上海交通大学

Commercial Aircraft Evolution

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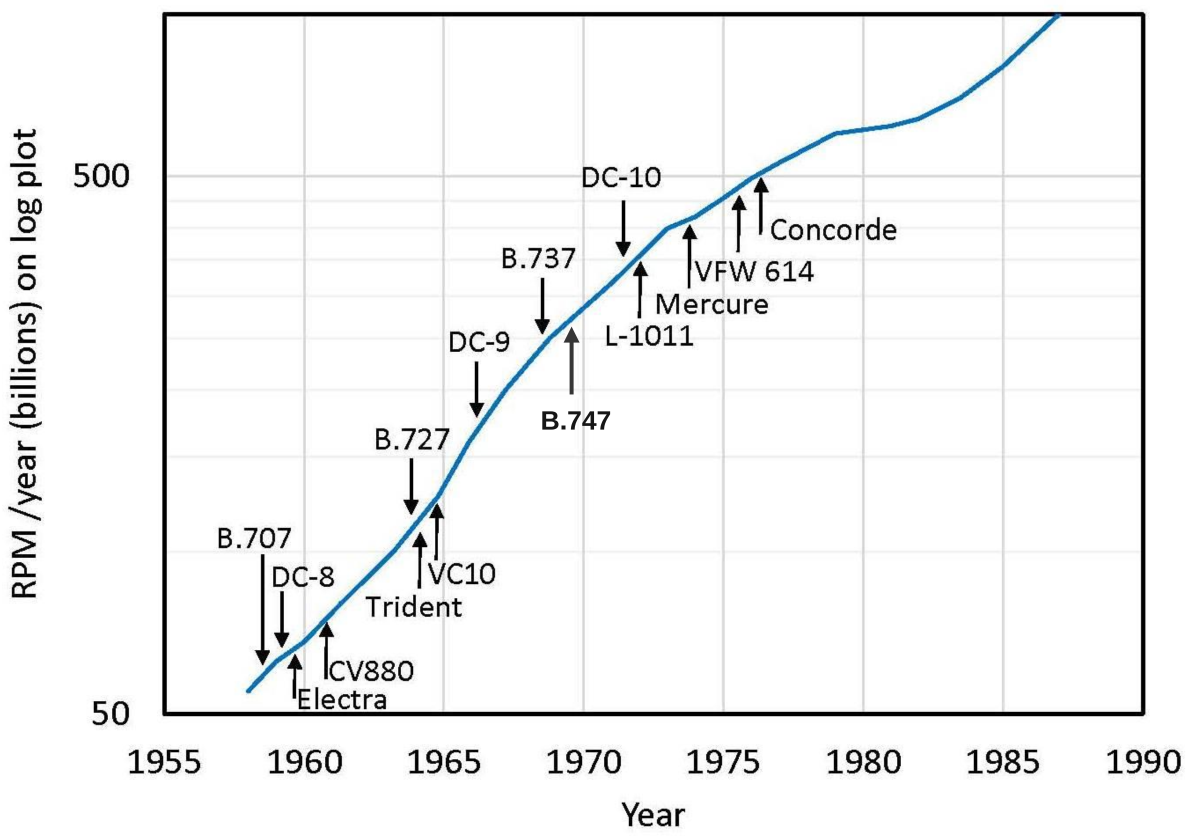
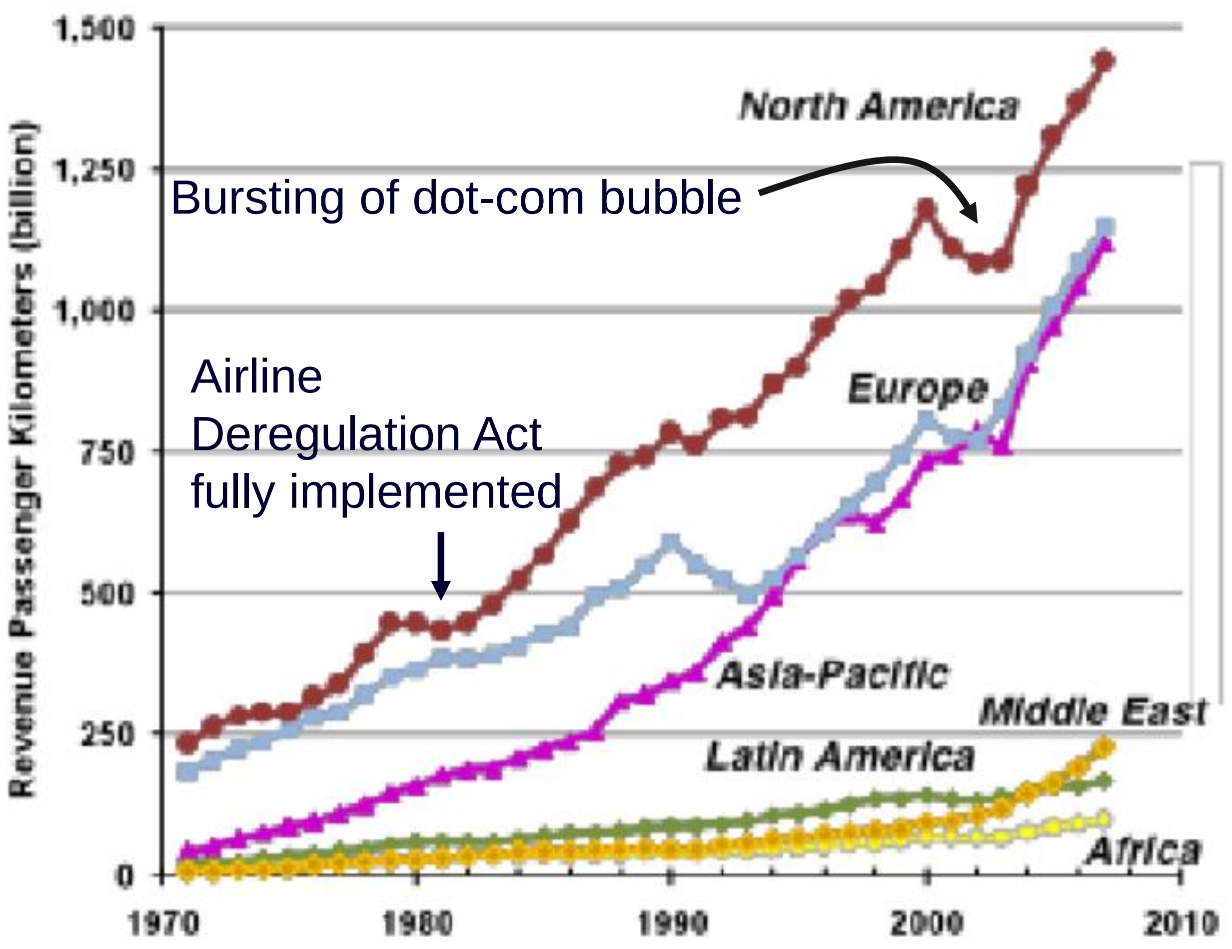
Growth in Worldwide RPMs (1955 – 1990)

Note log scale, so growth in revenue passenger miles (RPM) was close to exponential



ADAC
Aircraft Design & Consulting

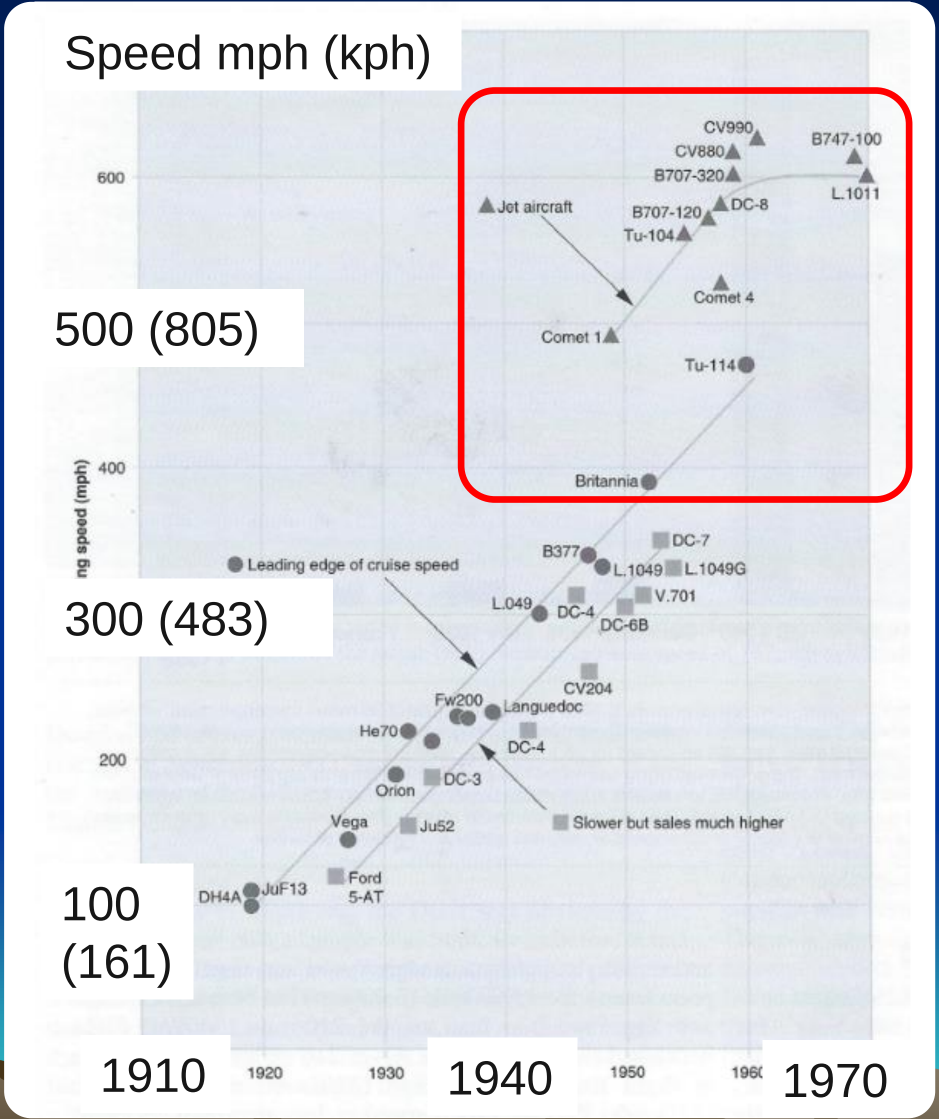
Growth in Worldwide RPK



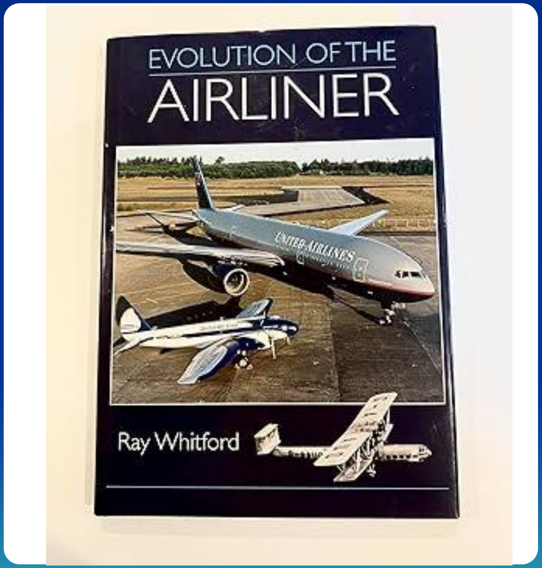
Passenger traffic growth (RPK) worldwide from 1971 to 2007 Data sources: ICAO (1970-2000), IATA (2001, 2007)

https://www.researchgate.net/publication/268425966_Dynamics_of_Implementation_of_Mitigating_Measures_to_Reduce_CO_2_Emissions_from_Commercial_Aviation?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6Il9kaXJlY3QiLCJwYWdlIjoiX2RpcmVjdCJ9fQ

