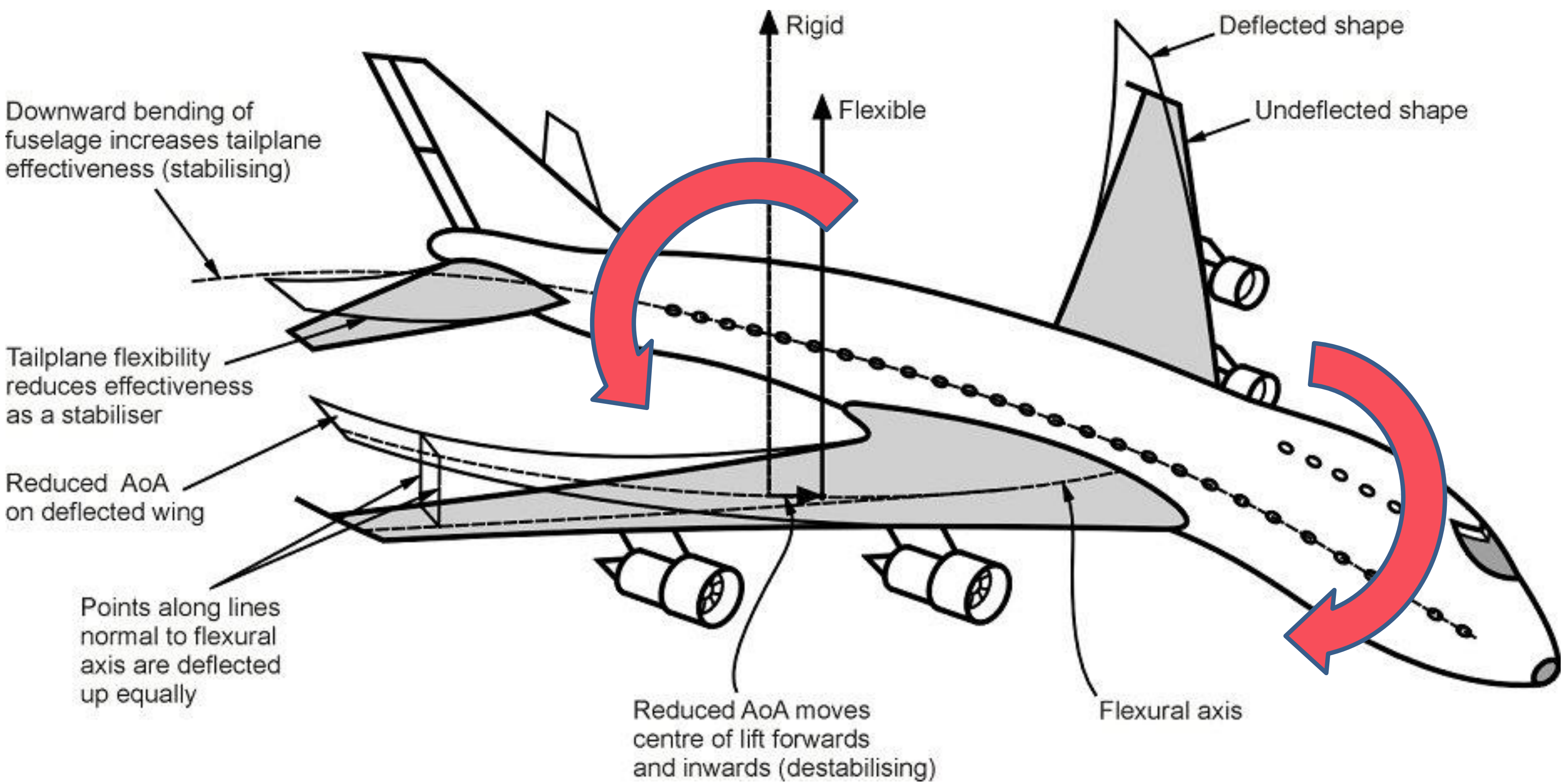
Stability with flexible structure







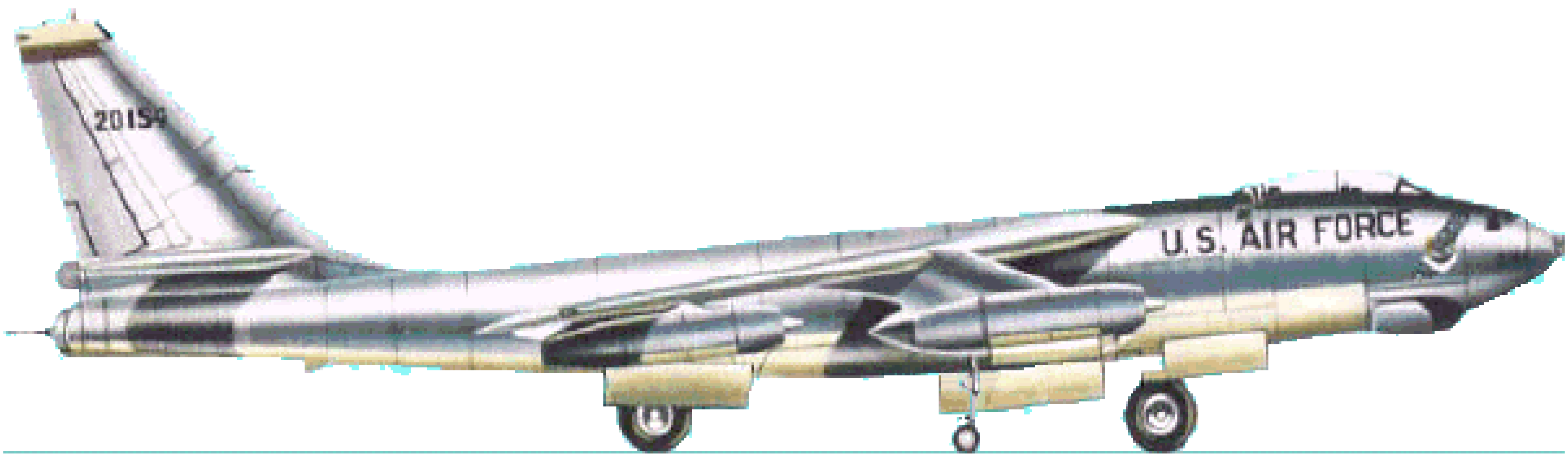
Stability with flexible structure
(still applies today - B747)



B-47 bicycle undercarriage

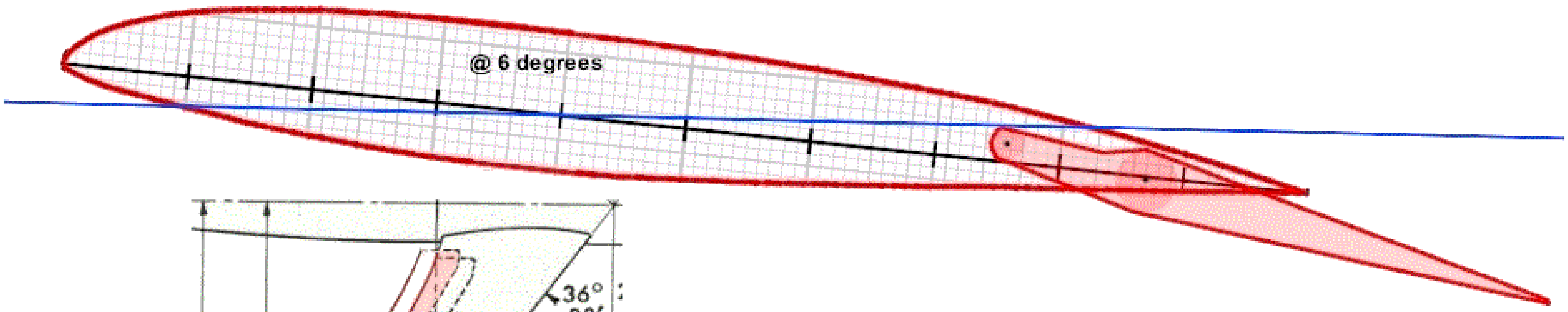
(to accommodate bomb bay)

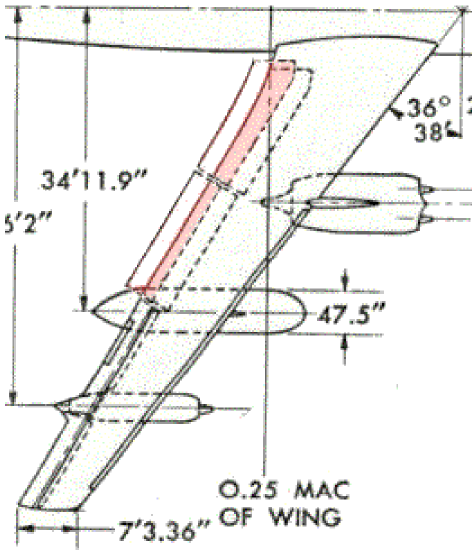
Prevented conventional take-off rotation
Wing was set at ¾ max lift AoA (6 deg) with 35 deg flap



