Evolution of the jet airliner shape
Boeing B-47 (1947) to Boeing 787 (2009)

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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
SWEEEPBACK
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

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

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

1944
Similar to B-45 & XB-46

June 1945
4 engines over wing

Nov 1945
Wing-pod engines
Tricycle gear

Sept 1945
Swept wing
2 aft engines added

April 1946
Bicycle gear
Extended wings

Slimmer fuselage
Even with pods & struts
wetted area was less

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

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

<table>
<thead>
<tr>
<th></th>
<th>BOEING B-47</th>
<th>AVRO Vulcan B.1</th>
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</thead>
<tbody>
<tr>
<td>WING AREA, FT²</td>
<td>1,430</td>
<td>3,446</td>
</tr>
<tr>
<td>SPAN, FT</td>
<td>116</td>
<td>99</td>
</tr>
<tr>
<td>ASPECT RATIO</td>
<td>9.43</td>
<td>2.84</td>
</tr>
<tr>
<td>MAX W/S, LB/FT²</td>
<td>140</td>
<td>43.5</td>
</tr>
<tr>
<td>MAX W/b, LB/FT</td>
<td>1,750</td>
<td>1,520</td>
</tr>
<tr>
<td>WETTED AREA, FT²</td>
<td>11,300</td>
<td>9,500</td>
</tr>
<tr>
<td>( (L/D)_{max} )</td>
<td>17.3</td>
<td>17.0</td>
</tr>
<tr>
<td>( C_L ) (opt)</td>
<td>0.68</td>
<td>0.26</td>
</tr>
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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)

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)

Lift distribution

Inertial load

Structure + fuel + engines
Wing bending
Boeing B-47

View From Wing Tip
Looking Along Wing Span
Wing Bending Observed
But No Change Observed in Angle of Attack

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 Loaded Up

Wing Loaded Down

A Rough Air Shock Absorber
Wing deflection
B-52 limit loads

22ft = 6.7m
10ft = 3m
Fix 1 for pitch-up at stall

Drooped leading edge

Wide wake blankets tail

Normal leading edge

Wide wake

Progressive stall starts at trailing edge

Drooped leading edge
Fix 2 for pitch-up at stall

Engine pylons straightened airflow and avoided pitch-up

Tip stall region leading to pitch-up and loss of aileron control
Effect of engine pylons – B-47

Lift
(Coefficient)

Pitching Moment
(Coefficient)

Nose up
Nose down

Pitch-up tendency

Nacelles ON, tail on
Nacelles OFF, tail on
Stability with flexible structure

1. Wing centre section clamped
2. Jack at tail lowered, allowing body to bend
3. Reduced lift
   - Change in tail AoA exaggerated
   - Centre of lift shifts fwd 15% at high loading

Tail becomes more stabilising

With loading, wingtip twists down, offloading tip

High g
Low g

Wing centre section clamped

Jack at tail lowered, allowing body to bend

U.S. AIR FORCE

With loading, wingtip twists down, offloading tip

Reduced lift
Stability with flexible structure
 stil applies today - B747

- Downward bending of fuselage increases tailplane effectiveness (stabilising)
- Tailplane flexibility reduces effectiveness as a stabiliser
- Reduced AoA on deflected wing
- Points along lines normal to flexural axis are deflected up equally
- Reduced AoA moves centre of lift forwards and inwards (destabilising)
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

Wing Tip Twist

Aileron Twists Wing at High Speeds Reducing Control

Spoilers Are Inboard and Forward Avoiding Wing Twisting

Aileron Effective at Low Speed Providing Maximum Control

Loose Fitting Screws

Twist of Structural Torsion Box Due to Slippage of Bottom Panel
Use of spoilers/lift dumpers

Boeing 367-80 spoilers and vortex generators

Boeing 707
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.

“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
RR Avon axial turbojets
36-40 seats
Tupolev Tu-16 & Tu-104

1952  First flight  1955
1954  Service entry  1956

50 seats
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)

Maynard Pennell
Chief Proj Eng -80

Ed Storwick
WT Eng

George Shairer
Chief Aero

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
Boeing B-47 and 707
Engine location

DH Comet
Boeing 707
Sud Caravelle

Buried
Wing-mounted
Aft-fuselage mounted
Engine mounting
Wing- versus aft-fuselage

Structural Weight Breakdown of Boeing 707-320
(24.6% of MTOW: 311000lb)

- Wings: 39%
- Fuselage: 28%
- Engine pylons and nacelles: 6%
- Undercarriage: 17%
- Empennage: 7%
- Control surfaces: 3%

Structural Weight Breakdown of VC10-1101
(25.7% of MTOW: 312000lb)

- Wings: 43%
- Fuselage incl'd engine) pylons and (nacelles: 31%
- Undercarriage: 13%
- Empennage: 9%
- Control surfaces: 4%

Engines provide wing inertia relief
Heavier but higher lift wing
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

Boeing 707
Airbus A340

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
They all look similar and they started with the B-47 Stratojet
Future airliners?
## Pros and cons of podded (707) versus buried engines (Comet)

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