Cruise Speed



See enlargement of this area



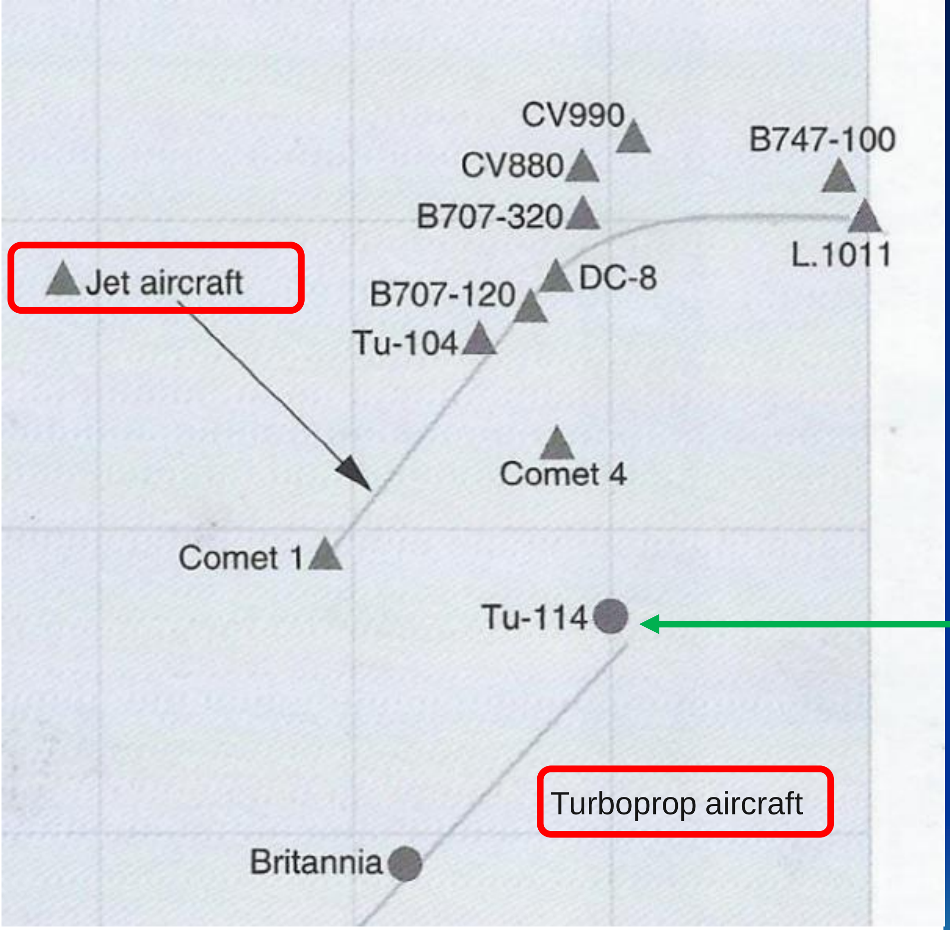
Ray Whitford: Evolution of the Airliner

Cruise Speed

1050 km/hr

Nearly 70% increase in speed

645 km/hr

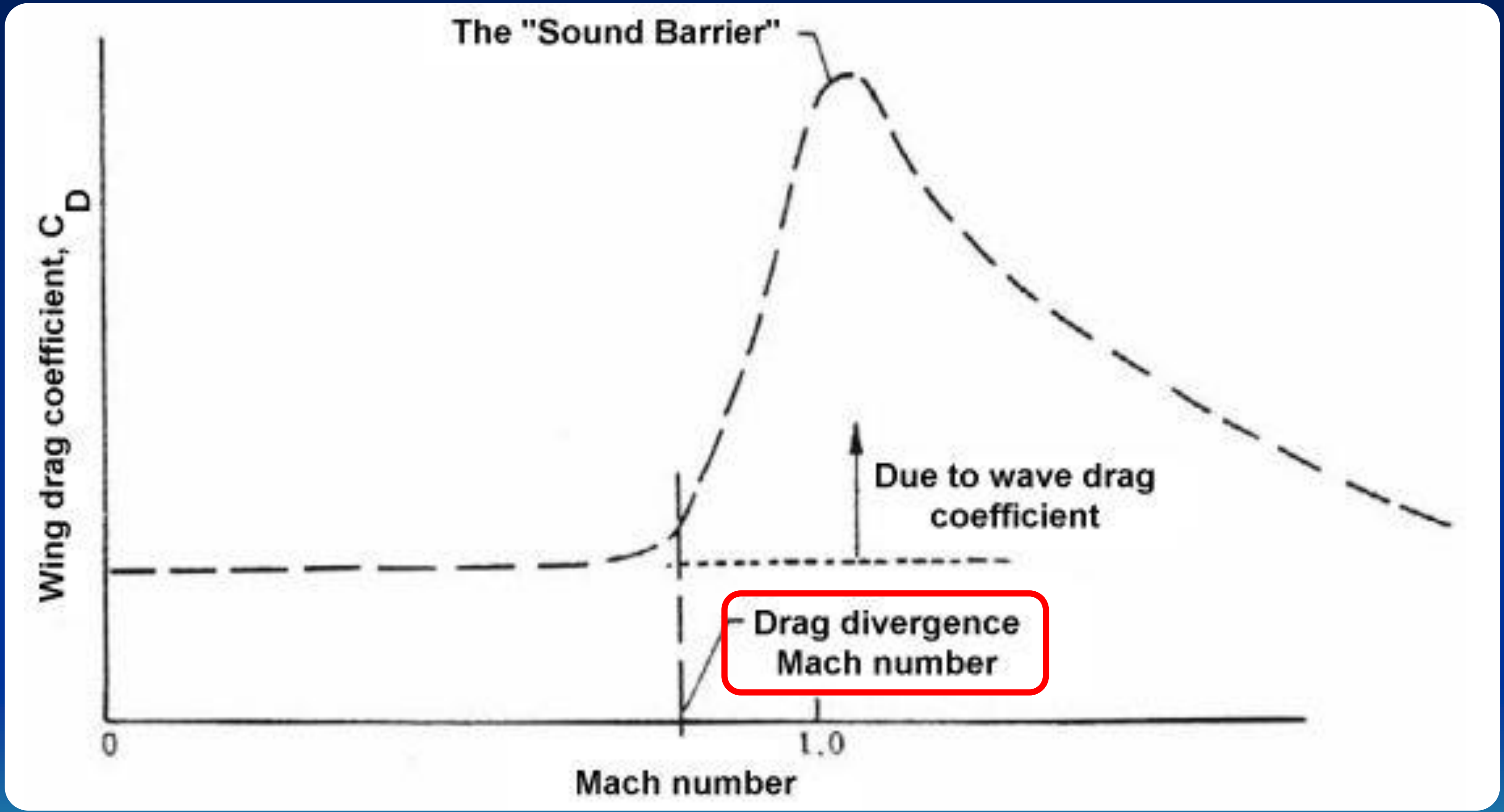


Speed limited by drag divergence

1940 1950 1960 1970

Ray Whitford: Evolution of the Airliner

C_D vs Mach No. at Fixed C_L

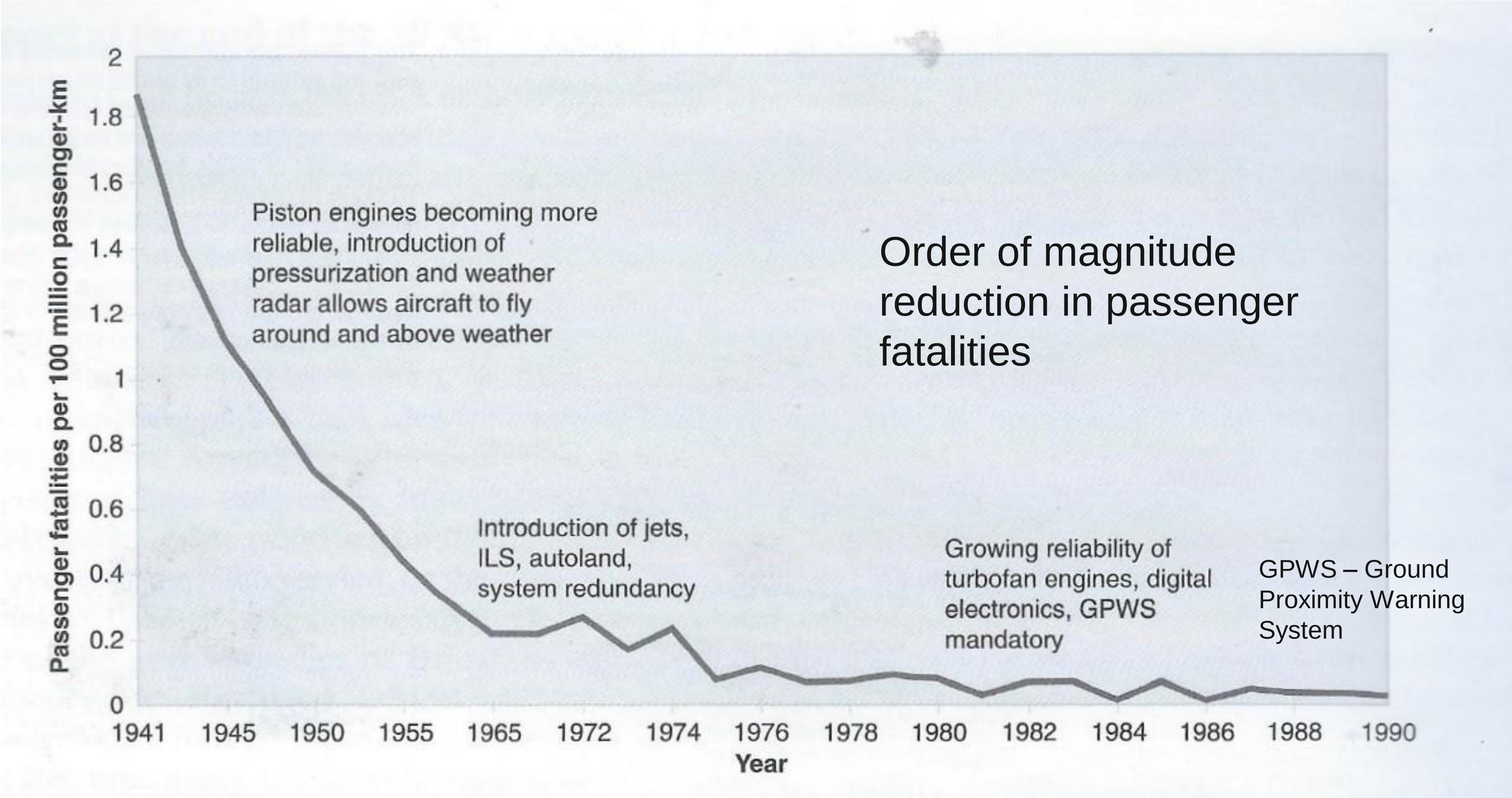


$M_{DD} \simeq$ 0.82 (prior to supercritical airfoils)

ADAC Aircraft Design & Consulting

Passenger Fatalities

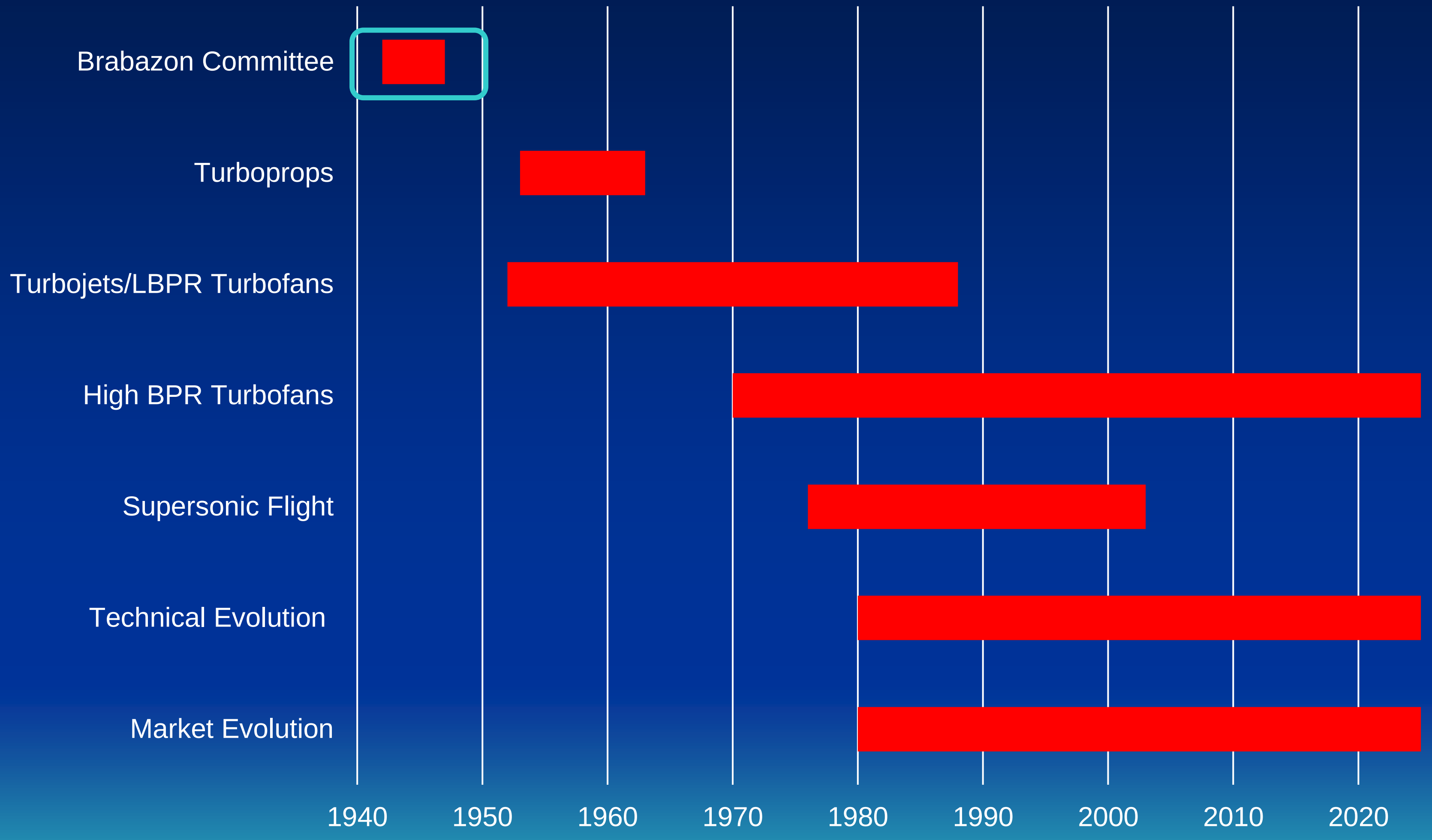
Order of magnitude decrease in fatalities/RPK



Ray Whitford: Evolution of the Airliner

- UK Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
- Advent of high bypass ratio engines
- Supersonic flight
- Technical Evolution
- Market Evolution

Commercial Aircraft Evolution



UK Brabazon Committee

- Formed in 1942 and chaired by Lord Brabazon
- Final report in 1945
- Goal was roadmap for post-war civil aircraft design
  – Bristol Brabazon (1)
  – Airspeed Ambassador (23)
  – Vickers Viscount (444) turboprop
  – Avro Tudor (33)
  – De Havilland Comet (136) turbojet
  – Miles Marathon (43)
  – De Havilland Dove (544)

Meanwhile – In the United States

U.S. Long Haul Airliners

- Lockheed L-1049F (Super) Constellation (856 sales)
  - First flight 1943-01-09 (Constellation)
  - Pax: 71-95 Range: 8,290 km (4,480 nmi) (Super Connie)

- Douglas DC-6/6A/6B (704 sales)
  - First flight 1946-02-15
  - Pax: 89 Range: 7,630 km (4,100 nmi) max fuel (6B)

- Boeing 377 Stratocruiser (56 sales)
  - First flight 1947-07-08
  - Pax: 114 Range: 6,800 km (3,600 nmi)

Back to the UK again

UK Brabazon Committee

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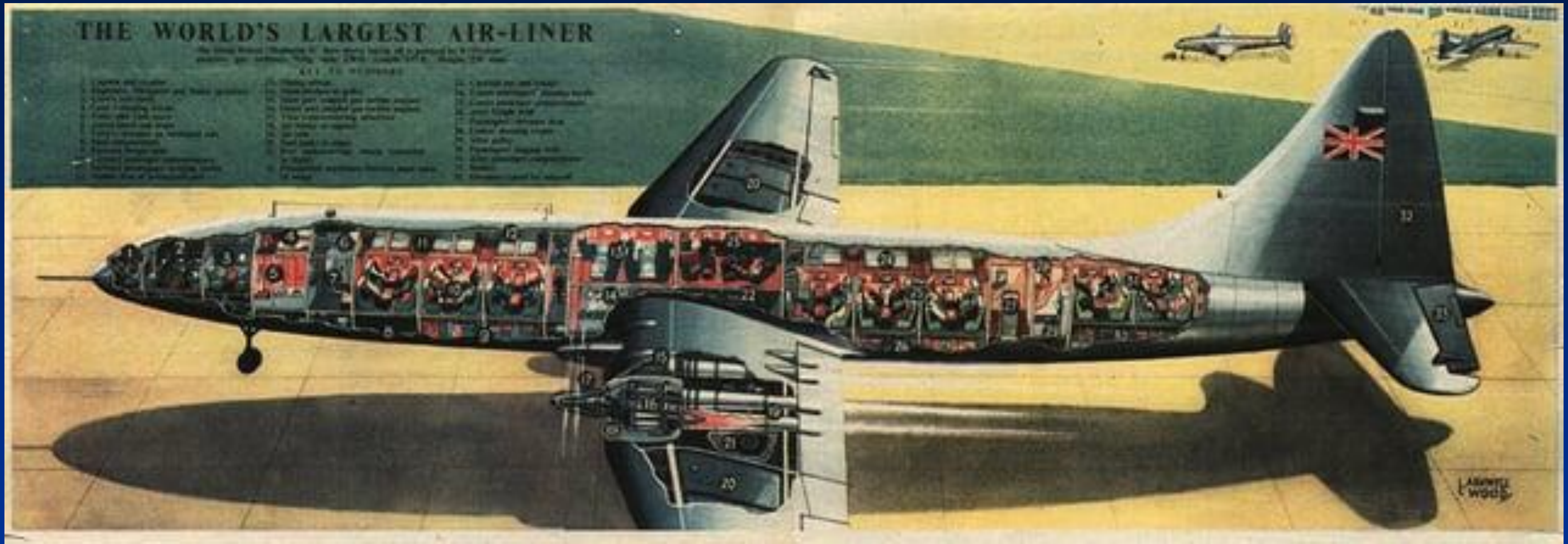
Bristol Brabazon Pax Cabin

- Long distance air travel only for the wealthy and government employees

- Did not consider higher-density seating with cheaper fares, as for DC-4, DC-6, Lockheed Constellation, or Boeing 377 Stratocruiser

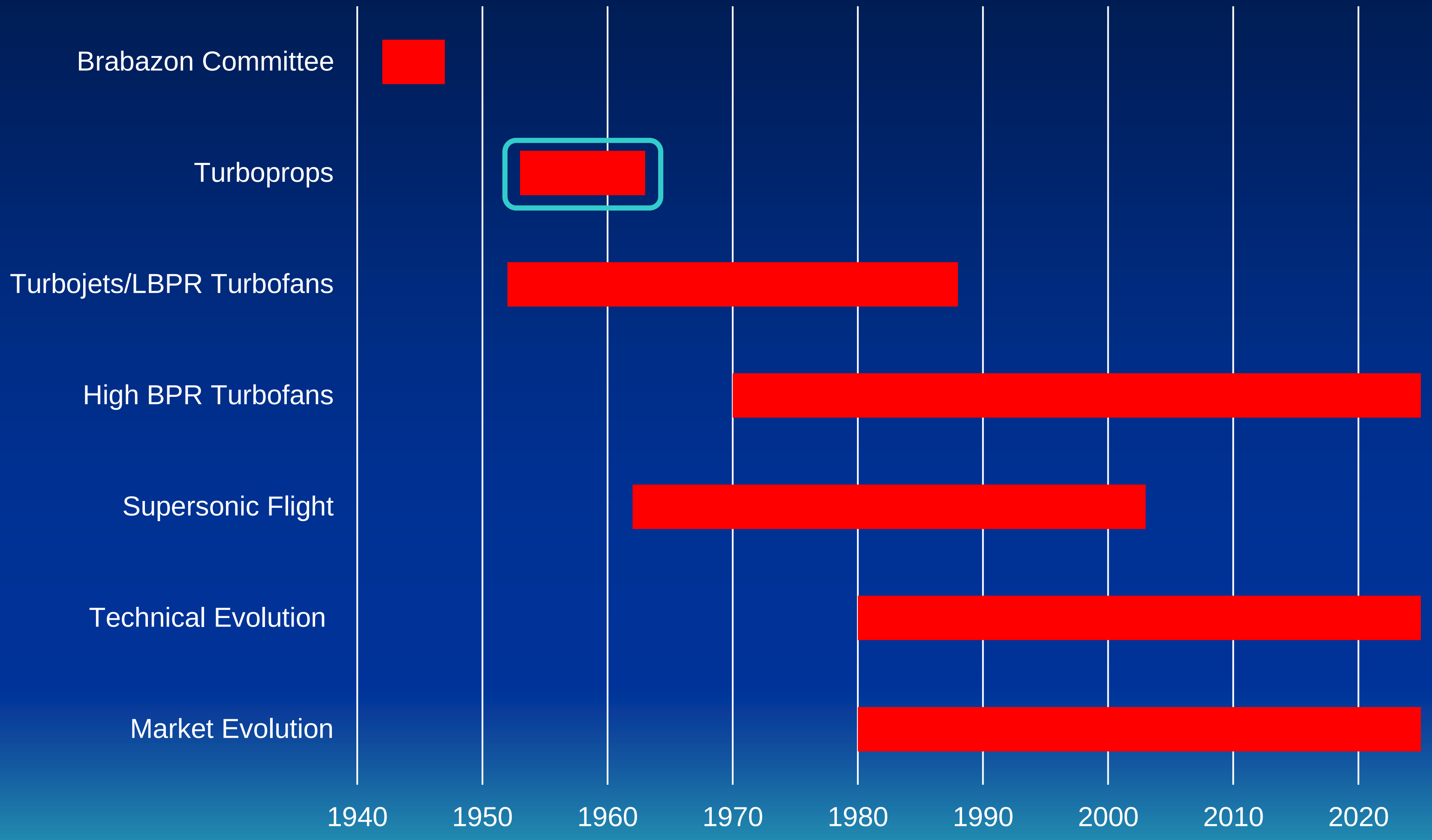
- https://www.superstock.com/asset/inside-world-biggest-passenger-plane-first-picture-first-picture-interior/5513-111409768

Bristol Brabazon



- MTOGW: 290,000 lb (132,000 kg) (MTOGW of 707-121: 257,000 lb with max payload of 189 pax)
- First flight: 1949-09-03
- Payload: 100 pax
- Powerplant: 8 x Bristol Centaurus air-cooled radial sleeve-valve engines
- Max speed: 260 KIAS (480 km/hr)
- Range: 4,800 nmi (8,900 km) (LHR-JFK : 3,000 nmi (5555 km))
- Total sales: 0

Commercial Aircraft Evolution



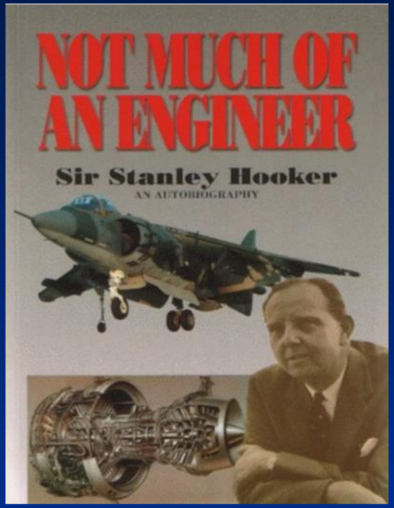
- First generation of turboprops
  - Vickers Viscount (UK)
  - Lockheed Electra (U.S.)