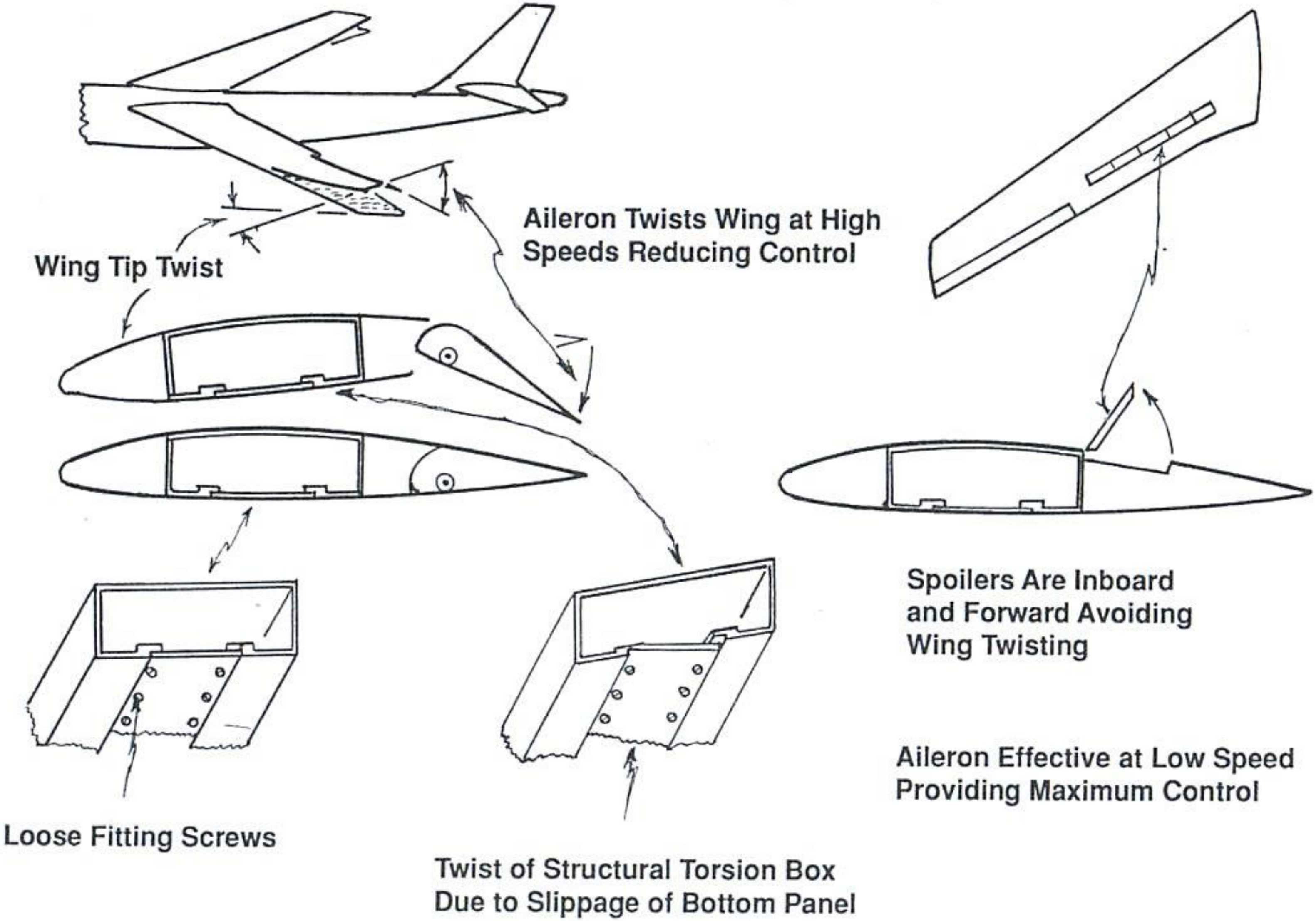
The B-47 was relatively difficult to land because of its high approach speed, unresponsive engines, and its unorthodox undercarriage.