Vickers Viscount (UK)

- First flight 1948-06-16
- Entered service 1950
- 4 X R-R Dart turboprops
- Up to 75 pax / 1,200 nmi (2,222 km)
- Total production of 445

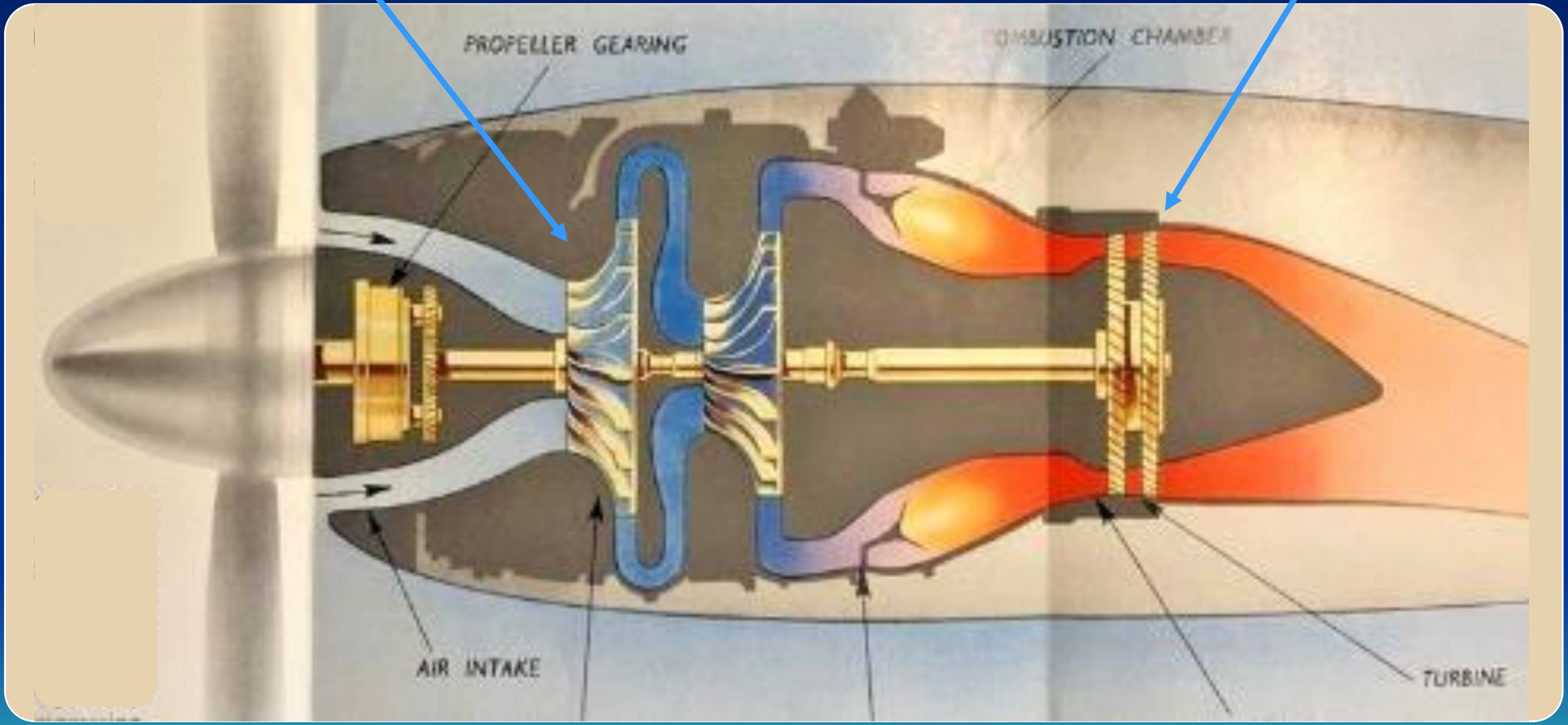
Source: commons.Wikimedia.org

Rolls-Royce Dart Turboprop



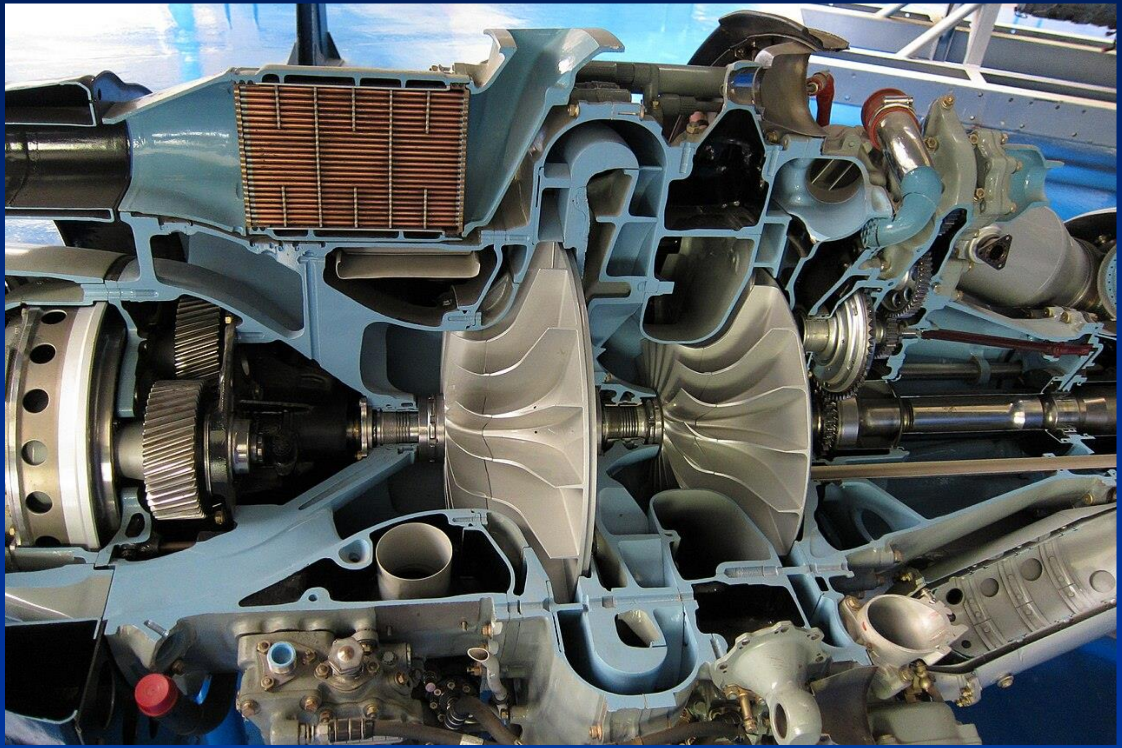
2-stage centrifugal compressor (derived from R-R Griffon supercharger by Stanley Hooker)

1-stage axial turbine

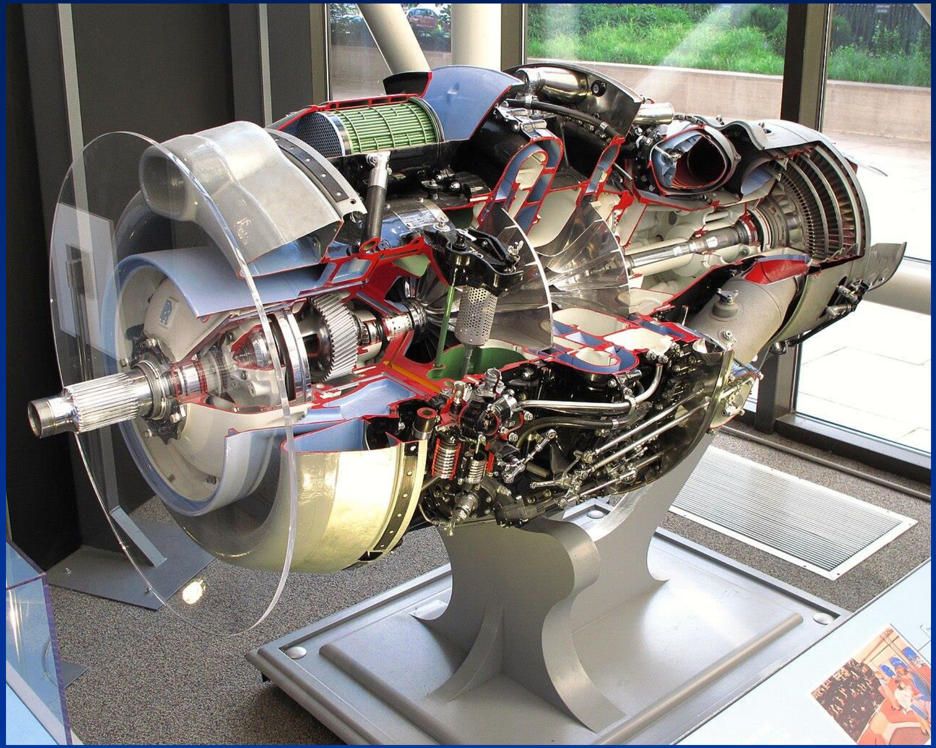


- First run in 1946
- First flight in Vickers Viscount in 1948
- Powered 15 aircraft types

Rolls-Royce Dart Turboprop



https://en.wikipedia.org/wiki/Centrifugal_compressor



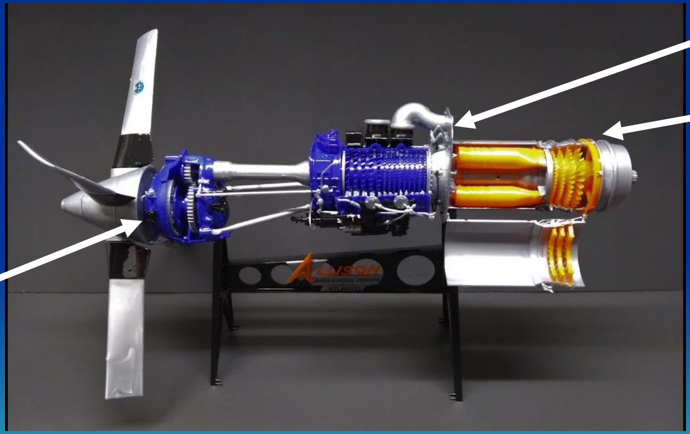
https://en.wikipedia.org/wiki/Rolls-Royce_Dart#/media/File:Rolls_royce_dart_turboprop.jpg

Lockheed L-188 Electra (U.S.)

Nearly 10 years after Viscount first flight!

- First flight Dec 1957-12-06
- First US commercial turboprop
- Up to 80 pax / 1,913 nmi (3,543 km)
- 4 X Allison 501-D13 (T56) turboprops
- Crashes in Sept 1959 and March 1960 due to weakened engine mounts from heavy landings
- Public lost faith
- Production ended in 1961 at 170 aircraft

By Clinton Groves - http://www.airlinefan.com/airline-photos/1782551/Varig/Lockheed/L-188-Electra/PP-VJW/, GFDL 1.2, https://commons.wikimedia.org/w/index.php?curid=20203439



14-stage axial flow compressor

2-stage turbine

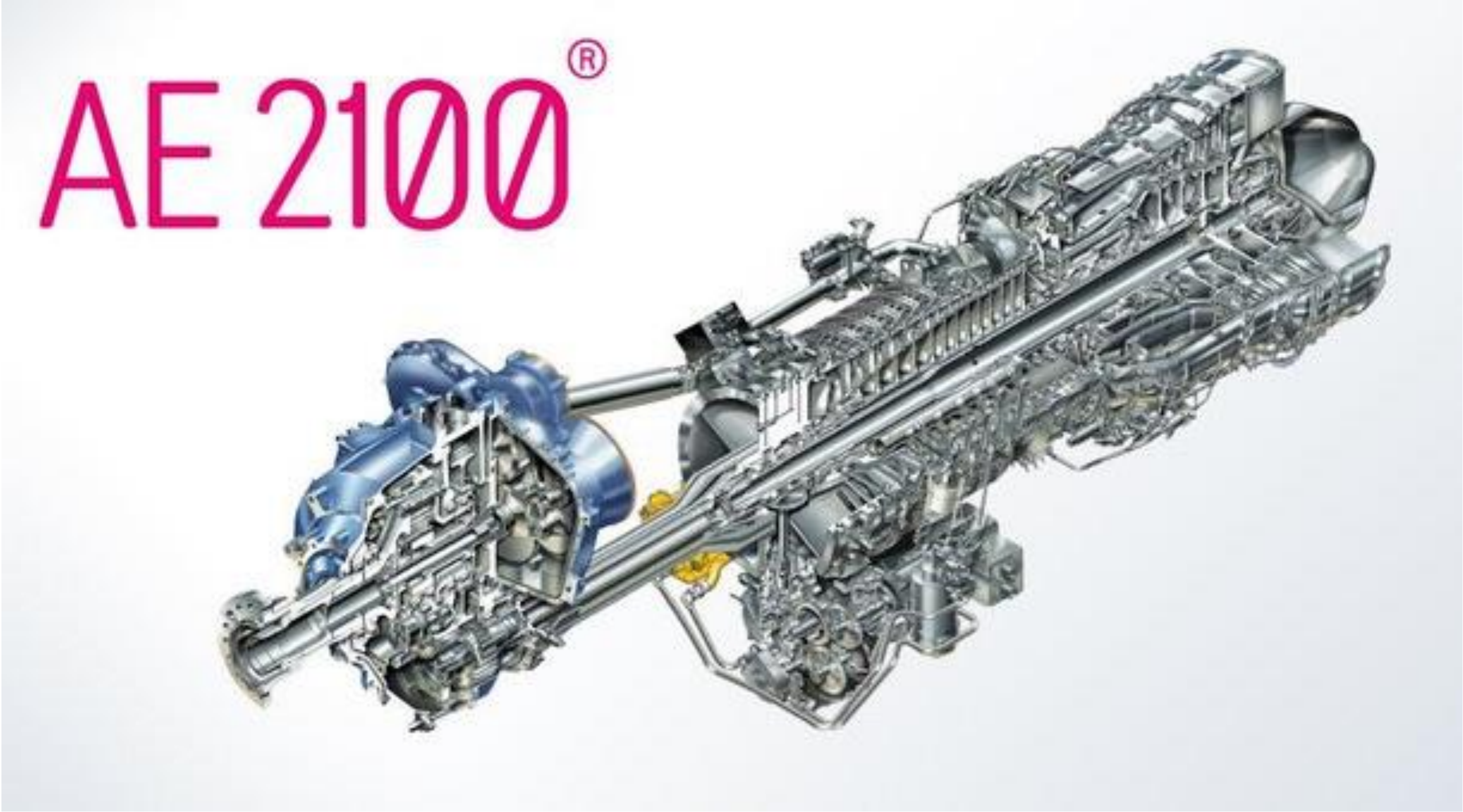
Single shaft

T56 in production until 2026 for Grumman E-2D Hawkeye

Reduction gearbox

Rolls-Royce AE2100

- Identical installation to that of Allison T56
- Internally very different – twin shaft
- Much better performance and power/weight ratio

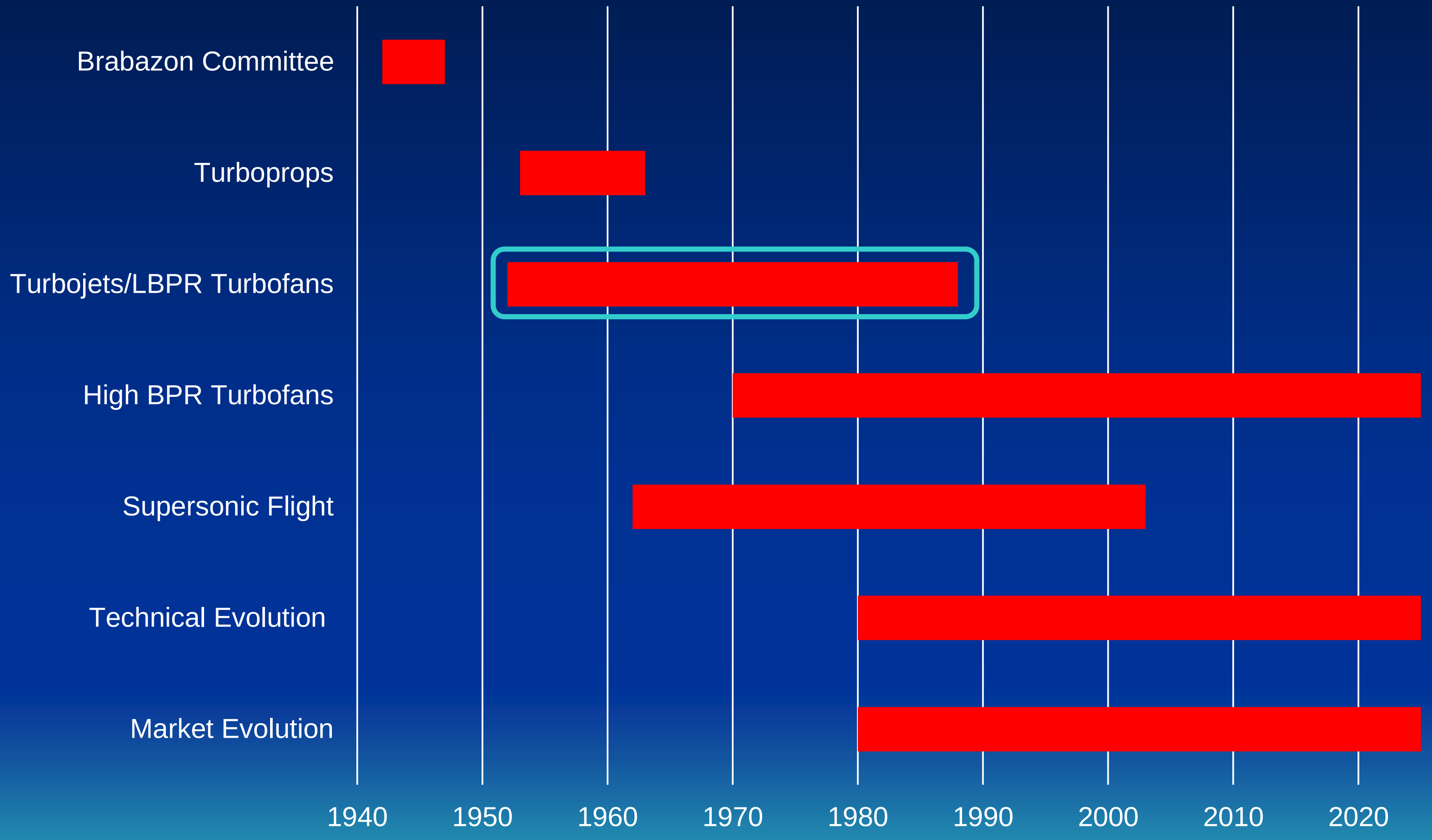


Success as P-3 ASW

- Total of 734 built
- Eventually to be replaced by Boeing P-8A (IOC in late 2013)

Source: US Navy

Commercial Aircraft Evolution



- UK Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
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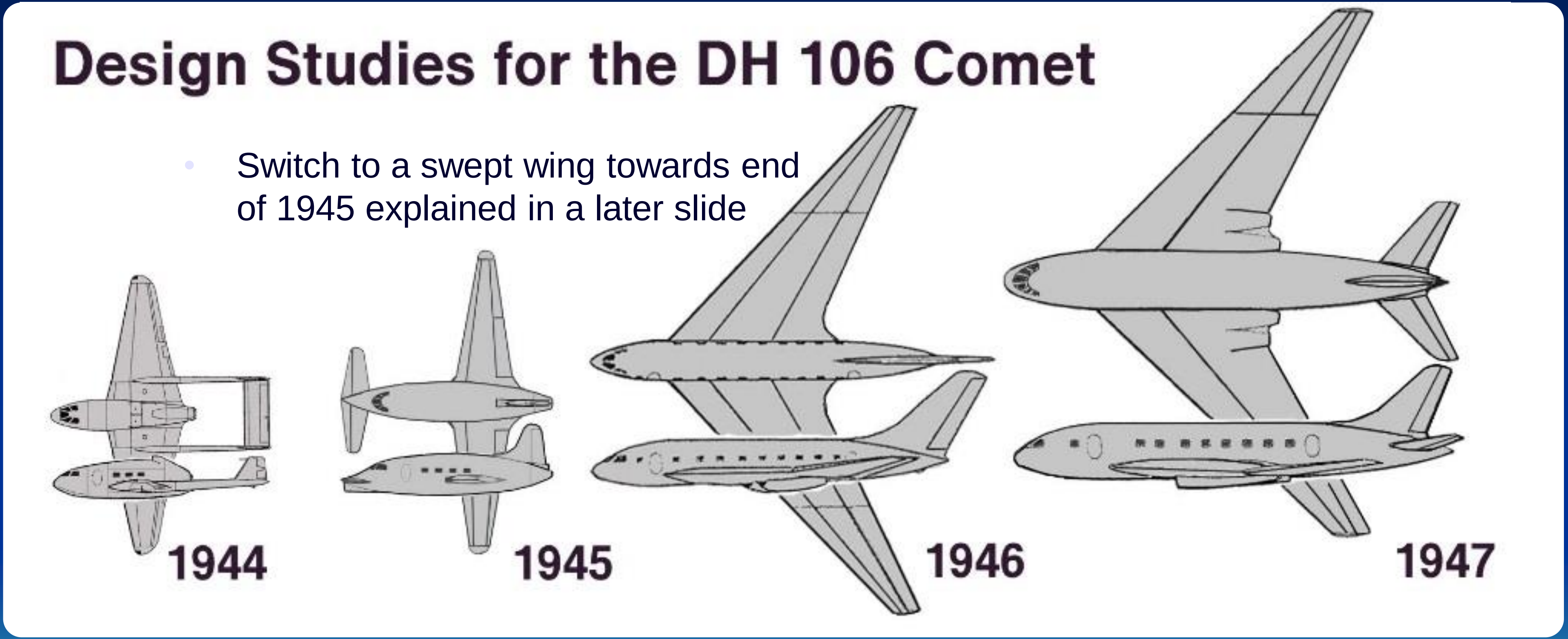
- Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
  - 4-engine, long range
  - 3-engine, medium range
  - 2-engine, short range
- Advent of high bypass ratio engines
- Supersonic flight

Conceptual Design Studies



- Switch to a swept wing towards end of 1945 explained in a later slide

Source: wikipedia commons

De Havilland DH 106 Comet (U.K.)