B-47 Fowler flap

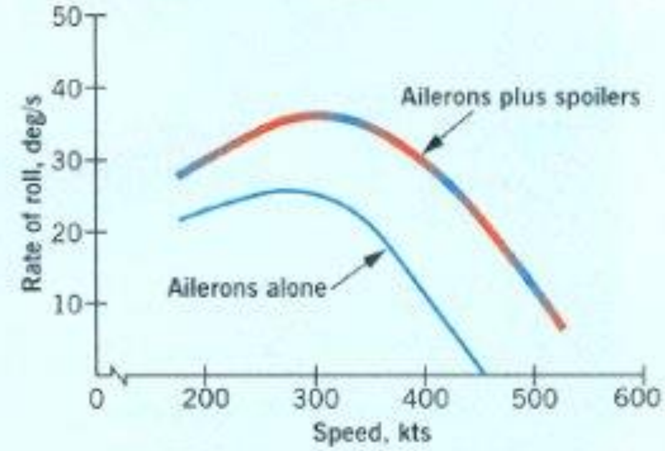


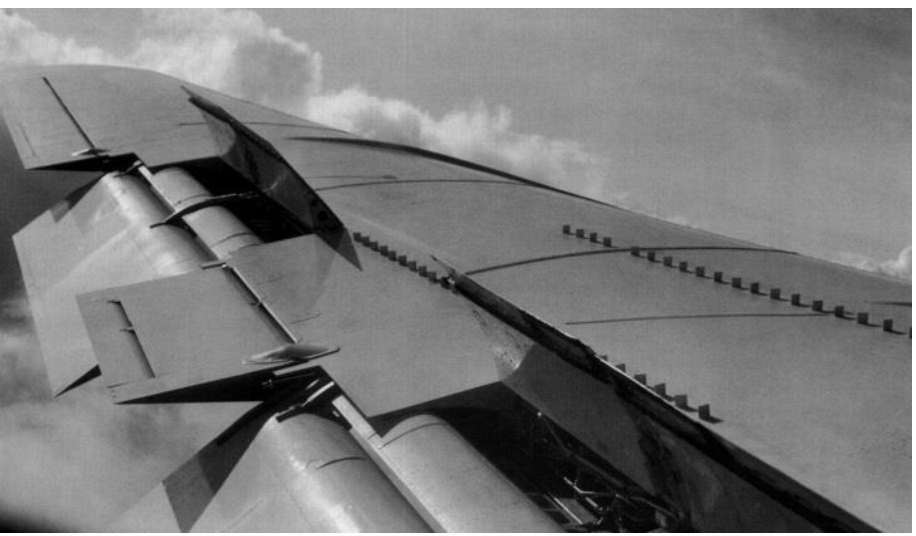


Inboard spoilers to reduce twist of thin swept wings

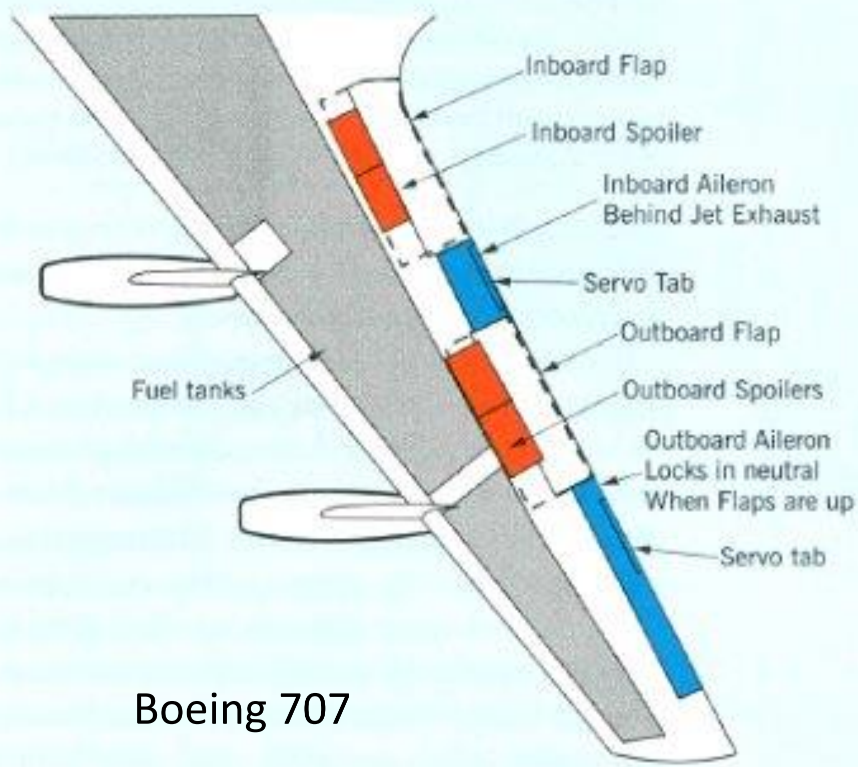


Use of spoilers/lift dumpers



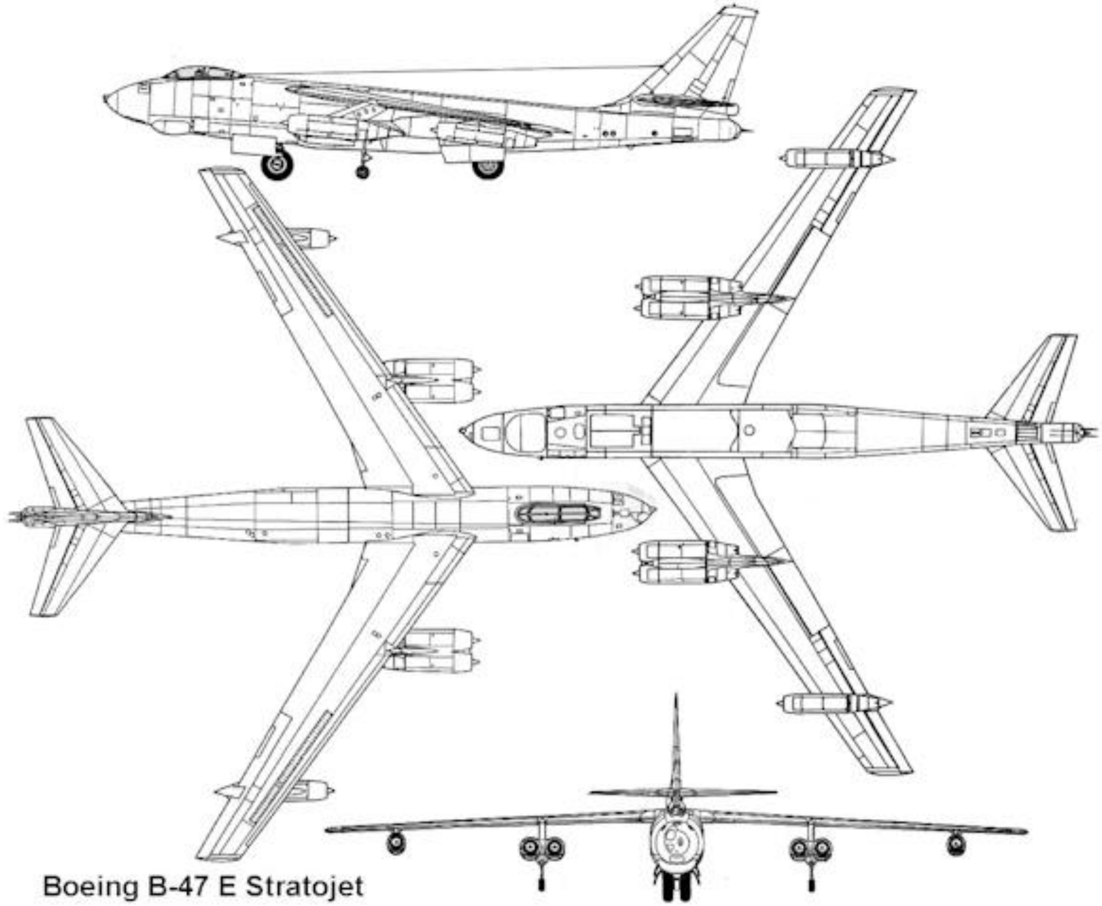


Boeing 367-80 spoilers and vortex generators



Boeing 707

Boeing B-47 Stratojet



Sir George Edwards (head Vickers Armstrong) said "Only Boeing would have the guts to design an aeroplane like that"

B-47 in service

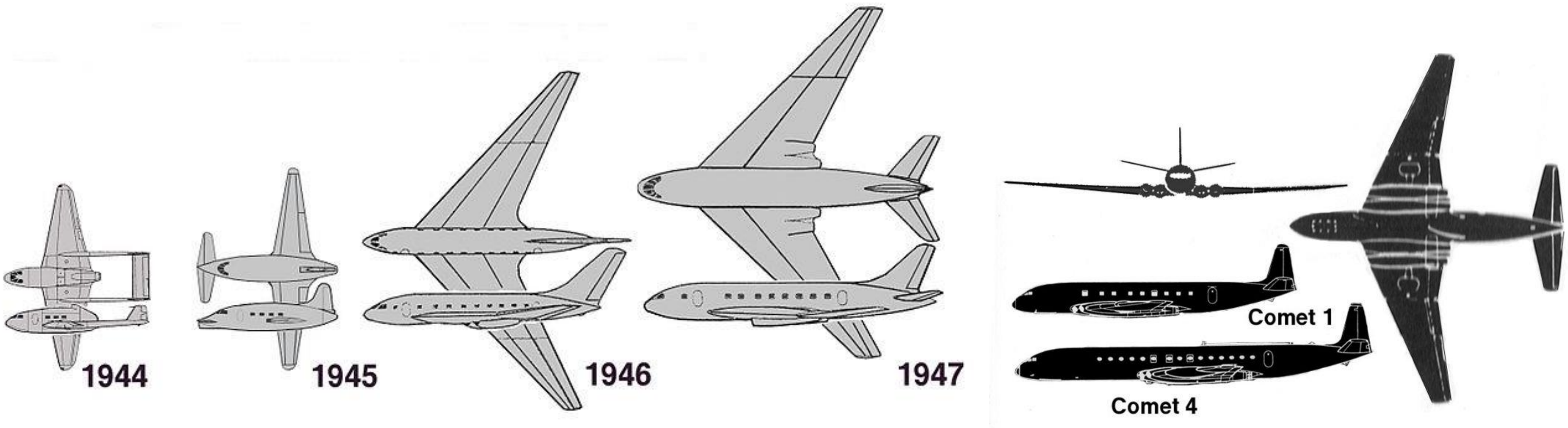
The early service of the B-47 was marked by frequent crashes and accidents, and the plane got a reputation as a crew-killer. Though there was nothing intrinsically wrong with the Stratojet, it was terribly unforgiving of crew mistakes or inattention.

B-47's last flight 1986

"the B-47 was often admired, respected, cursed or even feared, but almost never loved."

De Havilland DH 106 Comet

First flight July 1949
Entered service 1952



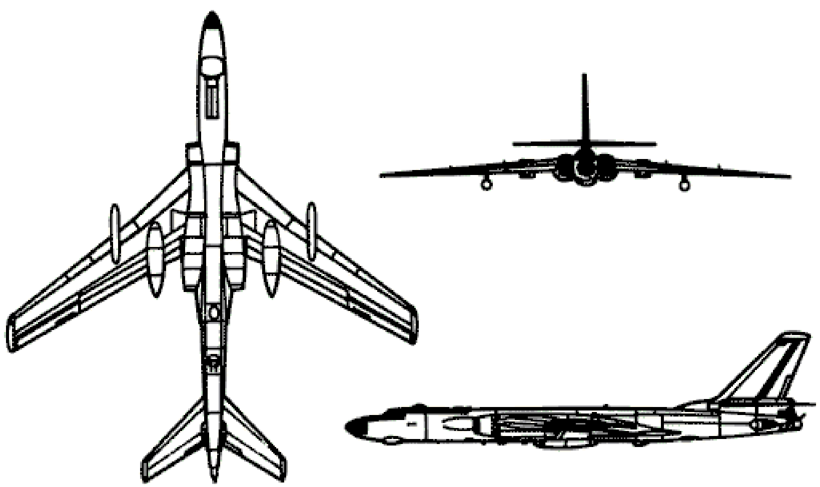
DH Ghost centrifugal turbojets

36-40 seats

RR Avon axial turbojets

Tupolev Tu-16 & Tu-104

1952	First flight	1955
1954	Service entry	1956



Contemporary American airliners

Douglas DC-6B 1946 (704)

Boeing 377 1947 (53)

Lockheed L.1049 1950 (259)

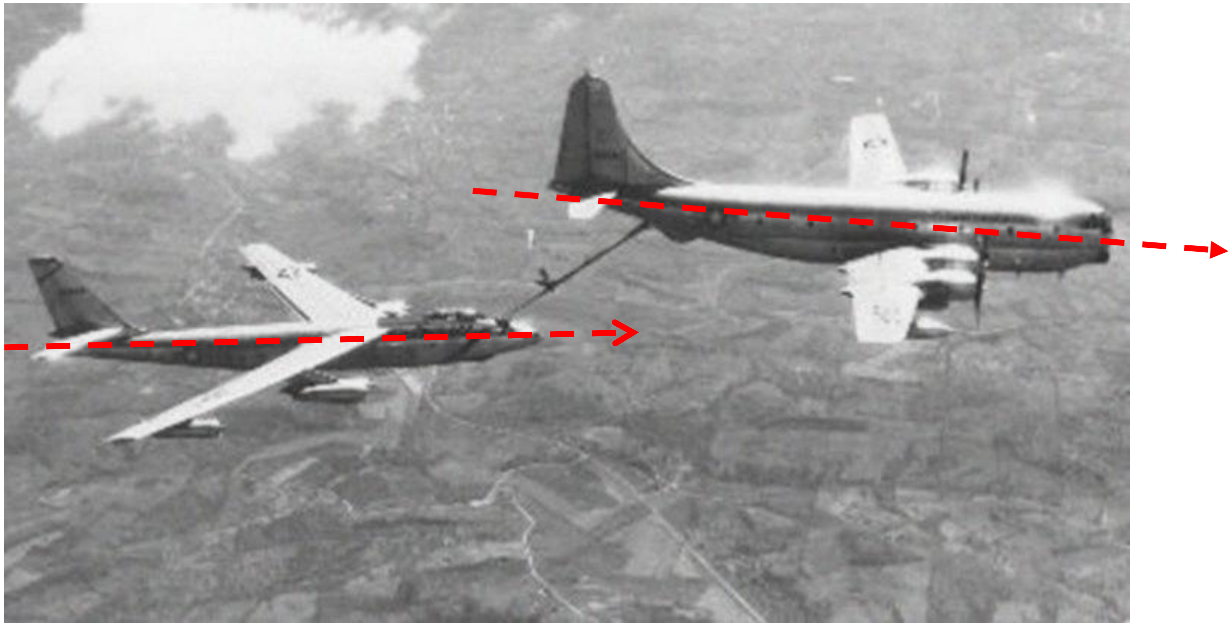
Douglas DC-7B 1953 (338)

Lockheed L.1649 1956 (44)

Lockheed L.188 1957 (170)

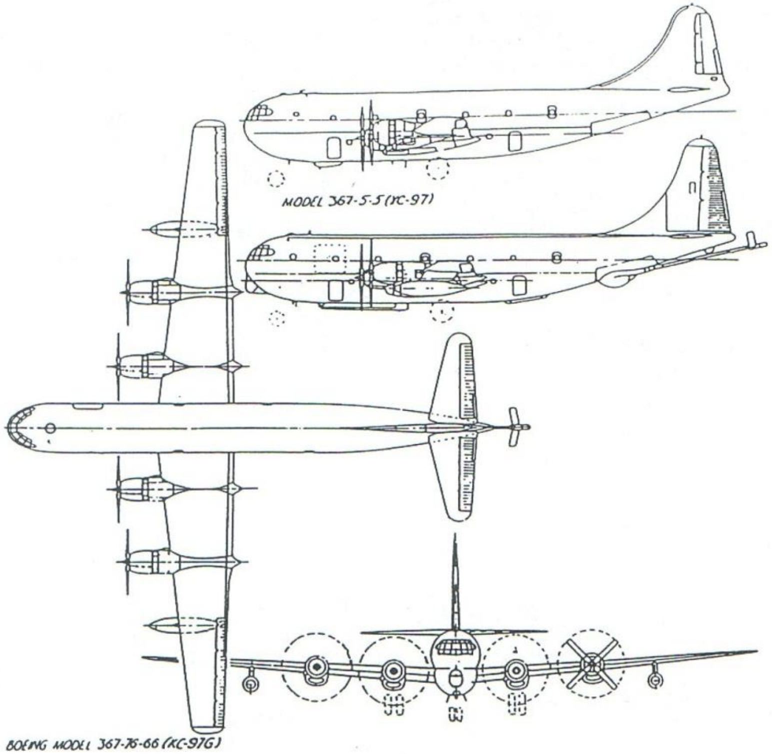
USAF needed new tanker for forthcoming B-52

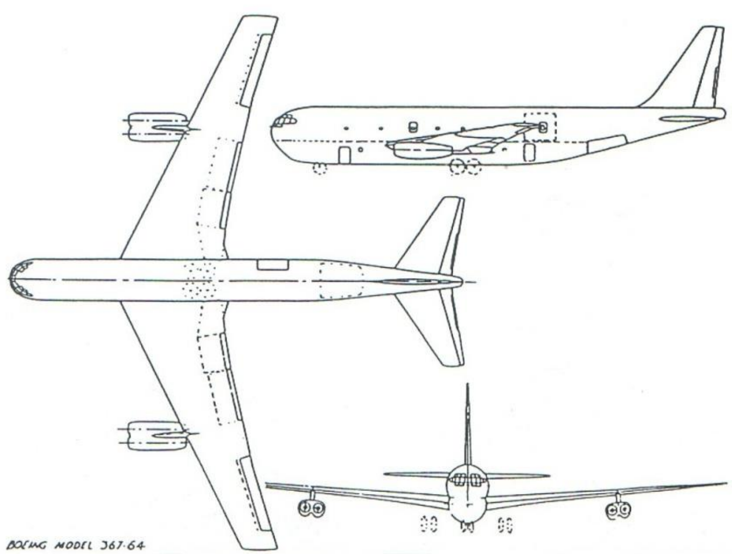
Boeing KC-97 & B-47



As fuel transferred, the increasingly heavy B-47 had to fly faster to stay above its stall speed. The KC-97 would begin a descent to keep its speed above the B-47’s stall speed. The B-47 used fuel in its descent, refuelling and climb back to altitude, so its net gain was much less than would be the case using a jet tanker.

Evolution of jet tanker from KC-97





Boeing B-52 & KC-135

B367-80 wind tunnel model

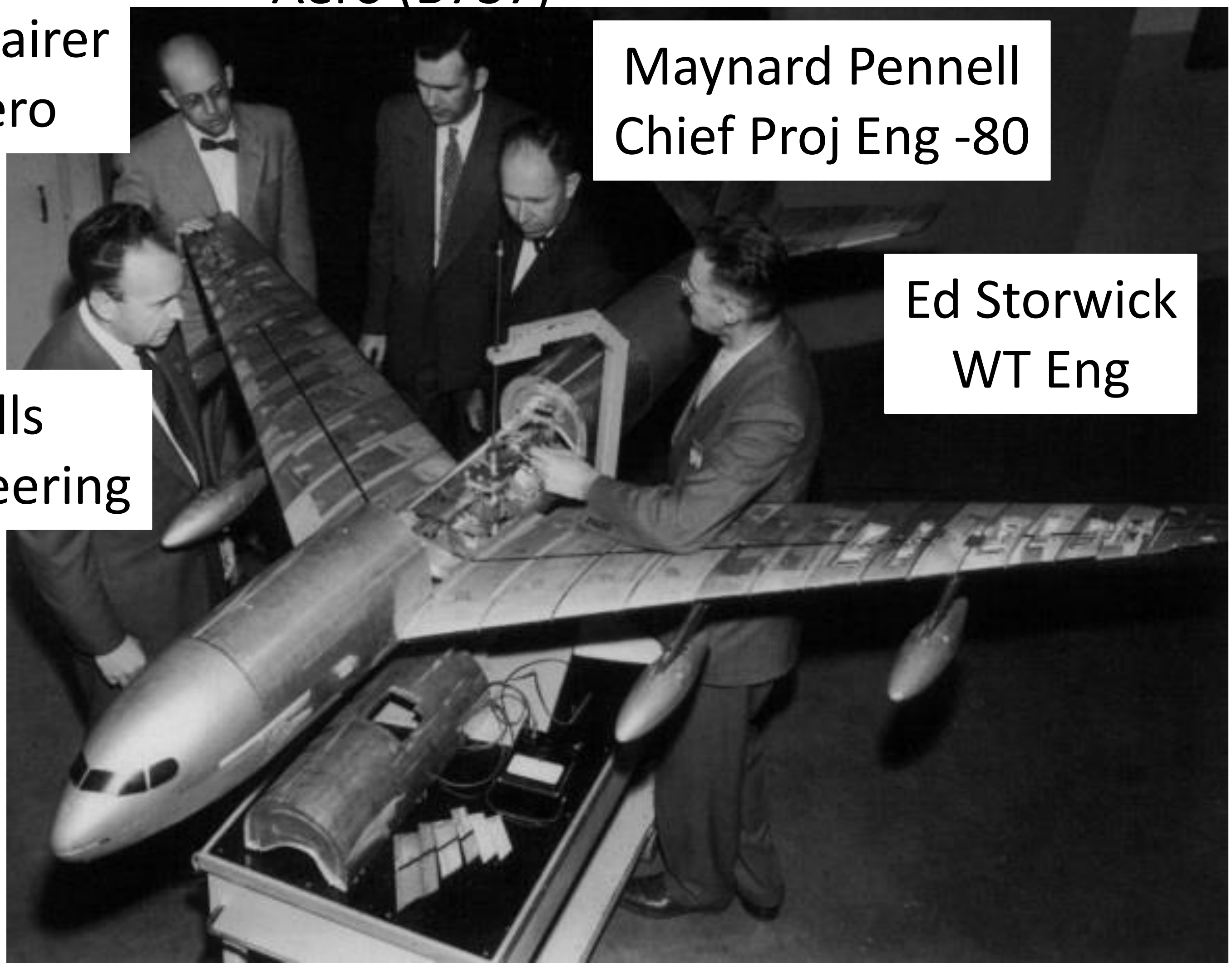
Jack Steiner
Aero (B737)