- First flight July 1949-07-27
- Entered service 1952-05
- Two aircraft broke up in flight in 1954
- Comet 4 entered service in 1958, with 30 year service life
  - Rolls-Royce Avon 524 turbojets

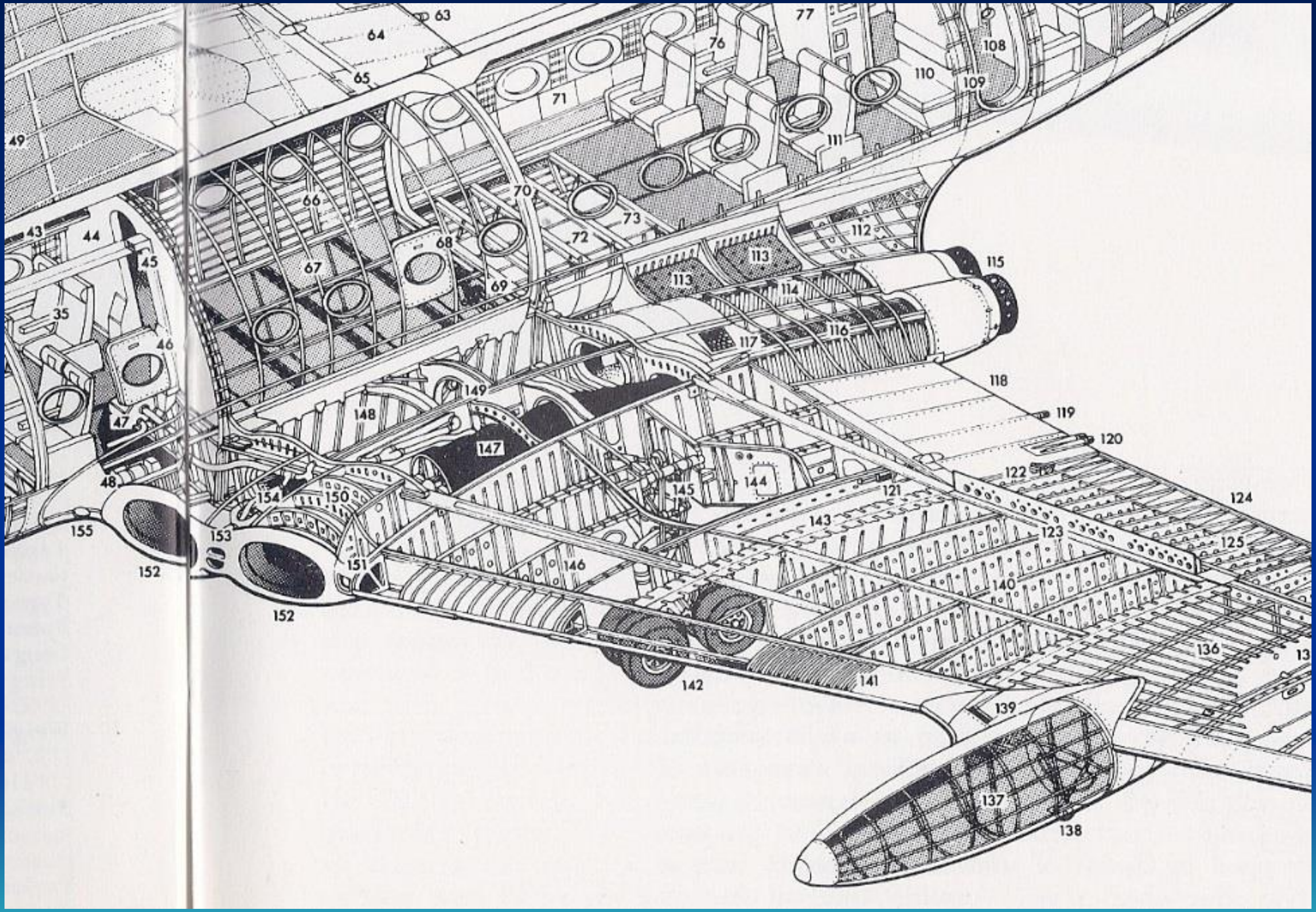
Source: www.extremetech.com

Comet 1

Comet Nacelle Cutaway

Disadvantages of wing-root-mounted engines

- Danger of fratricide
- Changing engine type requires major wing redesign
- Difficult access for maintenance



Source: Gunston ‘Commercial Aircraft’

Engines Embedded in Wing Root

- U.K. V-bomber triad – Vulcan, Valiant, Victor
- First generation of strategic jet bombers
- Contemporaneous with B-47
- British obsession with minimizing wetted area at expense of everything else

Famous Engineers

1. Name a famous aerodynamicist –

Famous Engineers

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Osborne Reynolds
Claude-Louis Navier
Sir George Stokes
Jacob Bernoulli
Ernst Mach
Theodore von Kármán
Richard Whitcomb
R.T. Jones
Bill Sears
Etc., etc.

Famous Engineers

2. Name a famous weights engineer –

ADAC
Aircraft Design & Consulting

Society of Allied Weights Engineers

CERTIFIED
SAWE
CMPE
MASS PROPERTIES ENGINEER

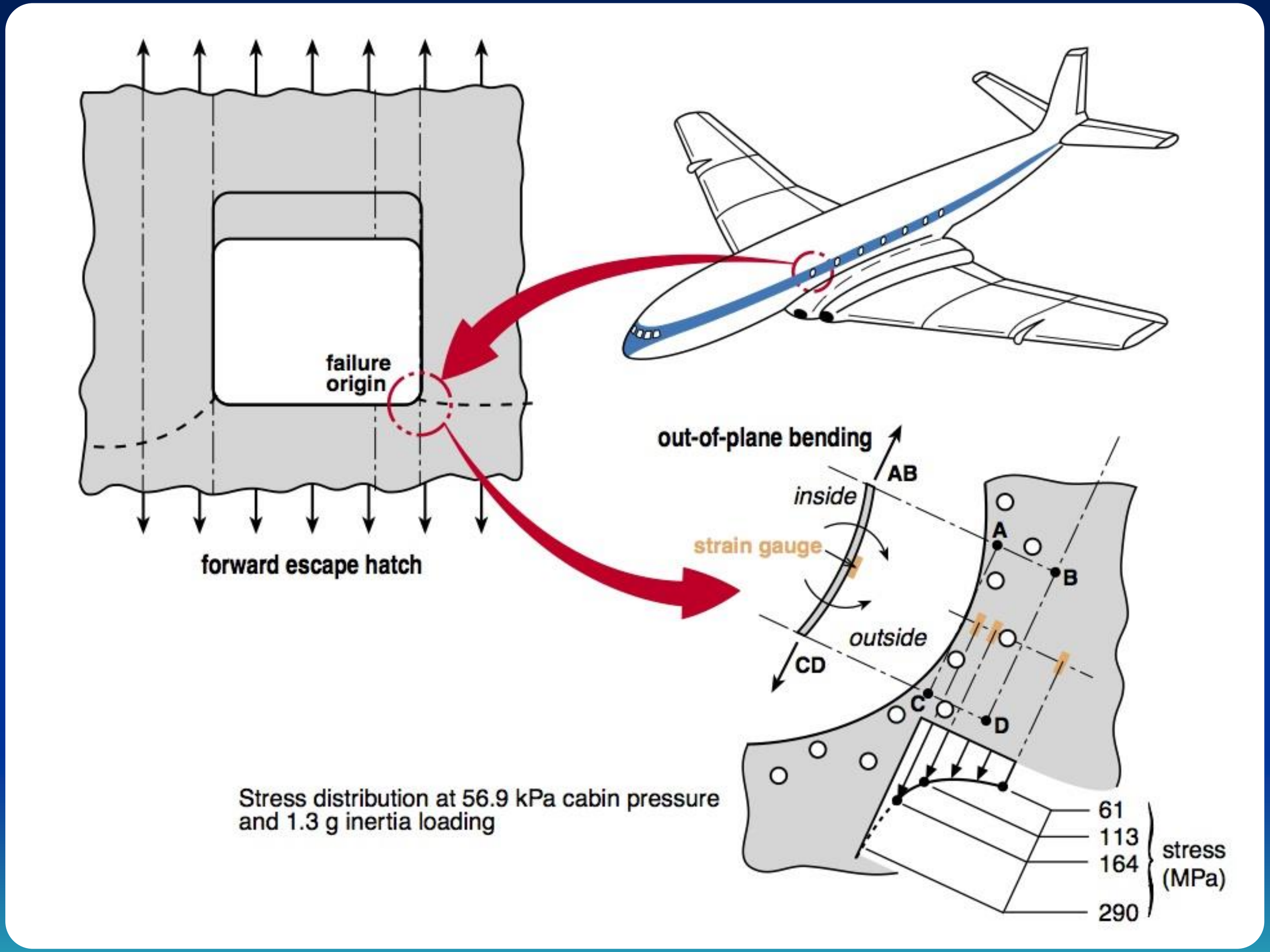
Accident Investigation

- Fatigue failure of frame of escape hatch
- Comet flights grounded for four years
- Eventually emerged as the Comet 4

Source: www.greatwen.com

Accident Investigation

Causes of fatigue failure are still not fully understood



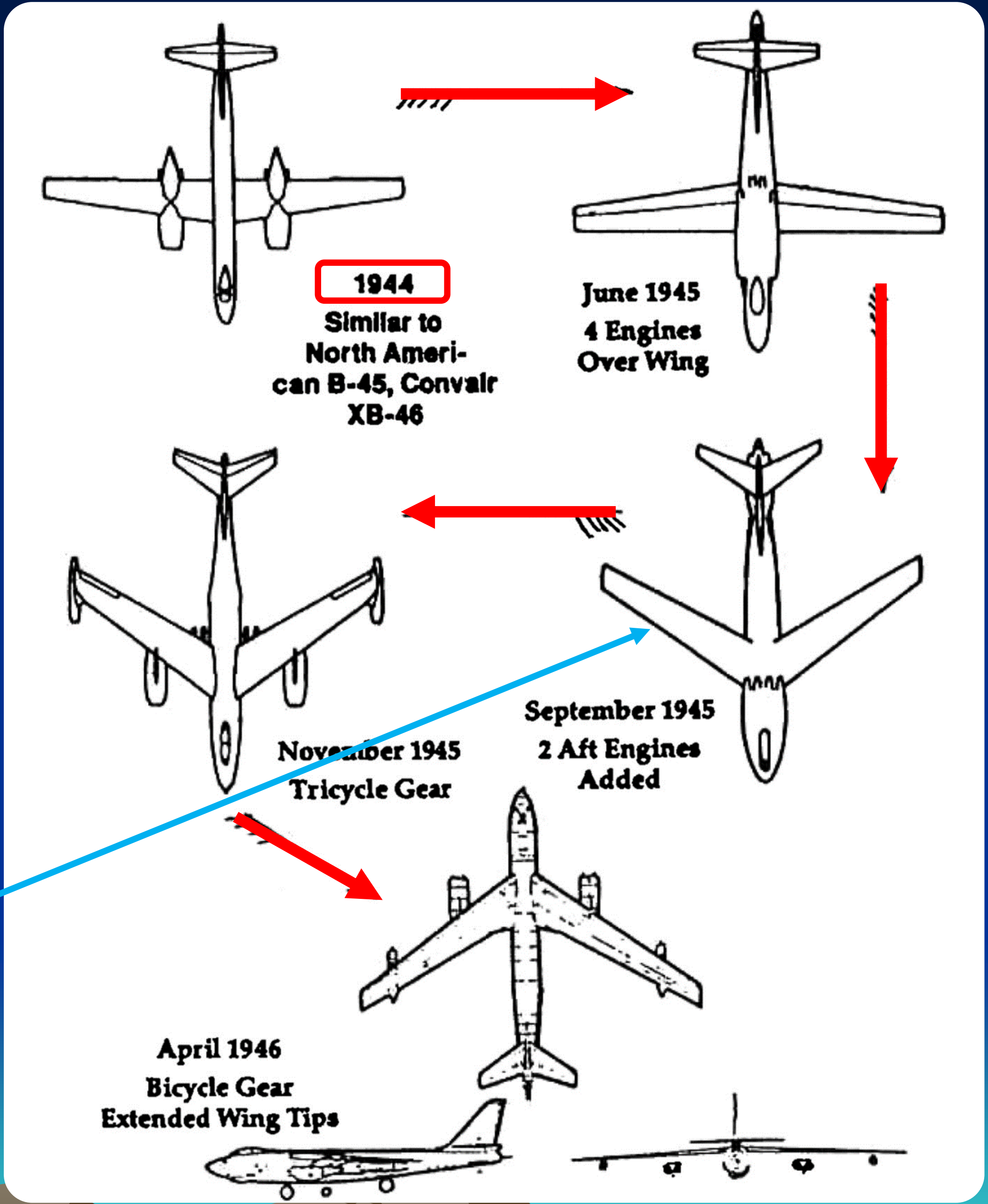
Source: www.fugahumana.com

- Meanwhile, in the U.S. (and going back in time to 1944)

B-47 Evolution

USAAF requirement for reconnaissance/bomber (other bidders: North American, Convair, Glenn Martin)

George Schairer reports back from Germany on benefits of swept wing

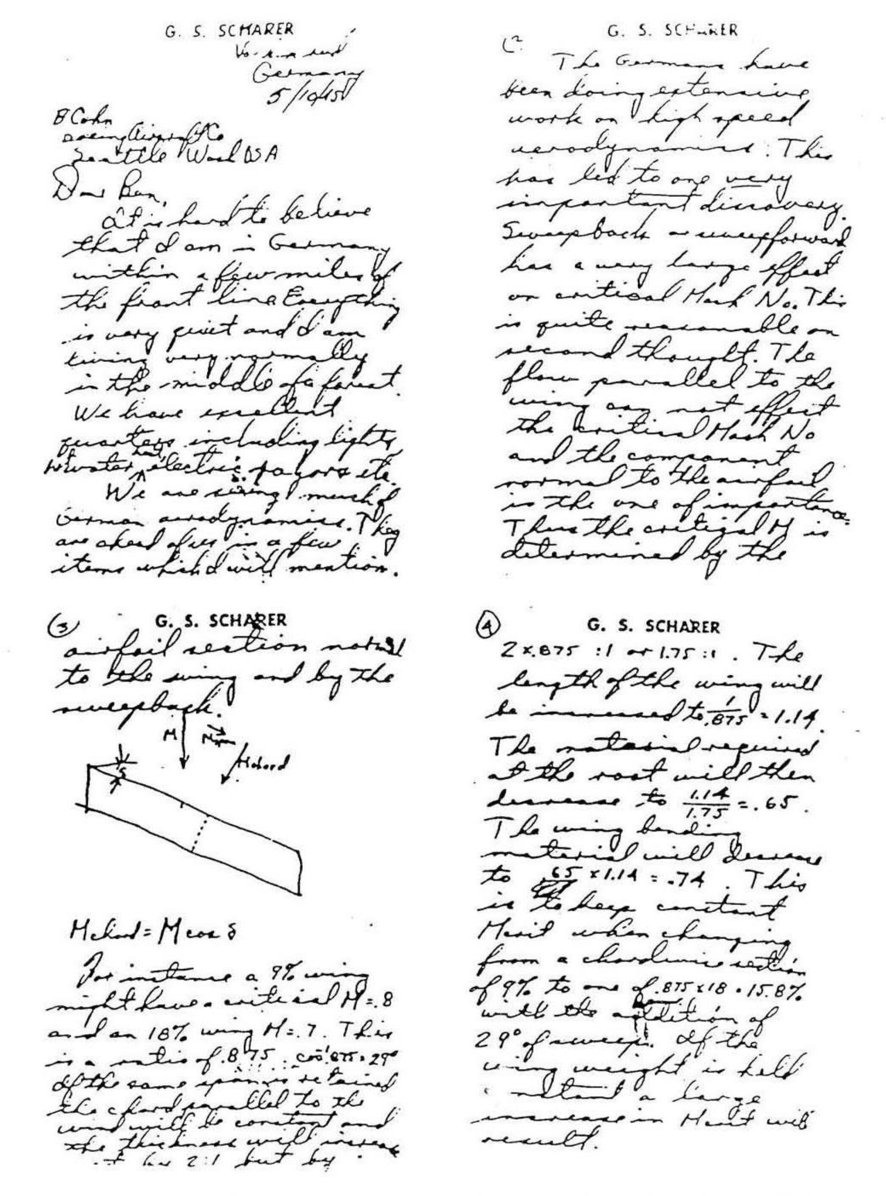


B-47 Evolution

Four-page letter dated 1945-05-10, from George Schairer in Germany to Ben Cohn, who was working on medium range reconnaissance/bomber proposal

Schairer told Cohn to pass information on to other contract bidders

The concept of swept wings was first proposed by Adolf Busemann at the Fifth Volta Conference in Rome in 1935; he presented his idea about using swept wings to reduce drag at high speeds. But until the jet engine was available, there was little interest from the US and UK



G. S. SCHARER
[illegible]
Germany
5/10/45

B Cohn
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 can 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

(3) G. S. SCHARER
airfoil section normal to the wing and by the sweepback.

M
M chord
δ

M chord = 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 [illegible] 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 M crit 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 [illegible] a large increase in M crit will result.

The Famous "Letter from Germany" by George Schairer (Dated May 5, 1945)
Which Led to the Use of the Swept Wing on the Boeing B-47 Bomber.

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Aircraft Design & Consulting

Swept Wing Concept 1935

General Crosso's Swept Wing Sketch
Rome, 1935

As Remembered by Dr. Adolph Busemann in 1977

https://www.secretprojects.co.uk/threads/adolf-busemanns-swept-wing-research.26233/

From: Cook, W.H. “The Road to the 707 The Inside Story of Designing the 707” 1991-01-01

B-47

- Schairer was more concerned about uncontained engine failure than wing bending load relief
- High wing so that wing box doesn't interfere with bomb bay
- First flight 1947-12-17 (Comet first flight 1949-07-47)

Boeing 367-80

- Development cost of $16M financed by Boeing (=nt to $182M today)
- First flight 1954-07-15
- Fuselage dia. 3.35 m (132 in.)
- Engines: 4 x P&W JT3C turbojets

https://www.wired.com/2010/07/0715boeing-707-test-flight/

Dash 80 first airplane to have
- Clamshell thrust reversers
- Engine exhaust noise suppression

First airliner to have:
- Integral wing fuel tanks
- Structural honeycomb panels in flap skins
- Leading edge slats

Boeing 367-80 with JT3D engines

Now at National Air & Space Museum, Washington DC

https://airandspace.si.edu/collection-objects/boeing-367-80-jet-transport/nasm_A19730272000

Boeing 707

- First flight 1957-12-20 (8 years after DH Comet)*
- Fuselage dia. 3.76 m (148 in.)
- Total production 1,010 between 1958 and 1978
- For 707-121, M_{econ} = 0.806

* Why so late? US airlines were privately owned, and risk adverse. BOAC was owned by the UK government, so the government bore the risk of failure

Douglas DC-8

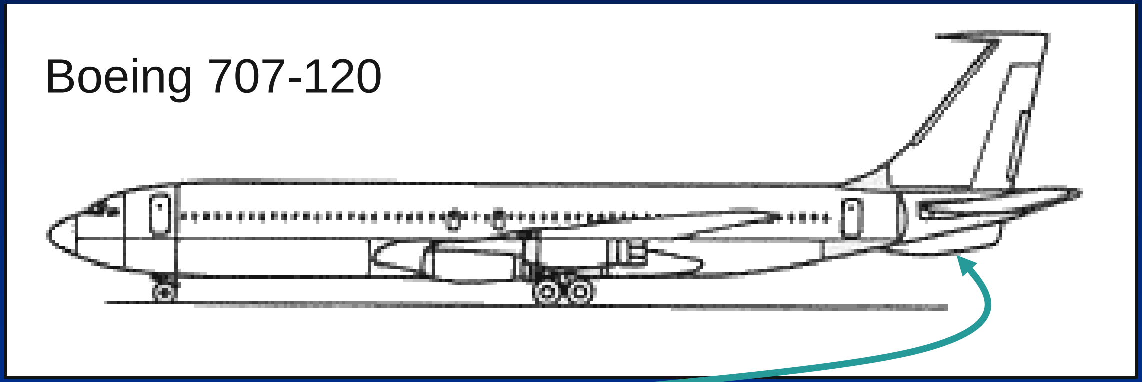
- First flight 1958-05-30
- Total production 556 between 1959 and 1972
- Smoke significantly reduced by closing some of the cooling holes in burner cans

Design for Growth

Comment from Ed Wells (Boeing Sr. VP and on BoD, helped design B-17, 707, 747) to Phil Condit (Boeing CEO):

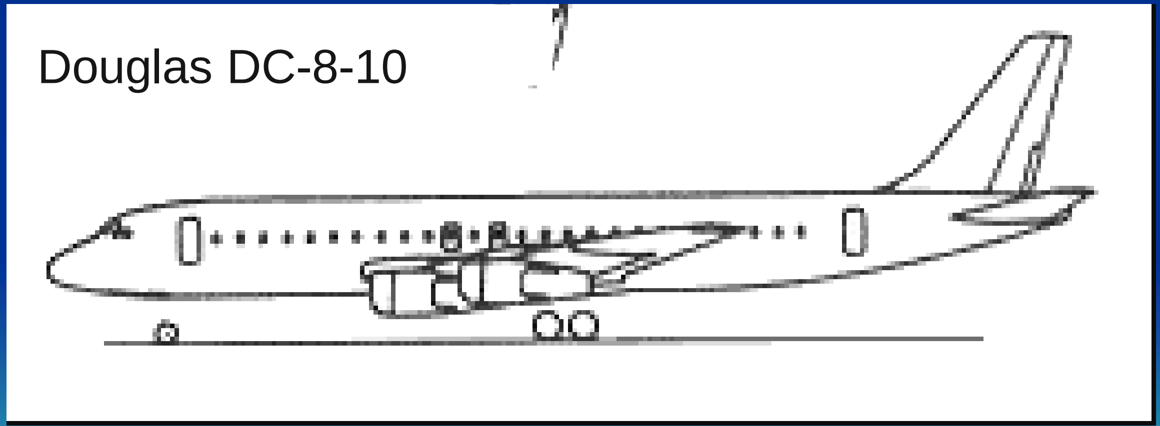
"Be careful how long or how short you make the landing gear"

Source: Bloomberg Business Week, 2018-02-19



http://www.aviastar.org/air/usa/boeing-707.php

DC-8-60 was 10.5 m longer than B.707-320



http://www.aviastar.org/air/usa/mcdonnel_dc-8.php

The UK Air Registration Board required a ventral fin on the B.707-120 (but not -320) for one engine inoperative (OEI) go around, but not the DC-8

Douglas DC-8-61/63

Longer landing gear permitted stretched fuselage without tail strike on takeoff rotation

First flight of DC-8-61 on 1966-03-14

Convair 880/990

- First flight 1959-01
- Belated attempt to enter four-engine transport market (B.367-80 first flight in July 1954)
- Fuselage diameter 128 in.
- Five abreast seating
  - CV 880 110 pax
  - CV 990 149 pax
- M_{cruise} = 0.84 (CV990)

Küchemann carrots

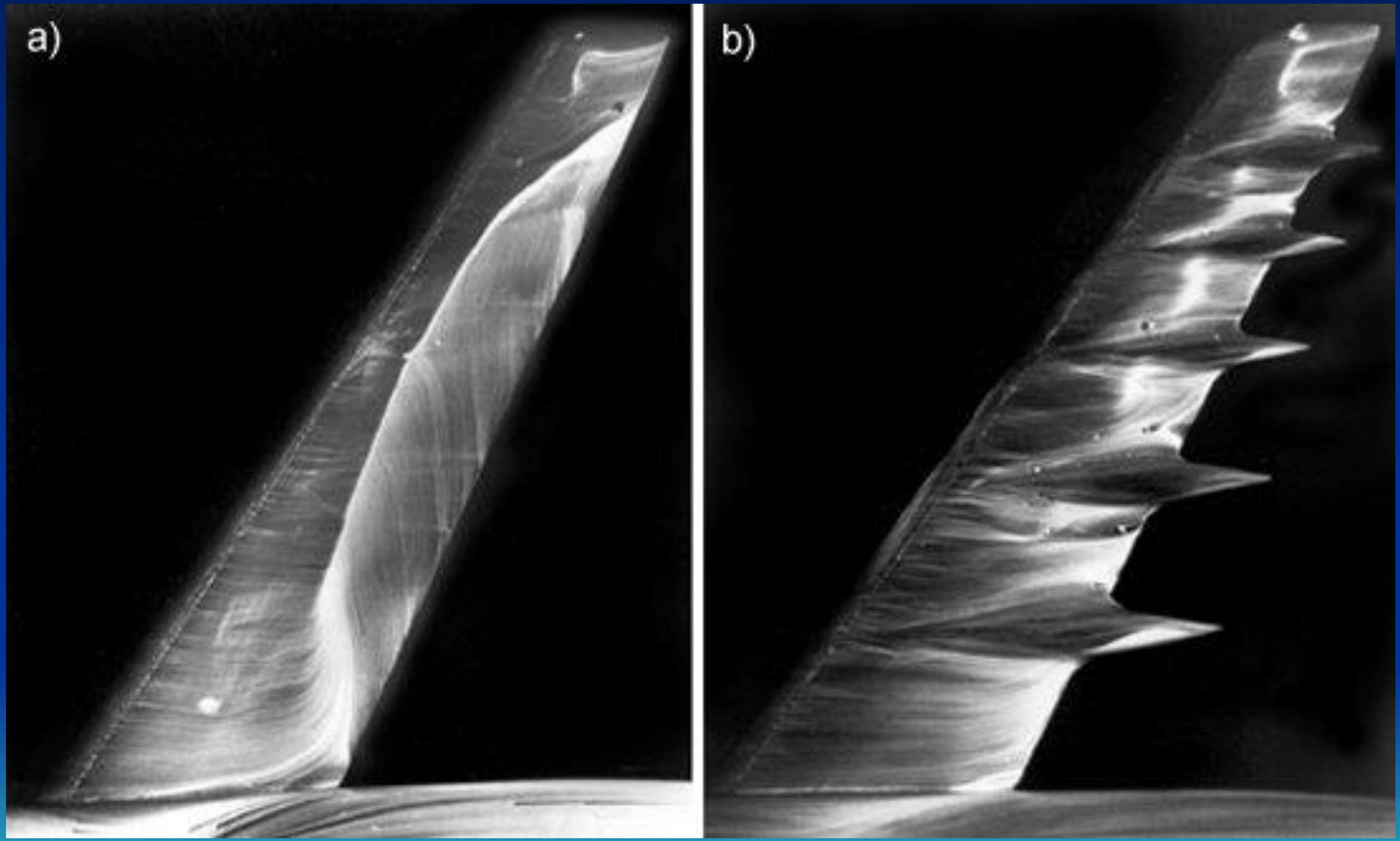
Convair CV 990

Source: commons.wikmedia.com

Küchemann Carrots Delay Shock-Induced Flow Separation

Applied to conventional (pre-supercritical) airfoils

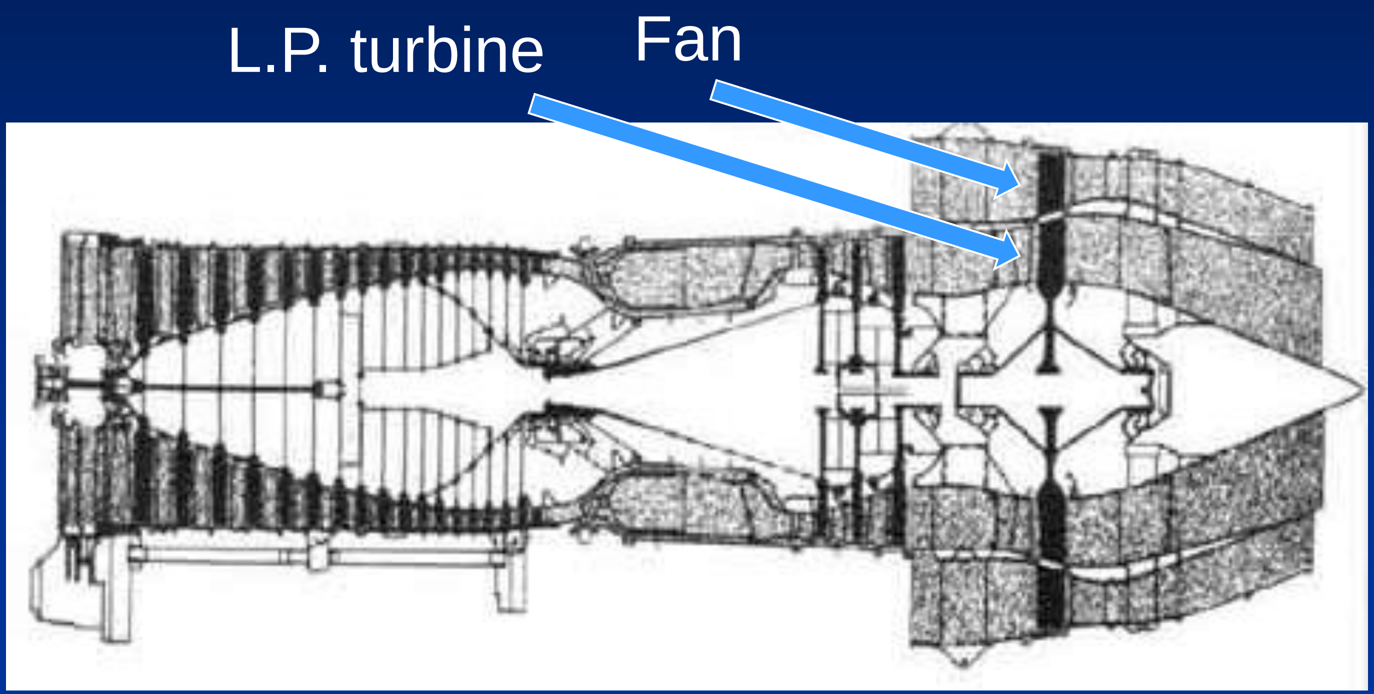
Dietrich Küchemann was head of aerodynamics at RAE Farnborough



Source: Aviation Stack Exchange

GE CJ805-23 Turbofan

- Derived from CJ805-3 turbojet (Convair 880) by adding L.P. turbine and fan
- Fan attached to ring of low pressure turbine
- Installed on Convair 990
- Relatively low BPR of 1.46



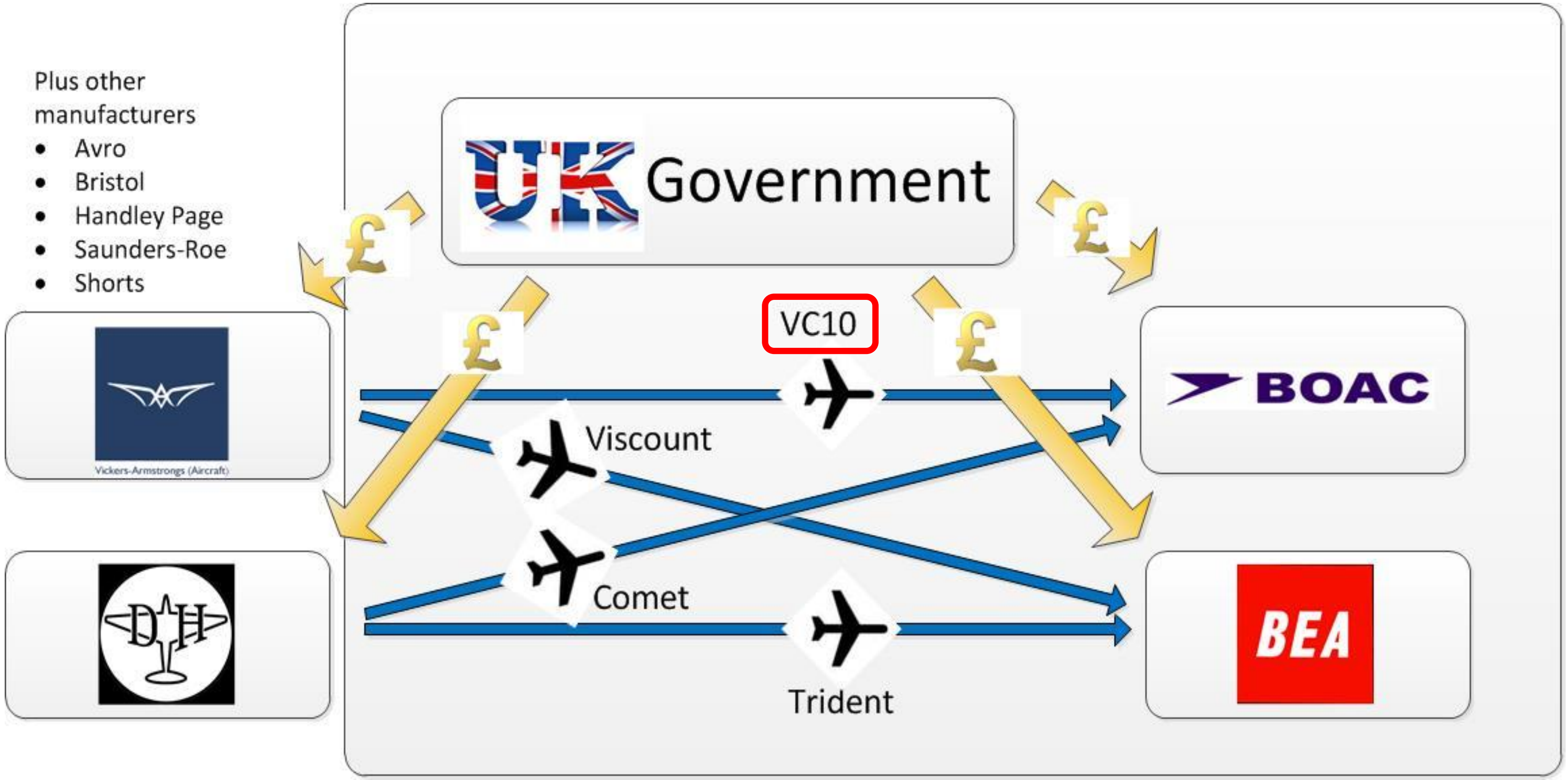
Source: www.military.ir

Convair 880/990 Lessons Learned

- Production
  - CV 880 65
  - CV 990 39
- Too late to the party
- Difficult to find niche on payload-range plot that can't be filled by derivative of another aircraft type
- Higher cruise Mach didn't result in significant reduction in operating cost