George Shairer
Chief Aero

Maynard Pennell
Chief Proj Eng -80

Ed Storwick
WT Eng

Ed Wells
V-P Engineering



Boeing 367-80

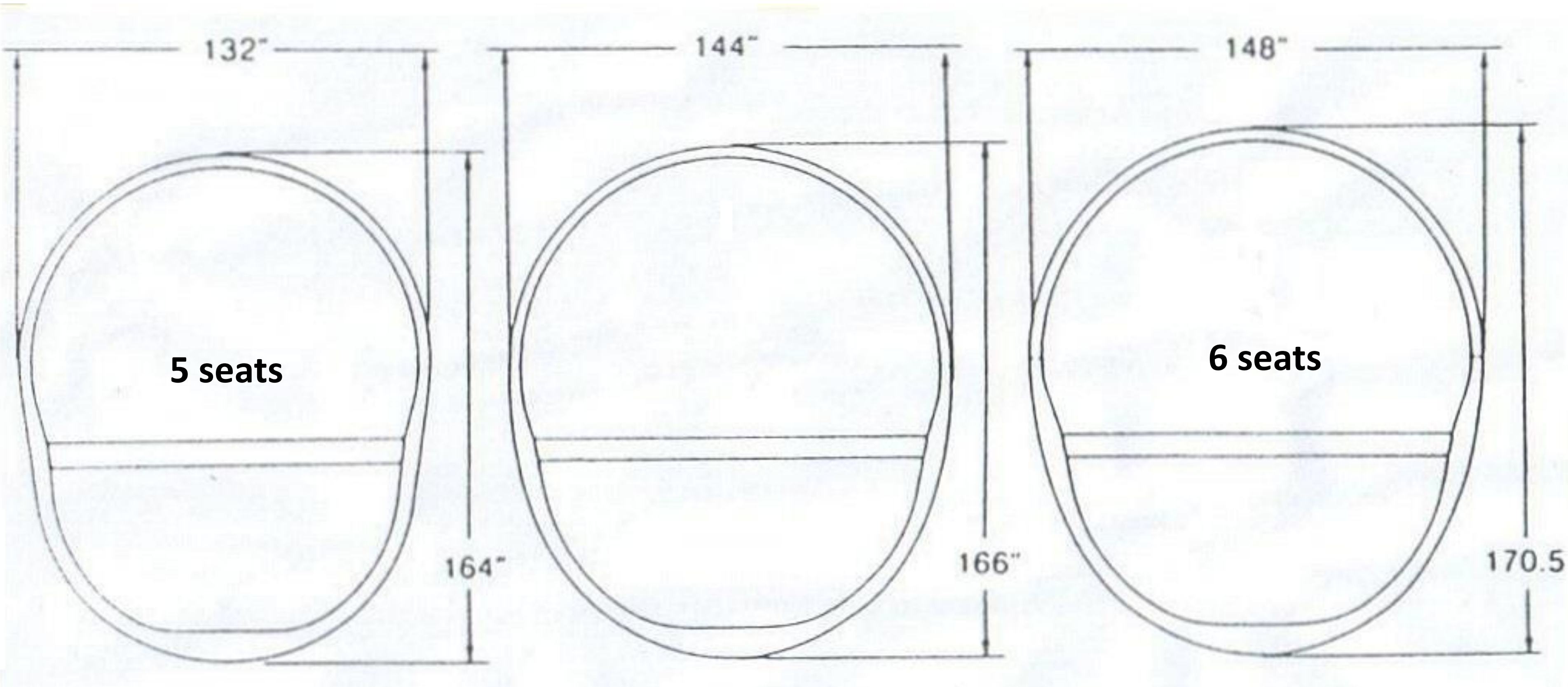
First flight July 15, 1954

Pratt & Whitney JT3 turbojets 10,000 lb (44.5 kN) each

On seeing the 367-80, Lord Hives (head of Rolls-Royce), said

“This is the end of British aviation”