- Returning to the UK

UK Government and Flag Carriers



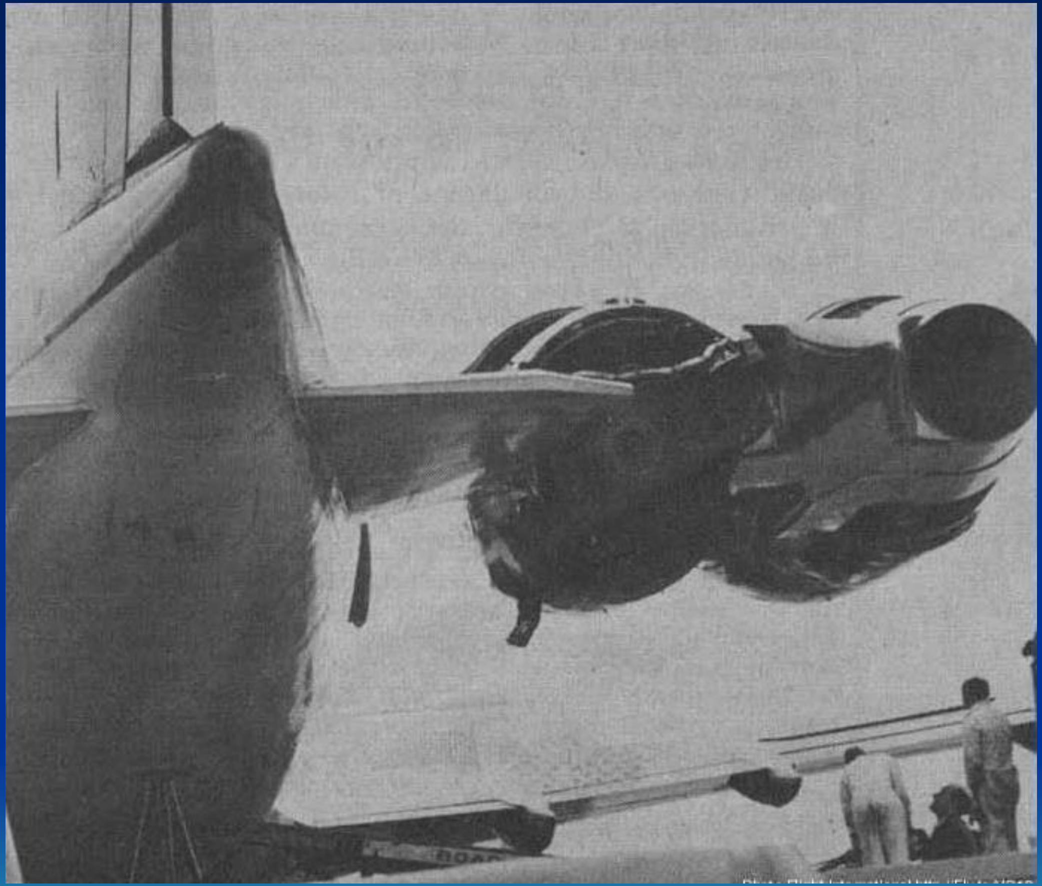
Vickers VC10 (UK)

- First flight 1962-06
- Designed to BOAC requirement ‘hot and high’ airfields on “Empire” routes
  - Shorter runways required full-span flaps
- 4 R-R Conways (BPR: 0.3:1)
- Entered service 1964-04
- Production ended in 1979 with only 54 aircraft manufactured (inc. Super)

Source: wikimedia

VC10 Uncontained Failure

- Departed LHR, 1969-11
- LP turbine blades shed from No. 3 engine
- Penetrated No. 4 engine which caught fire (quickly extinguished)
- Returned to LHR 41t (90K lb) over max landing weight
- Blew fusible tire plugs



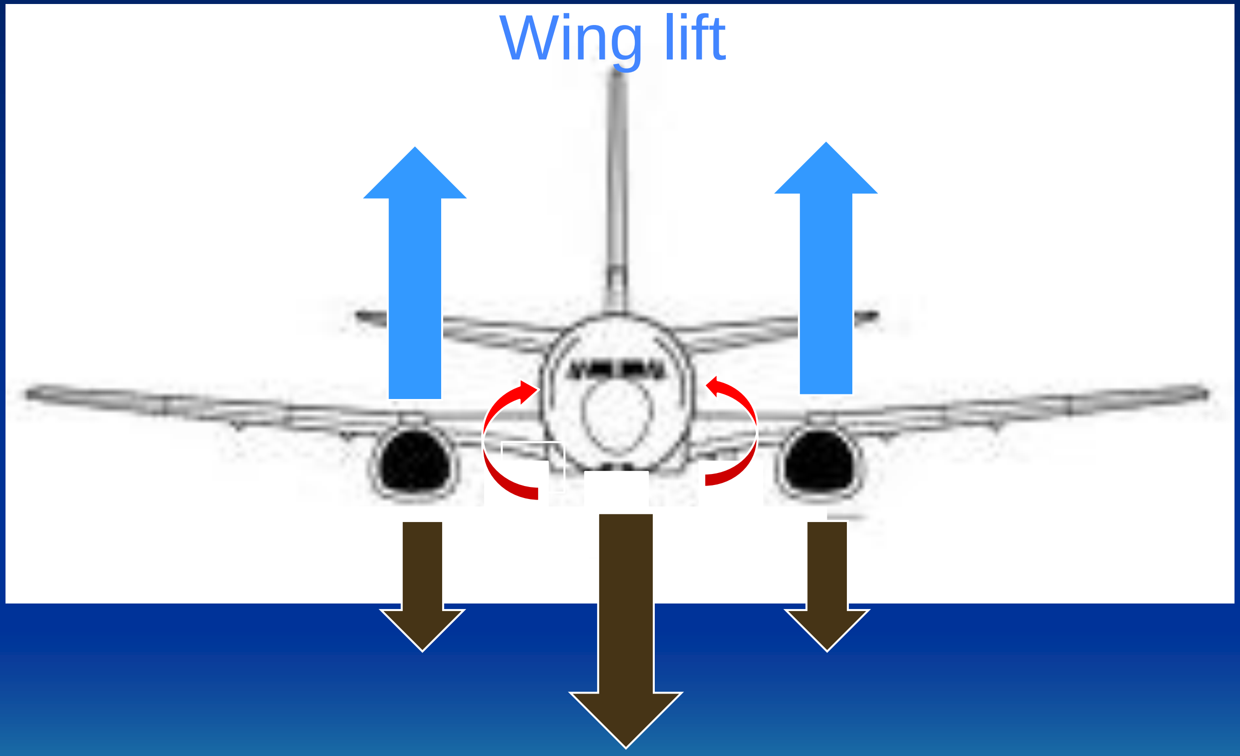
http://www.vc10.net/History/incidents_and_accidents.html#Engine Disintegrates

VC10 Characteristics

- Clean wing (V_{app} approx. 10 kt less than 707)
- TOFL = 8,280 ft, LFL = 6,380 ft
  - (For 707-320 TOFL = ~10,800 ft, LFL = ~7,500 ft)
- Low cabin noise
- BOAC calculated DOC/pax mile approx. 3% higher than for 707 (and made this public)

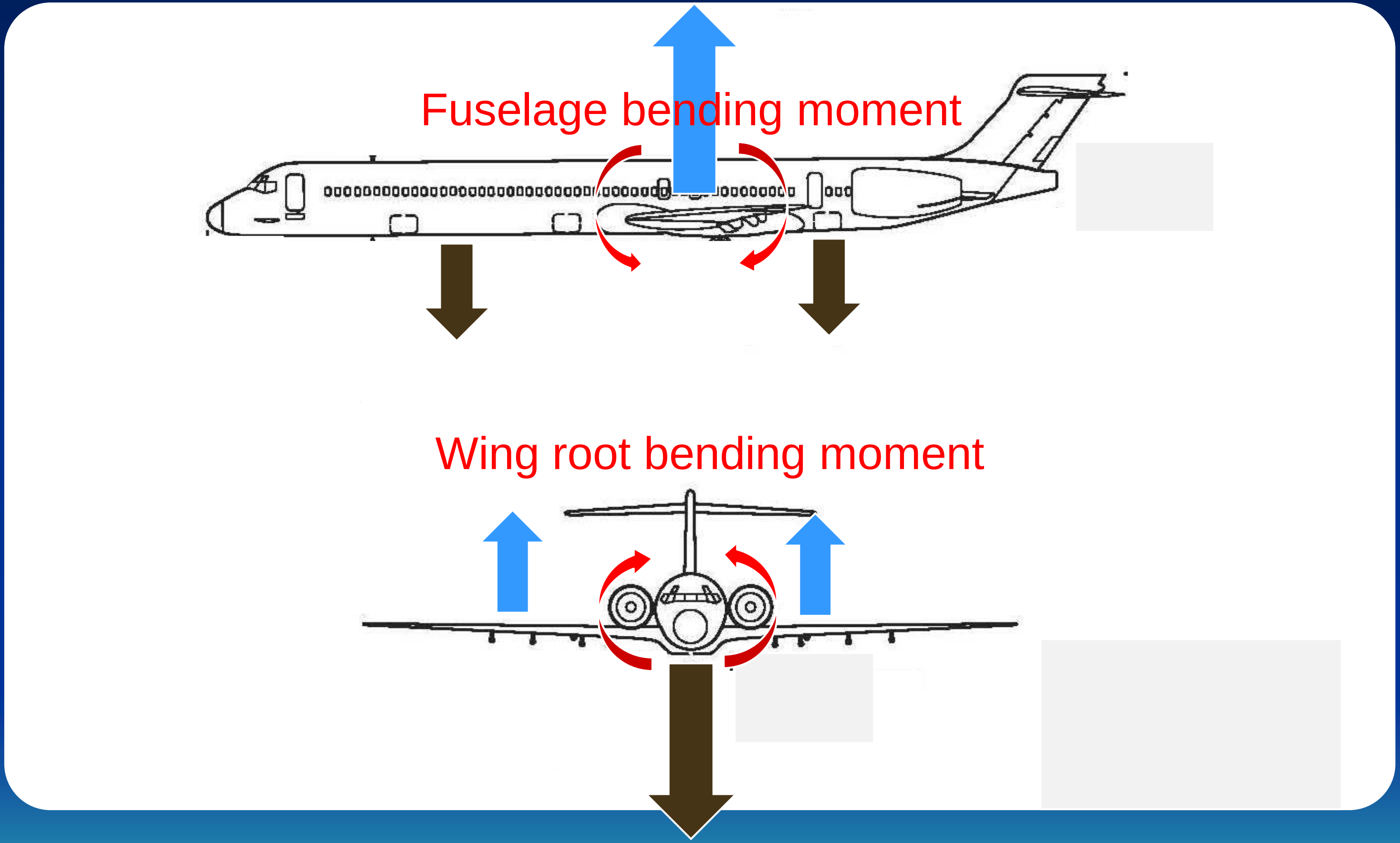
Wing Root Bending Relief

- Engines mounted on wing reduce wing root bending



Fuselage And Wing Root Bending

- Engines mounted on rear fuselage induce additional wing and fuselage bending moments
- Made worse by
  - Stretched fuselage
  - HBPR (heavier) engines



Executive Jet Engine Installation

https://jettly.com/fleet/okpho

- Rear fuselage installation on an executive jet is ok, because fuselage length/diameter ratio is much smaller

VC10 Handicaps

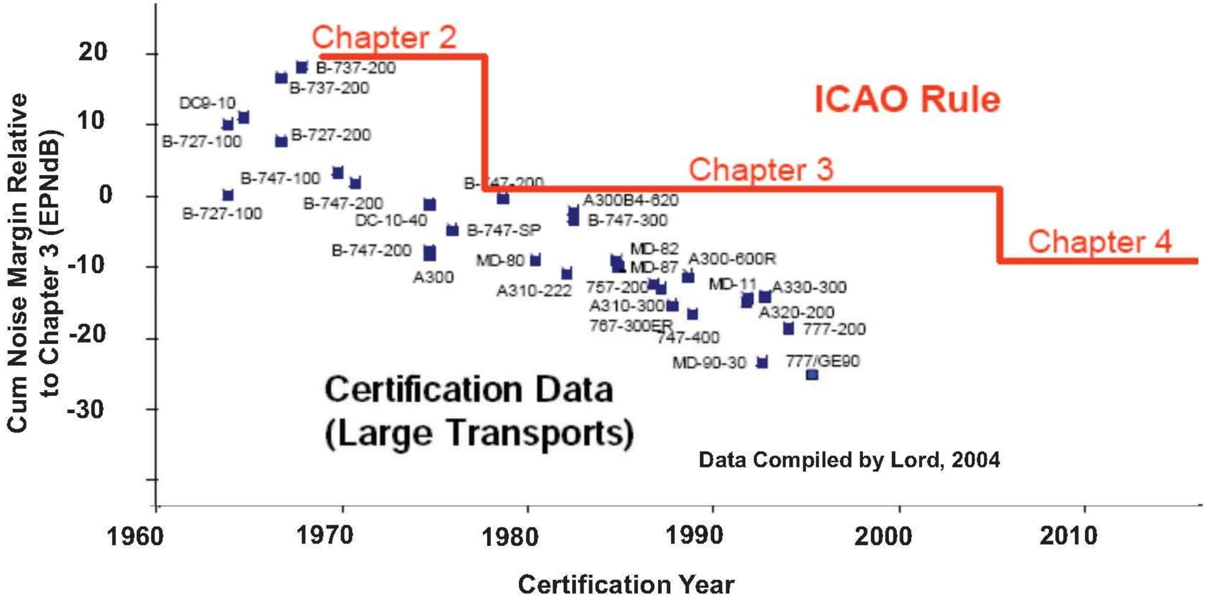
- W_e/W_{to} = 0.47 compared with 0.44 for B.707-320
- Higher cruise drag than predicted
- Runways lengthened to accommodate B.707 and DC-8

Federal Aviation Regulations (FARs)

- 14 CFR Part 23: Airworthiness standards for aircraft with < 20 seats, and with MTOGW < 19,000 lb
- 14 CFR Part 25: Airworthiness standards for commercial transports, jets with > 9 pax or with MTOGW > 12,500 lb, and propeller aircraft with >19 seats, or with MTOGW > 19,000 lb
- 14 CFR Part 34: Exhaust emissions for civil transport aircraft with gas turbine engines (1990-08-10, but EPA standards set via 40 CFR Part 34 in 1970)
- 14 CFR Part 36: Noise emissions. Issued 1969-11-08, successive “Stages” applied stricter requirements
- 14 CFR Part 121: Air Carrier Certification, i.e. commercial transport operations

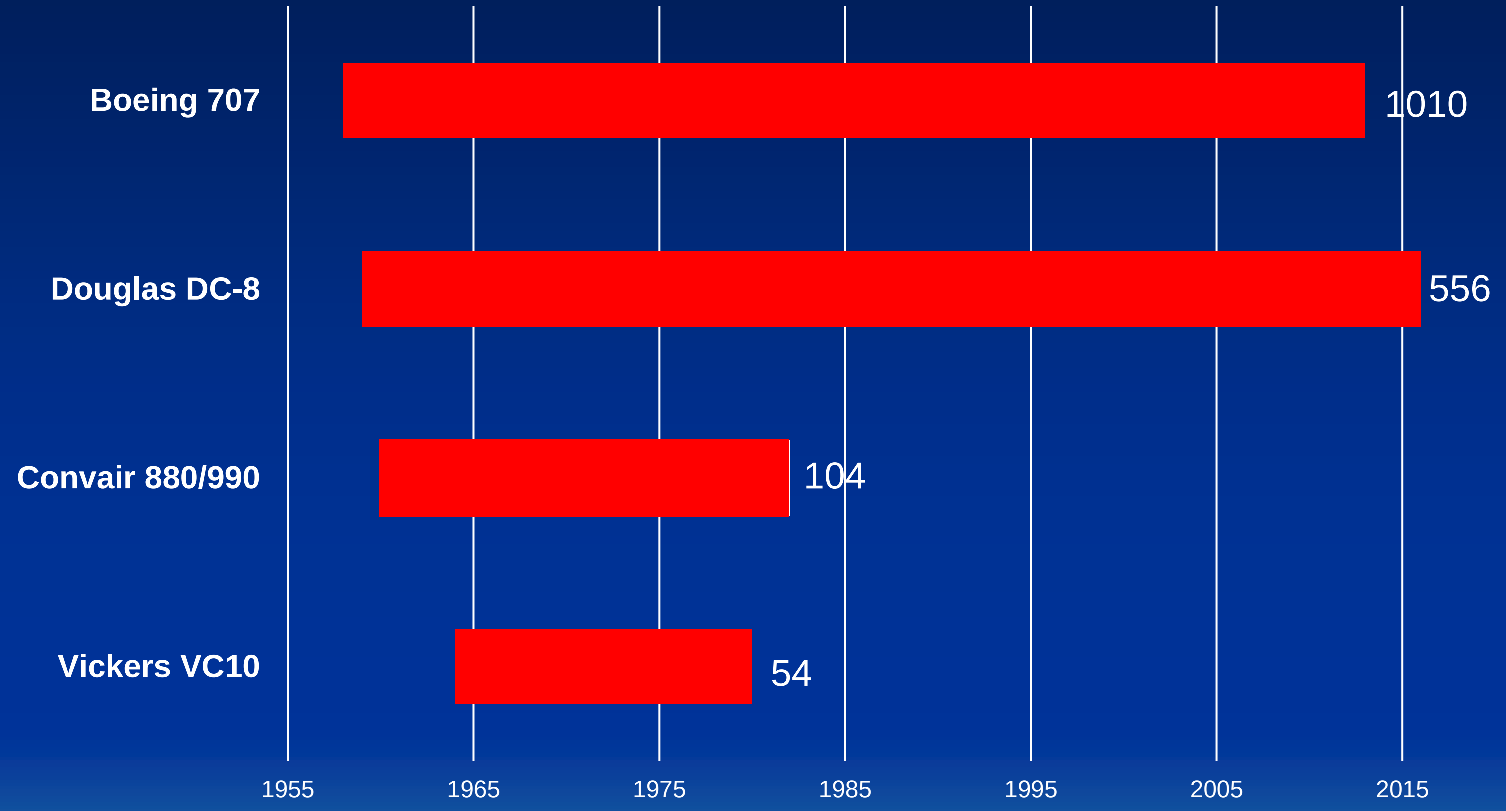
ICAO Annex 16

- **ICAO categorizes jets into Chapters 1, 2, 3, and 4**
  - Almost exactly the same as Stages 1, 2, 3, and 4
  - Standards have forced noise levels down over time
  - **Stage 4 aircraft must be 10 EPNdB quieter than Chapter 3 standards summed across all three measurement locations**