Airlines force Boeing to increase to 6-abreast seating for 707 airliner

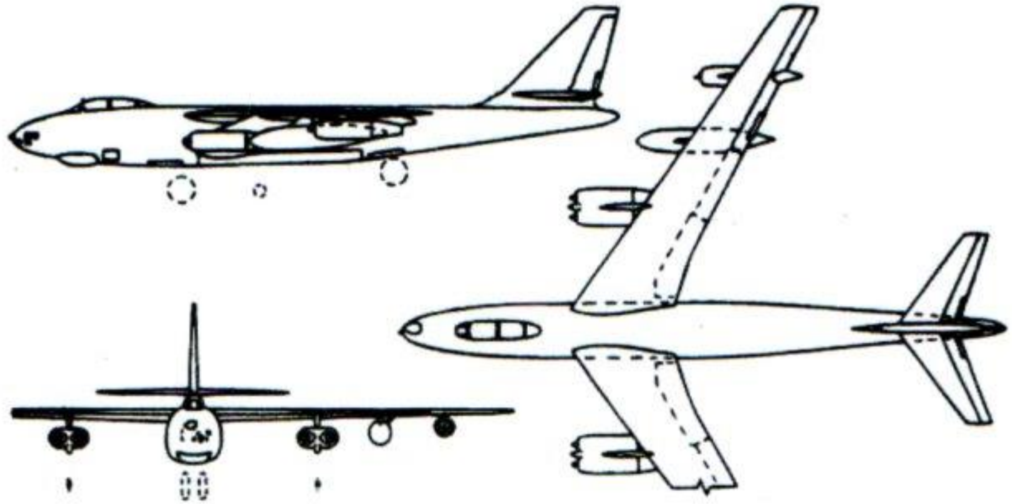


367-80
Demonstrator

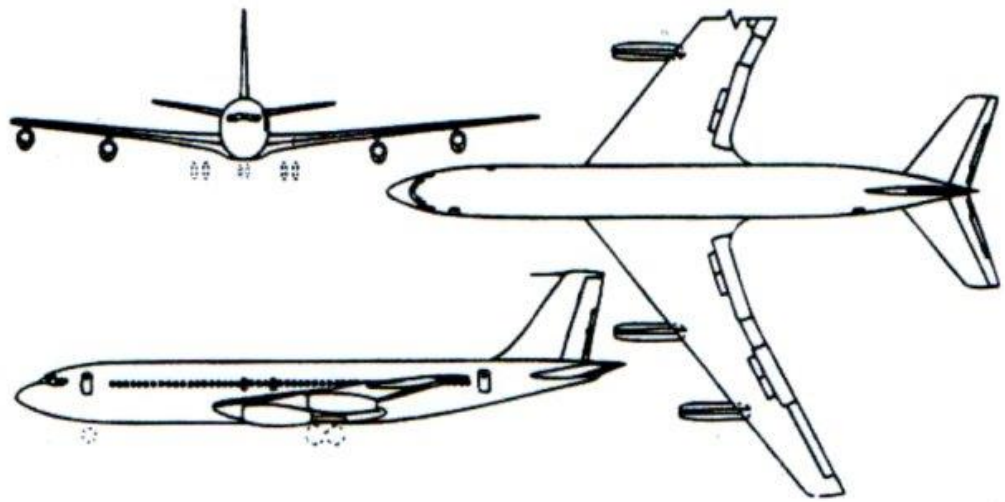
KC-135
USAF tanker

707

Boeing B-47 and 707



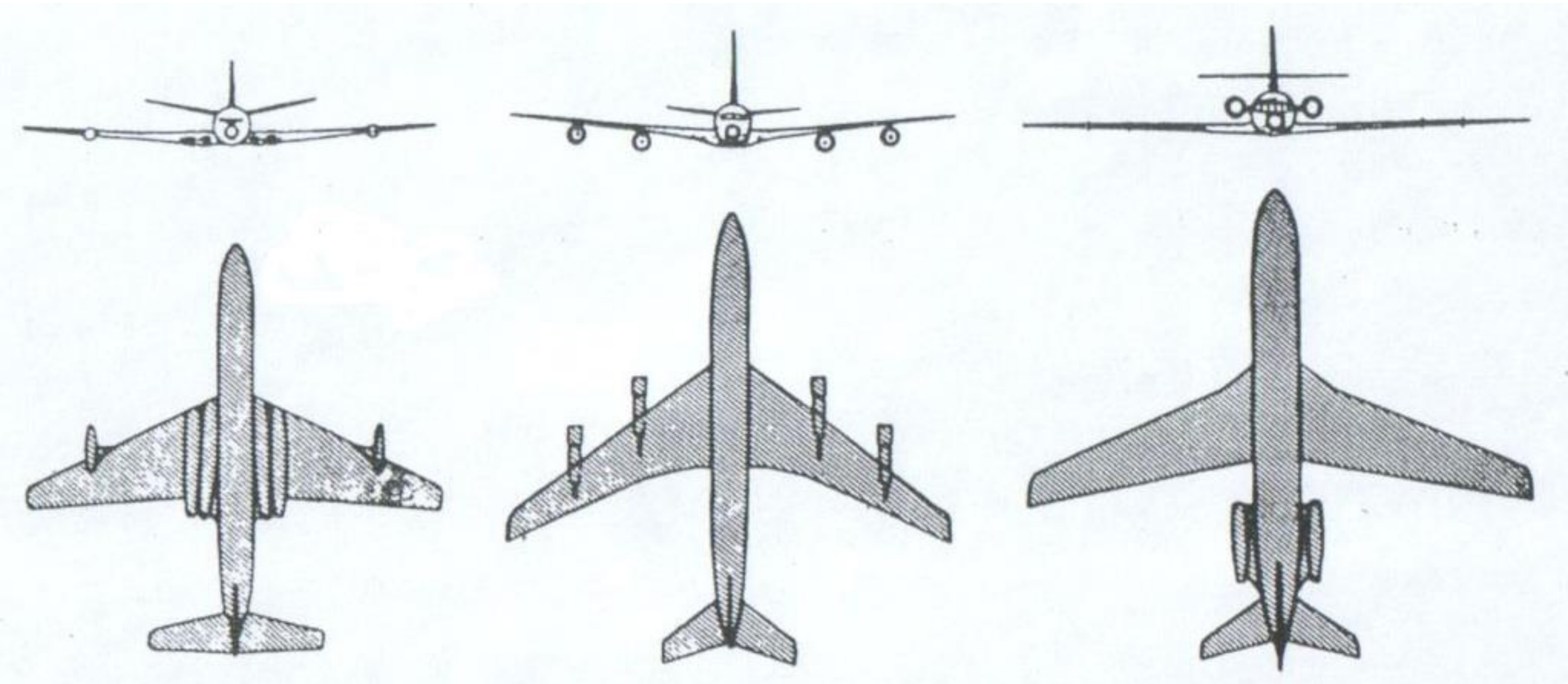
Boeing B-47



Boeing 707

Engine location

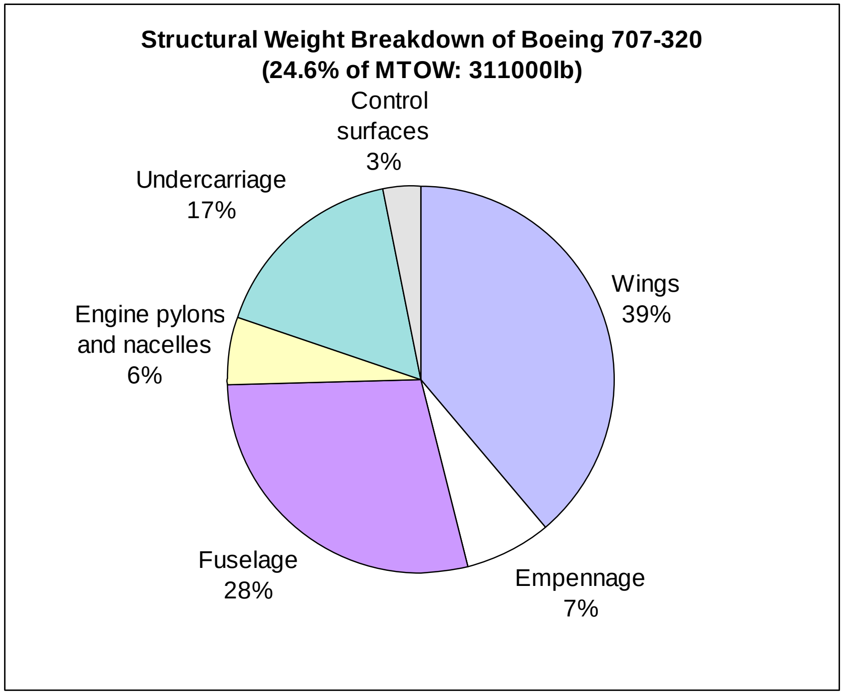
DH Comet | **Boeing 707** | **Sud Caravelle**

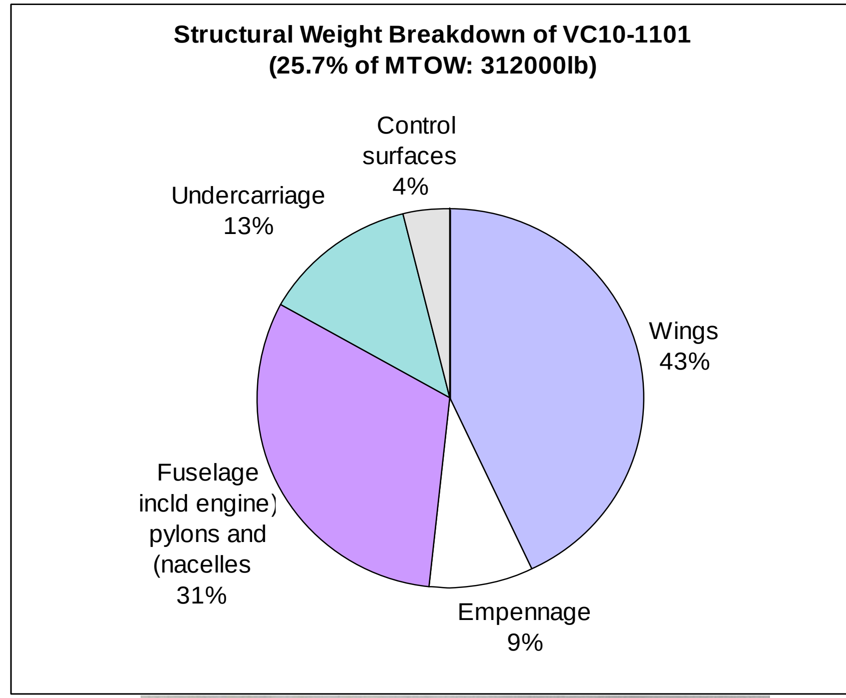


Buried | **Wing-mounted** | **Aft-fuselage mounted**

Engine mounting

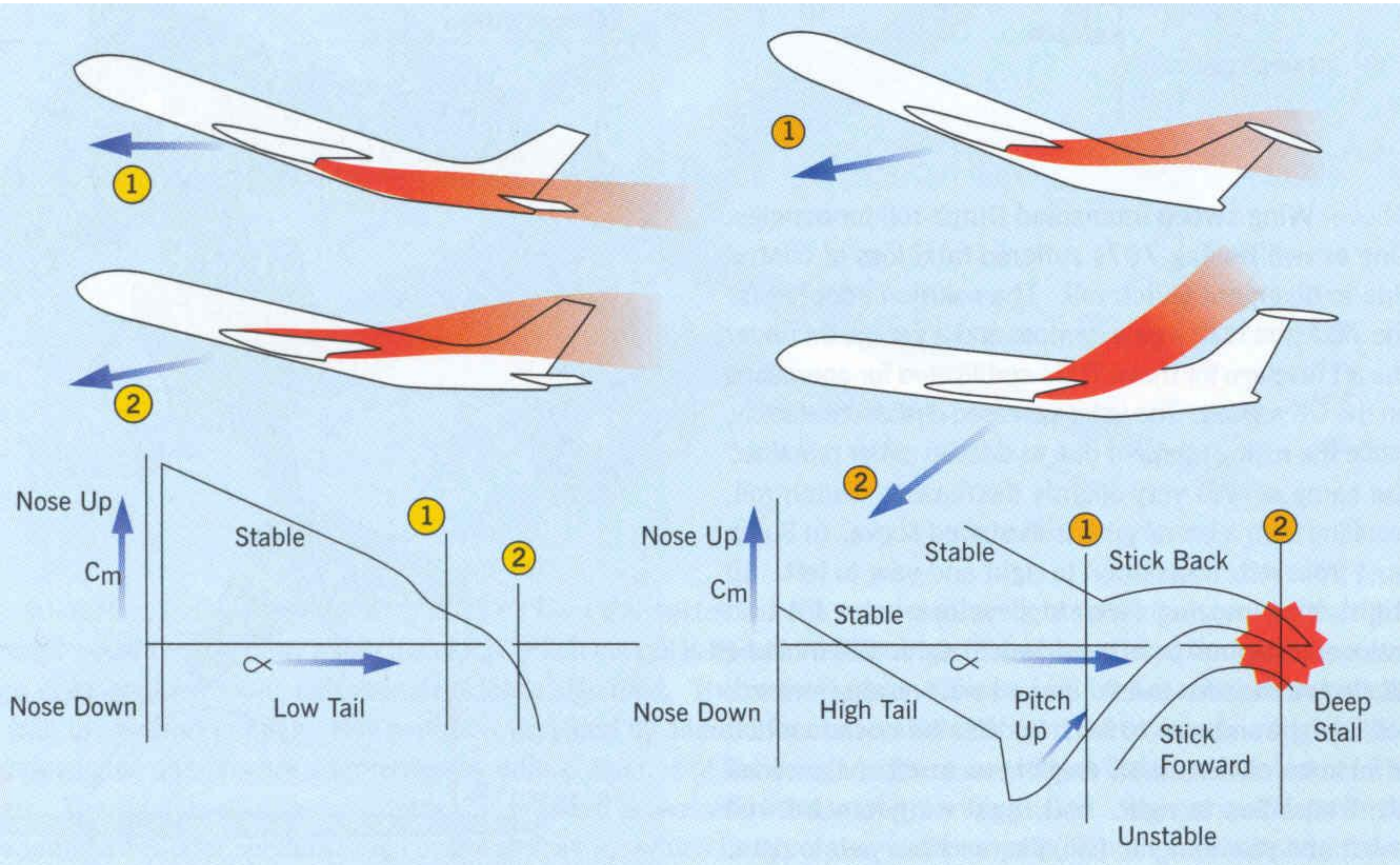
Wing- versus aft-fuselage





Engine mounting

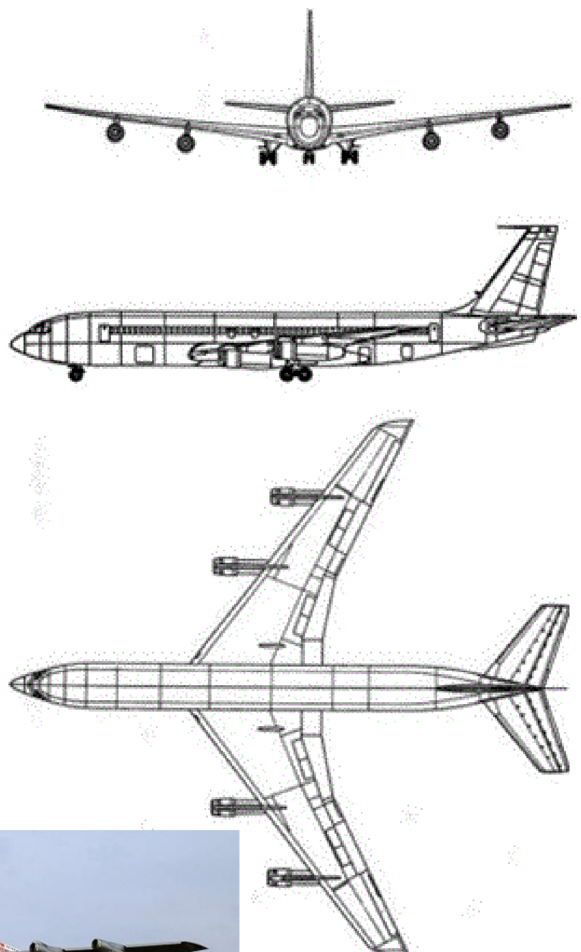
Wing- versus aft-fuselage (SUPERSTALL)