Source: Baldwin (Harris Miller Miller & Hanson)

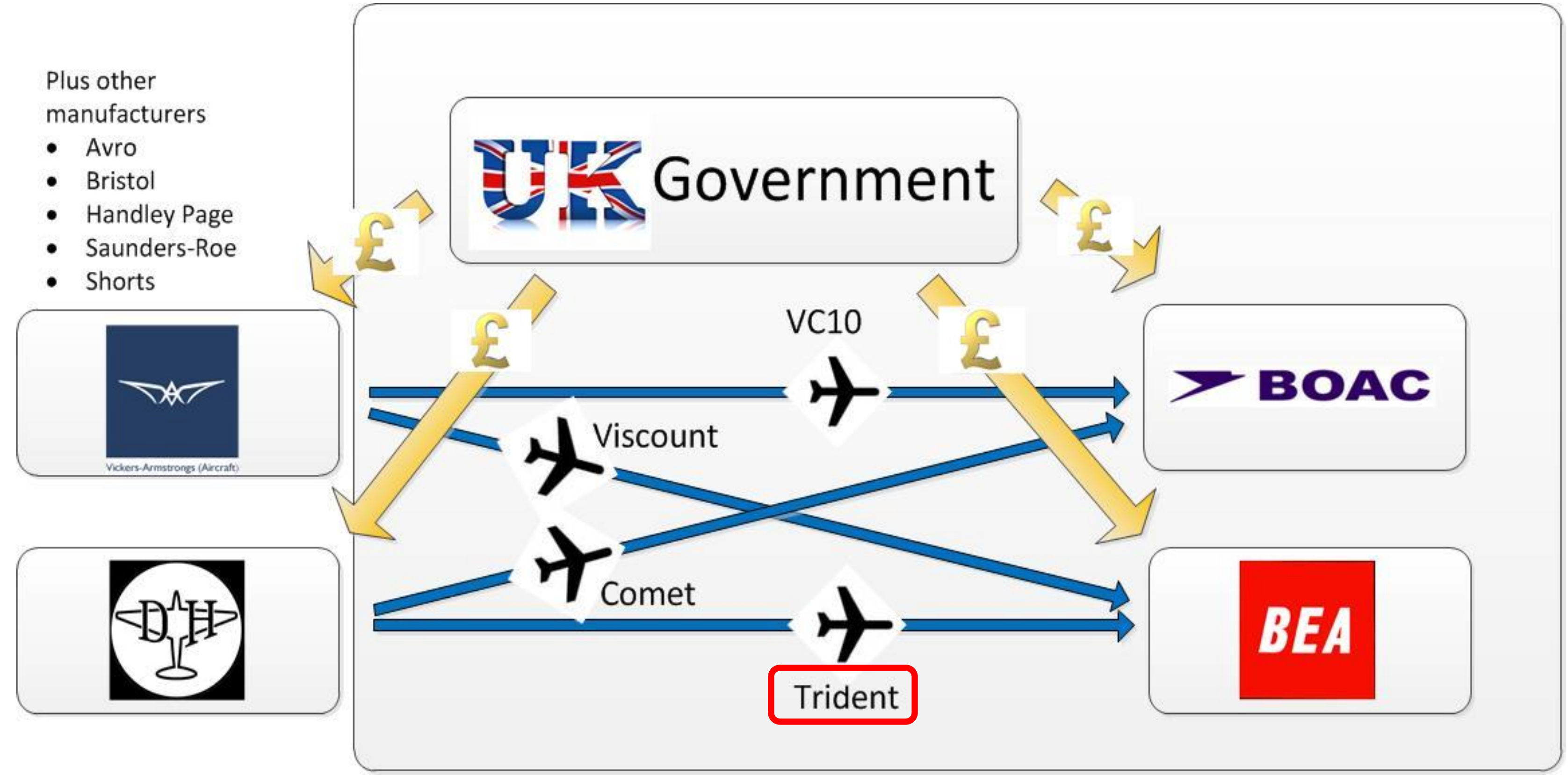
Service Period and Production Quantity



Data source: Wikipedia

- Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
  - 4-engine, long range
  - 3-engine, medium range
  - 2-engine, short range
- Advent of high bypass ratio engines
- Supersonic flight

UK Government and Flag Carriers



De Havilland DH 121 Trident (U.K.)

- First flight 1962-01
- Designed to 1957 BEA requirement for 88 pax
- 3 R-R Speys
- Entered service March 1964
- Production ended in 1979 with 179 aircraft
- CAAC purchased 33 aircraft

Source: century-of-flight.net

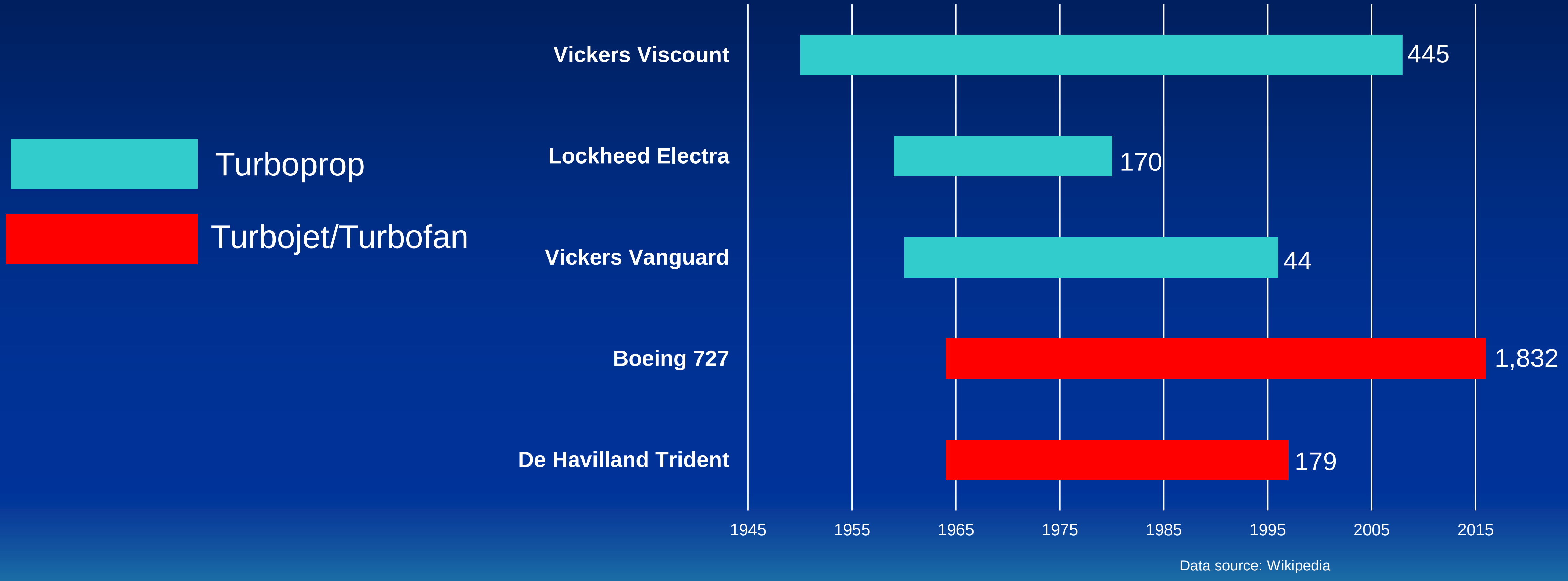
Trident Handicaps

- UK government insisted on merger with losing competitor (to form Hawker Siddeley)
- Too small for worldwide market
- Shared design details with Boeing
- Long flight test cycle (two years vs. one for Boeing)
- Low production rate (12/year vs. 80-100 for Boeing)
- Limited growth potential (couldn’t re-engine)

B.727 Replaced Lockheed Electra

- Up to 189 pax
- Design development ~1960
- First flight Feb 1963
- Entered service 1964-02
- Fuselage dia. = 3.76 m (148 in.) (same as B.707)
- Production ended in 1984 with 1,832 aircraft built

Service Period and Production Quantity



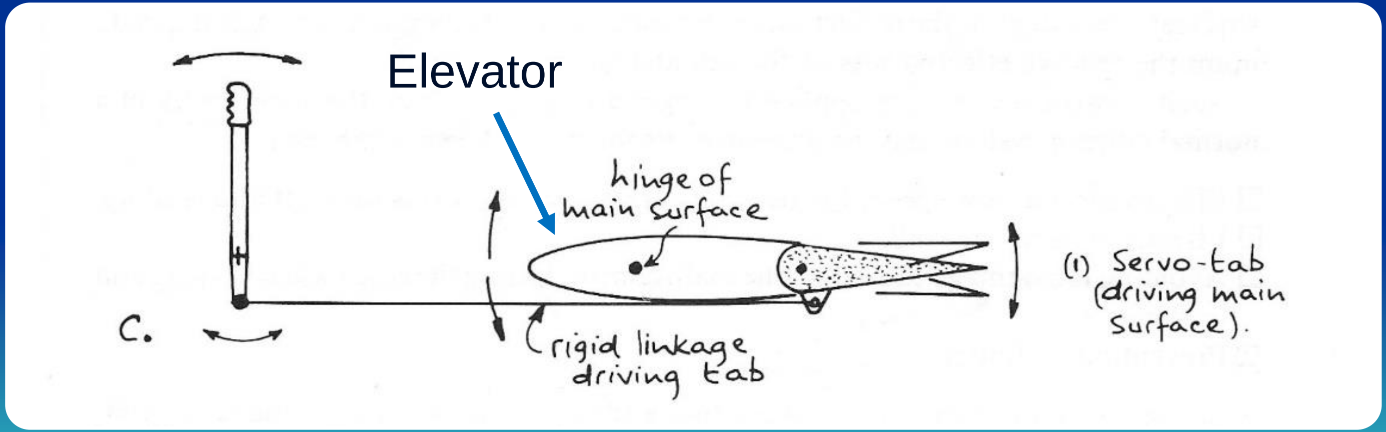
- Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
  - 4-engine, long range
  - 3-engine, medium range
  - 2-engine, short range
- Advent of high bypass ratio engines
- Supersonic flight

BAC 1-11

- Up to 189 pax
- Design development ~1960
- First flight 1963-02
- Entered service 1964-02

BAC 1-11 Flight Test Crash

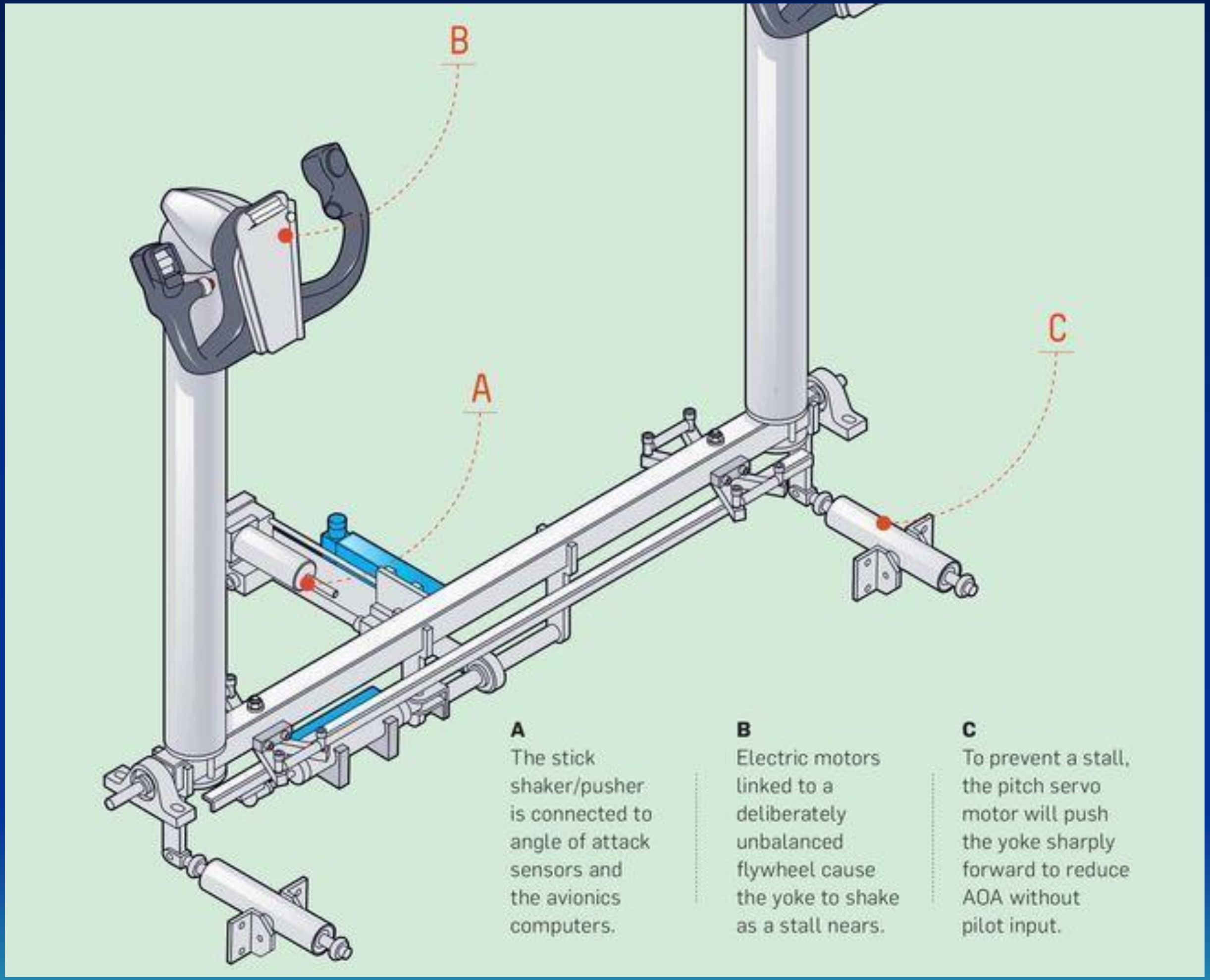
- 1963-10-22
- Pilot: Mike Lithgow plus 6 flight test crew
- Aft c.g.
- Entered stall at 16,000 ft
- Hit ground a low forward speed
- Exacerbated by servo-tab-operated elevator



Source: Stinton, The Design of the Aeroplane, Fig. 12.7

Stick Shaker/Stick Pusher

- Stick shaker typically uses out-of-balance rotating weight to simulate effect of pre-stall buffet on control column
- Stick pusher moves control column (and thus elevator) to prevent stall
- Installed on BAC-111 after 1963 accident



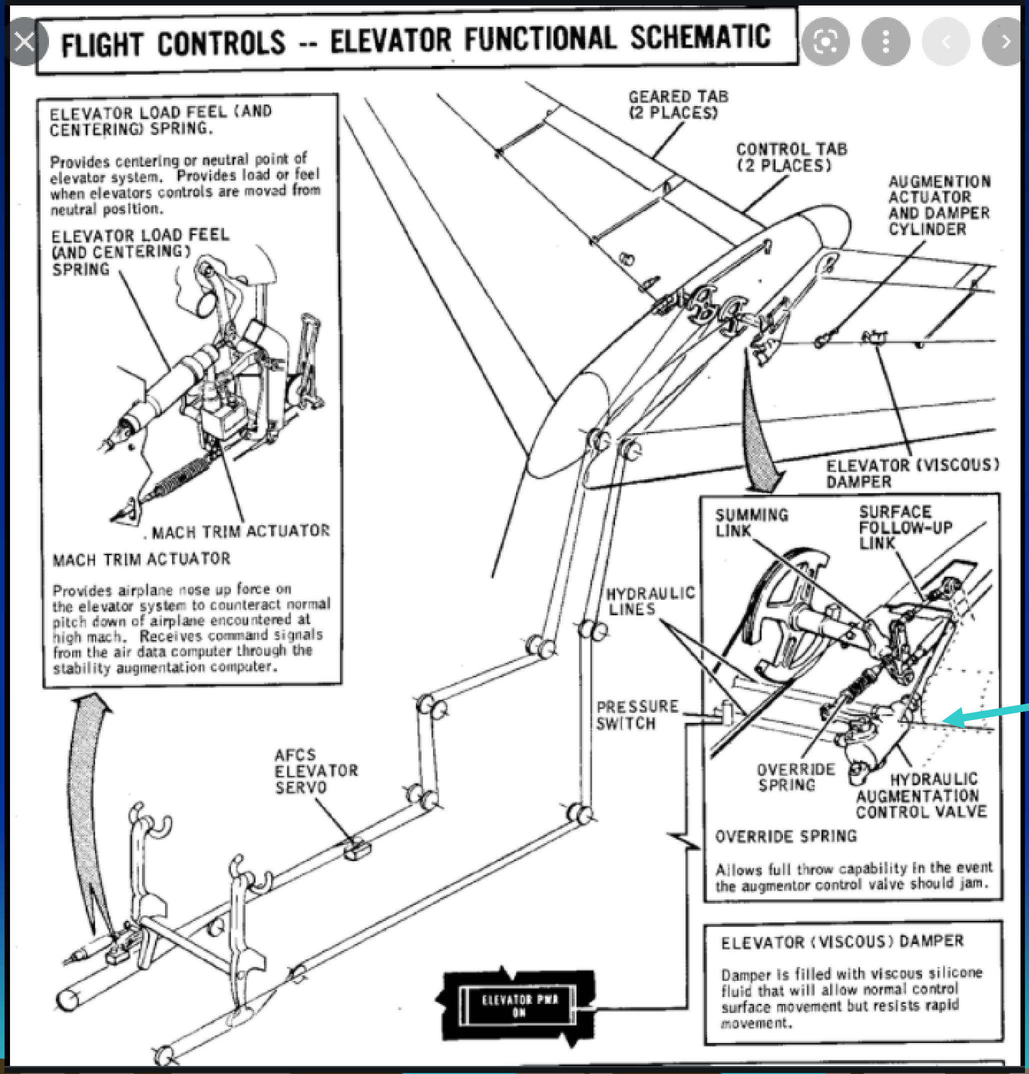
Source: https://www.flyingmag.com/how-it-works-stick-shaker-pusher

ADAC Aircraft Design & Consulting

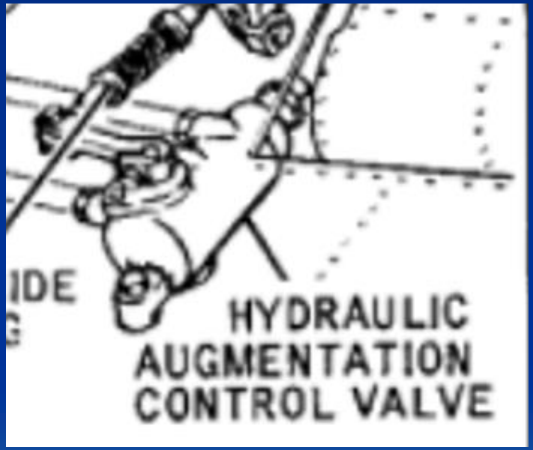
Douglas DC-9-10 (U.S.)