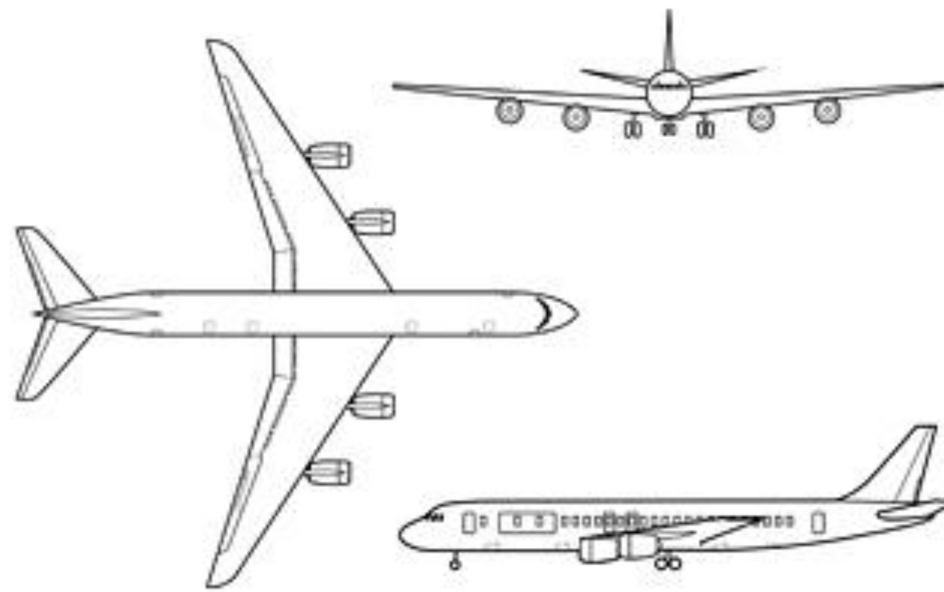


Boeing 707 versus Douglas DC-8

Dec 20, 1957
1010 built

May 30, 1958
556 built

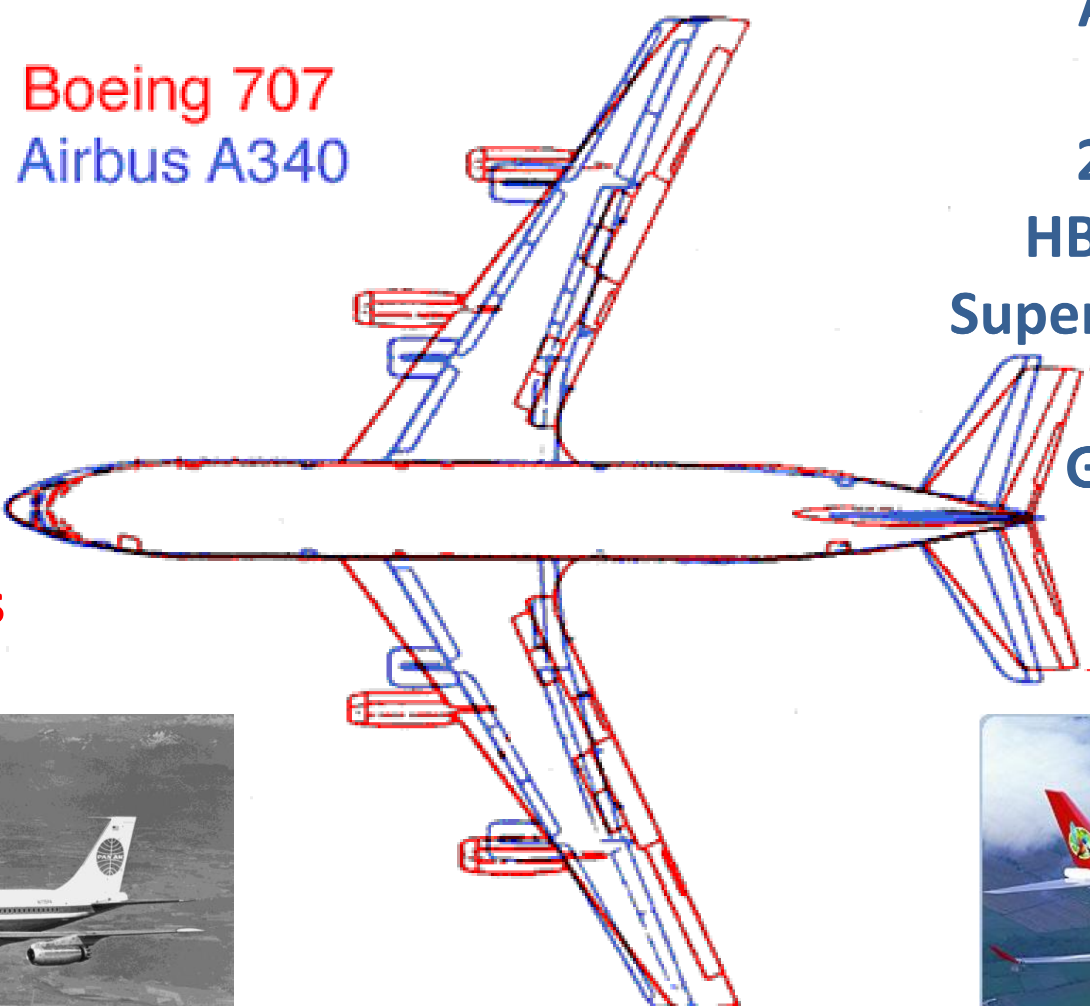




Enduring configuration

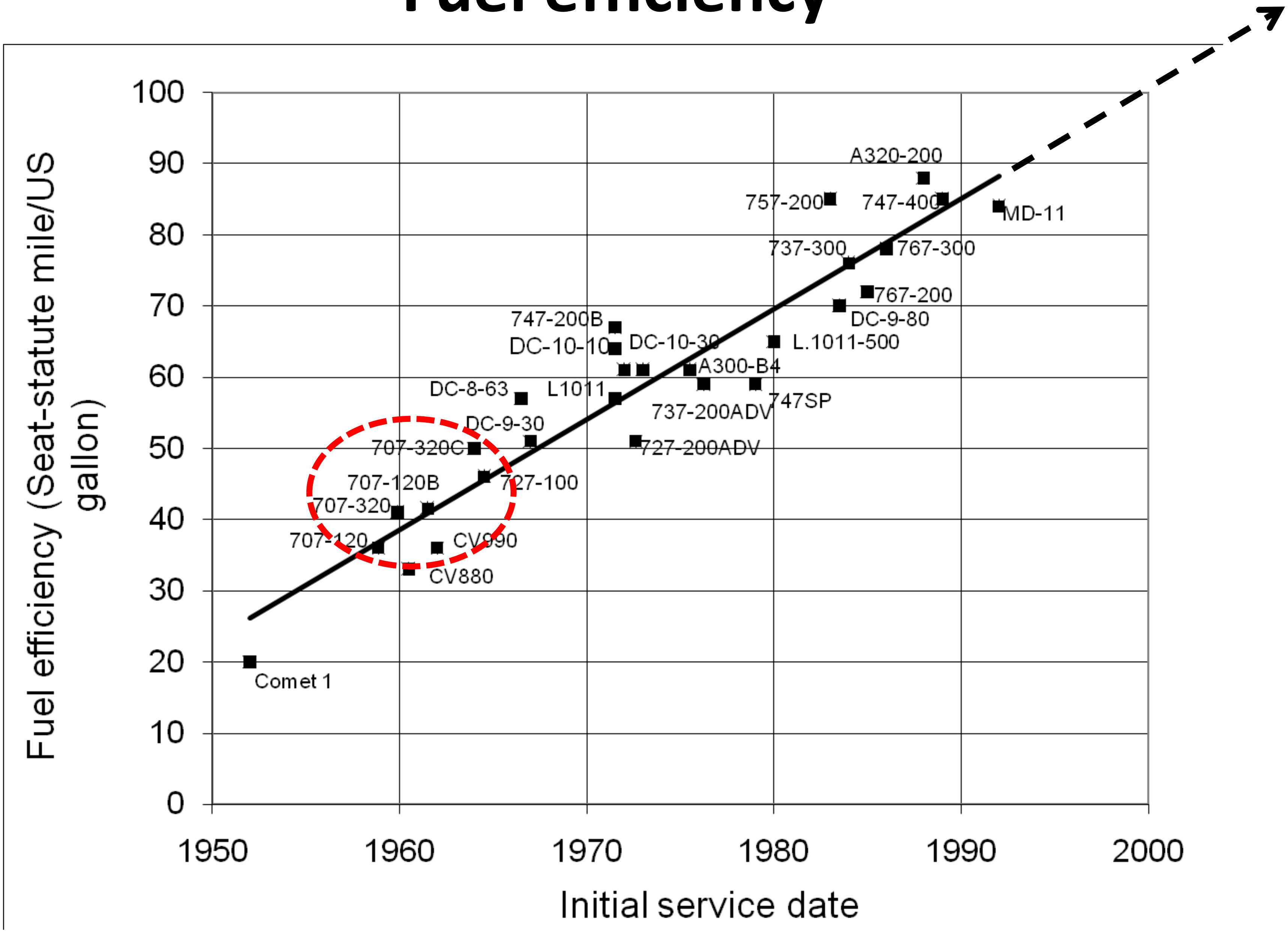
34 years between first flights

B707 (1957)
Single aisle
179-202 pax
Turbojets
Integral tanks



A340 (1991)
Twin aisle
240-380 pax
HBPR Turbofans
Supercritical aerofoils
FBW
Glass cockpit
CFCs

Fuel efficiency



They all look similar and they started with the B-47 Stratojet

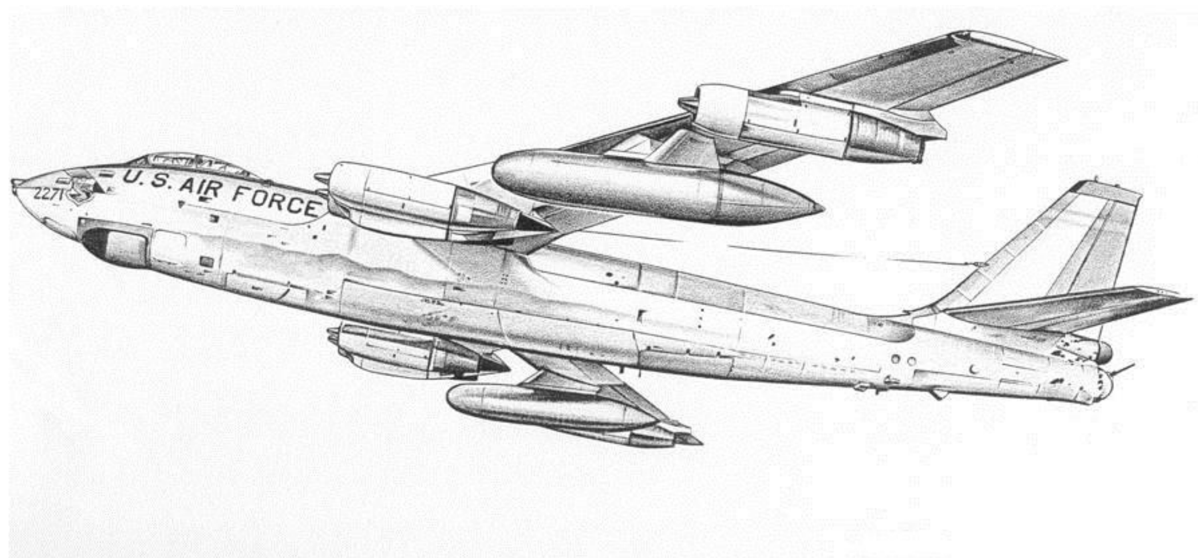












Future airliners?

Pros and cons of podded (707) versus buried engines (Comet)

Podded engines	Buried engines
Engine well spaced for safety in the event of fire	Less drag due to lower wetted area and the elimination of wing/pylon/nacelle interference
Short intake and exhaust ducts are good for engine performance	Lower wing loading and cruise lift coefficient gives bigger buffet margin
Mass of engines and pylons give structural inertia relief to wing allowing large wing weight saving	Greatly reduced asymmetric-thrust yawing moment following engine failure
Engine mass ahead of wings give mass balance against flutter	Lower aspect ratio makes for stiffer wing less prone to aeroelastic problems
Engines much more accessible at low weight because pods are not stressed structures	Low wing loading gives better low speed performance. A higher maximum lift coefficient is available from a clean wing and from a flap uninterrupted by a gap for engine exhaust
Engine pylons have favourable effect on wing airflow by acting like the wing fences needed on so-called 'clean' wings	Low aspect ratio wings less prone to pitch-up. Gives reduced induced drag at high lift due to vortex from wing/pylon/nacelle junction

The arguments are only valid to a degree and the subsequent development of large diameter high BPR engines along with more efficient high lift systems settled the argument in favour of high wing loadings, high aspect ratio and podded engines.