- First flight 1965-02-25

DC-9 Hydraulic Augmentation

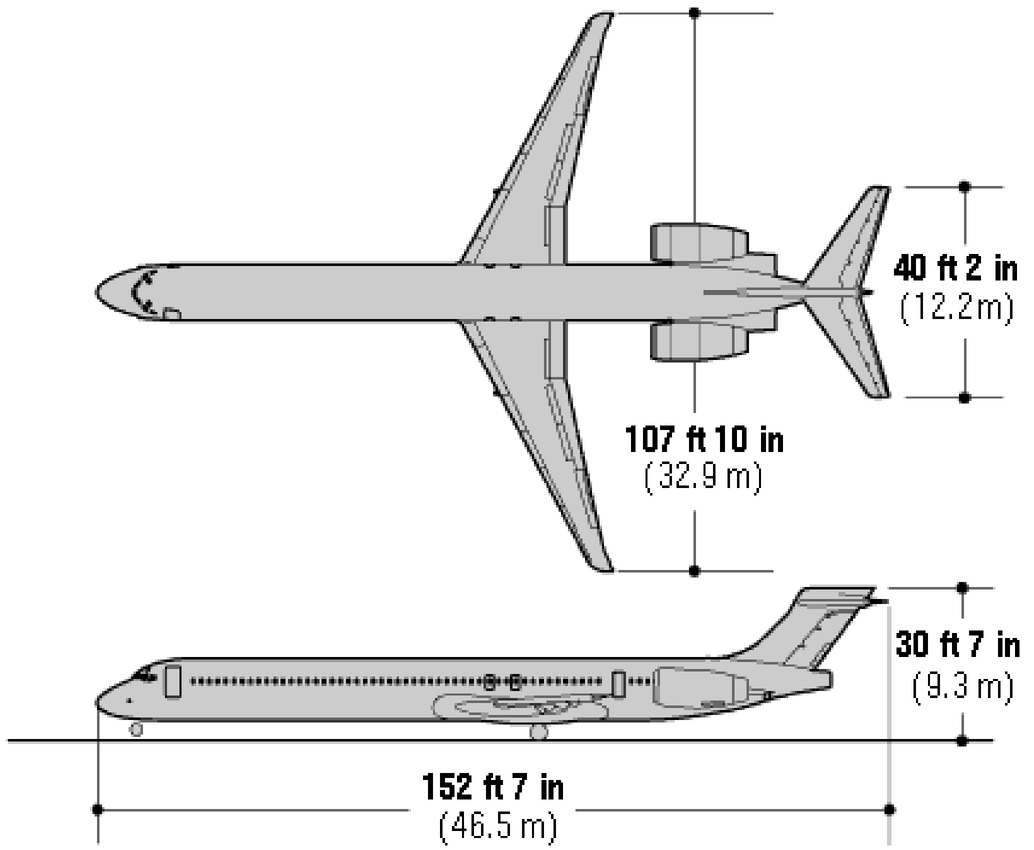


At high α, hydraulic actuator moves elevator t.e. down



Passenger cabin location forward of wing

- MD-80
- HBPR engines force cabin further forward
- Must control c.g. travel carefully
- But with auto-trim, pilots are not concerned by large trim changes



Boeing 737

https://aeropedia.com.au/content/boeing-737-100/

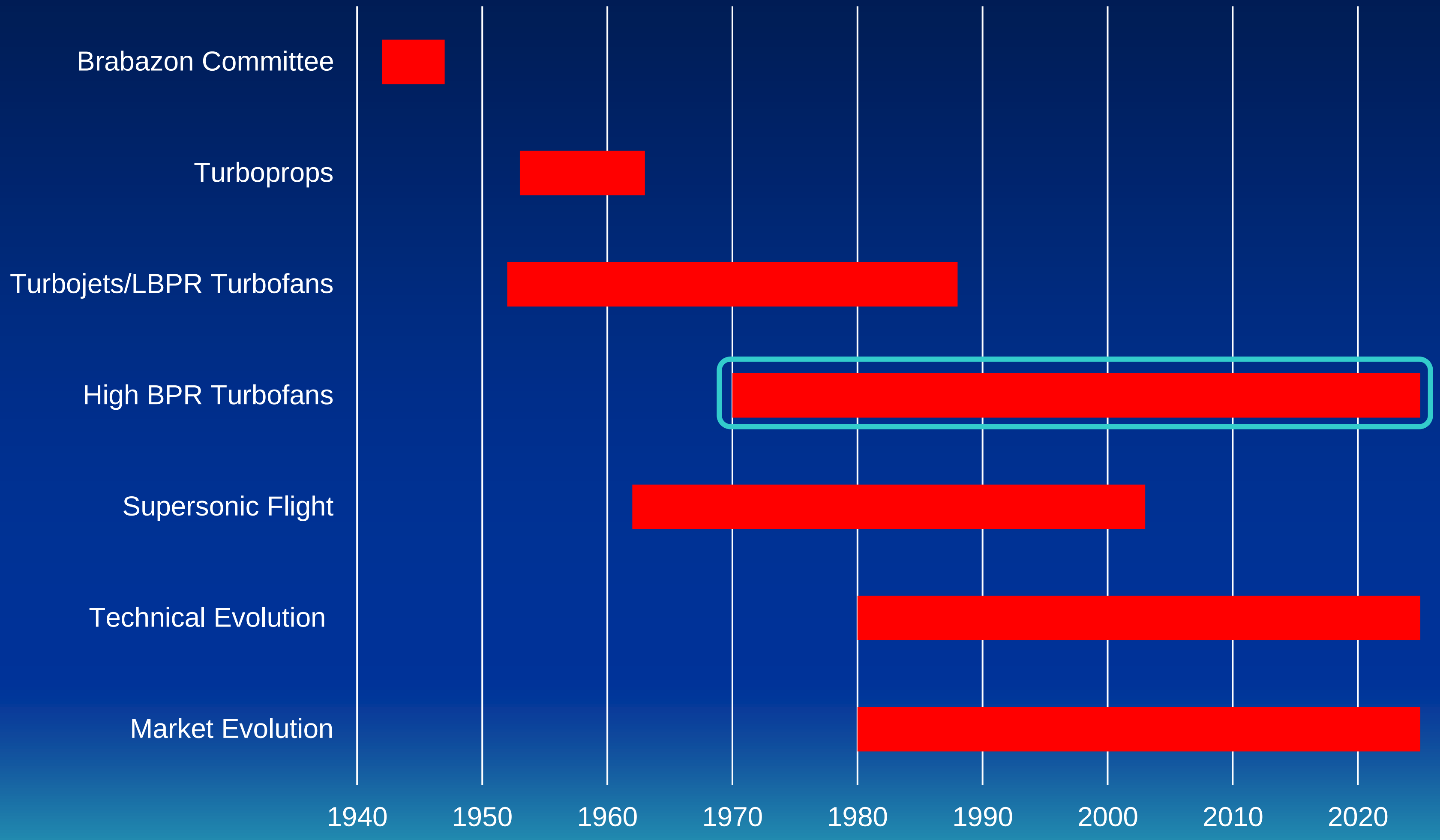
- First flight 1967-04-07
- Pax: 85-130

AVCO Lycoming PLF-1A

- First run in 1962-02
- BPR 6:1
- Fan diameter: 102 cm (40 in.)
- Boeing designers should have anticipated the larger diameter of future engines and designed longer landing gear

- Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
- Advent of high bypass ratio engines
- Supersonic flight
- Technical evolution
- Market evolution

Commercial Aircraft Evolution



CX-HLS Program (1963) (U.S.)

(Cargo Experimental – Heavy Logistics System)

RFP issued 1964-04

- Requirement to carry M60 battle tank
- Payload: 56,700 kg (125,000 lb)[1]
- Range: 12,875 km (6,952 nmi)
- Max payload: 113,400 kg (250,000 lb)
- TOFL @ MTOGW: 2,440 m (8,000 ft)
- LFL: 1,220 m (4,000 ft) on semi-prepared strip
- Design life: 30,000 flight hours

Aircraft submissions

Lockheed CX-HLS

Douglas CX-HLS

Boeing CX-HLS

Engine submissions

GE TF-39

P&W JT-9D

Boeing 747-100/200

- Design requirements from Juan Trippe at Pan Am
- Pan Am VP Engineering – John Borger
- Boeing Chief Engineer – Joe Sutter

Comparative Fuel Burn

	707-100	747-100
Take-off weight (kg) [lb]	117,800 [260,000]	321,600 [710,000]
Empty weight (kg) [lb]	56,600 [125,000]	167,600 [370,000]
Economy seating	175	500
At average load factor (pax)	87	250
Fuel burn/trip (kg) [lb]	36,200 [80,000]	72,500 [160,000]
Fuel burn/passenger (kg) [lb]	410 [910]	290 [640]

Ray Whitford: Evolution of the Airliner

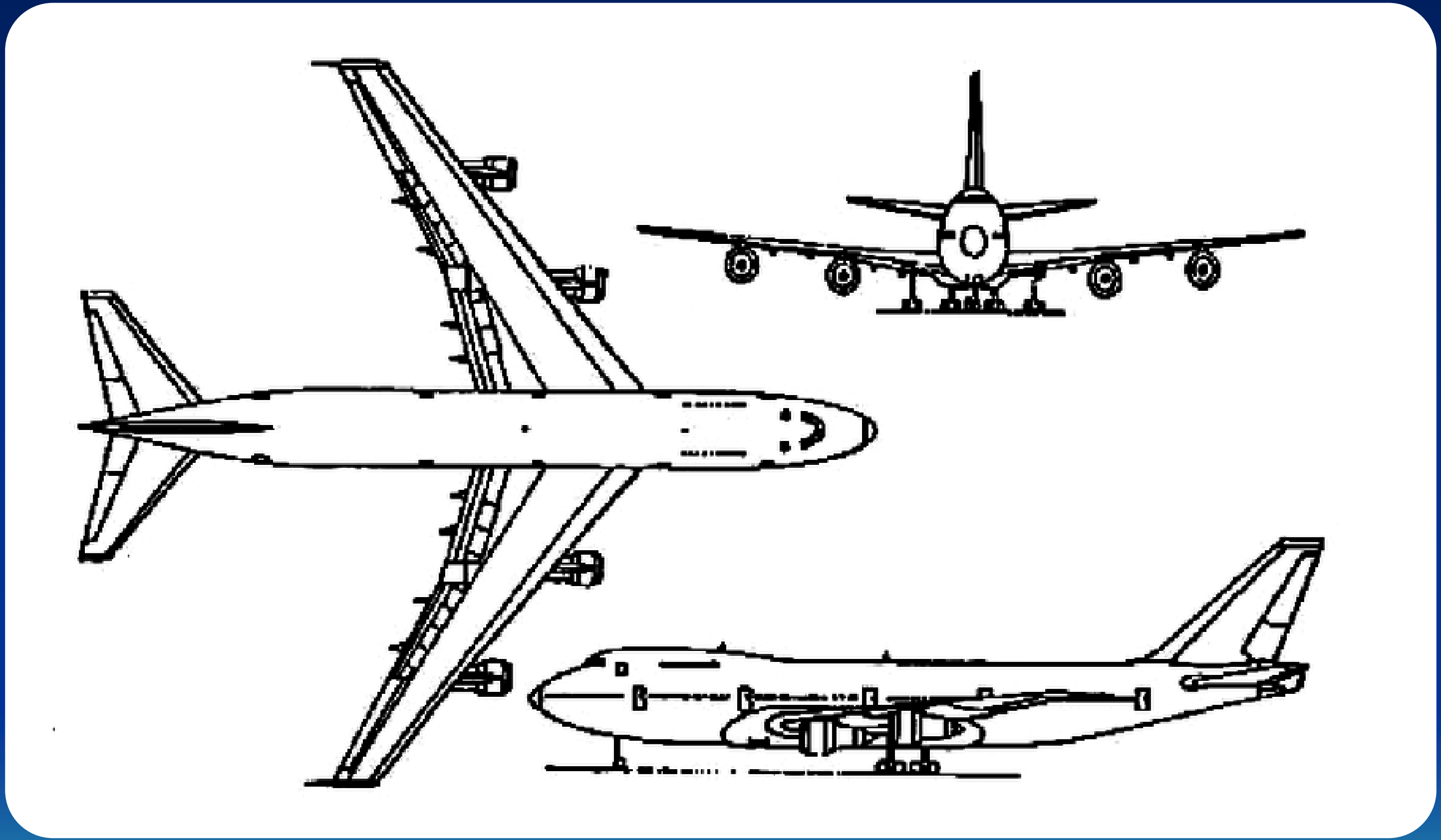
Fuel burn per pax
reduced by almost 30%

Boeing 747-100

Range: 5,300 nmi (9,815 km) with 385 pax and reserves
MTOGW: 735,000 lb (333 t)

SFO-NRT 5,108 nmi (9,460 km)
SFO-PEK 5,139 nmi (9,155 km)

Could make SFO-NRT with full load, but could not quite make SFO-PEK

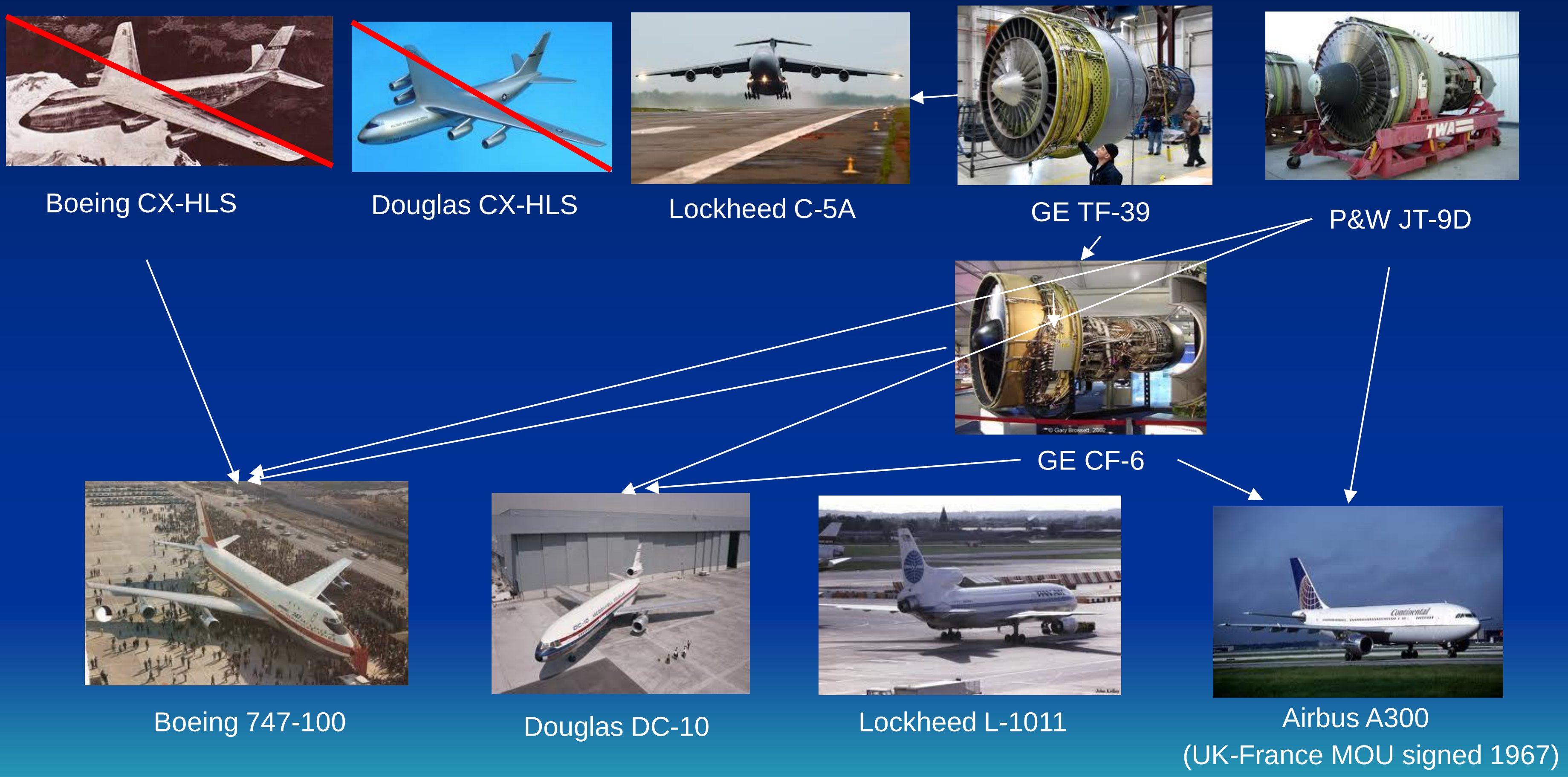


Boeing 747SP

- Range: 6,655 nmi (12,325 km) no reserves
- Payload: 276 pax

- Purchased by
  - CAAC (5 orders, entered service 1980-04-02)
  - Pan Am (11 orders, aircraft later acquired by UAL)
  - Total of 45 orders

Where's Rolls-Royce?



Rolls-Royce – Lockheed Contract

- Lockheed meant to leave nothing to chance
  - Contract ran for 483 pages
- But, no sufficient provision for inflation
  - Formula was inadequate for R-R
- Savage penalty clauses with huge cash penalties for delivery after 1971-11
- Typically contract would have penalties for failure to meet guarantees on
  - Thrust
  - Sfc
  - Engine weight

R-R Bankruptcy

- 1971-01-26 R-R board decides to place company in receivership
- 1971-02-04 Announcement of receivership (i.e., bankruptcy) in Parliament. Rupert Nicholson of Peat, Marwick & Mitchell (accountants) takes control of company
- Assets acquired by U.K. government
  - New company “Rolls-Royce (1971) Ltd.”
- Lockheed lays off 6,000 employees

Rolls-Royce Is Bankrupt; Blames Lockheed Project

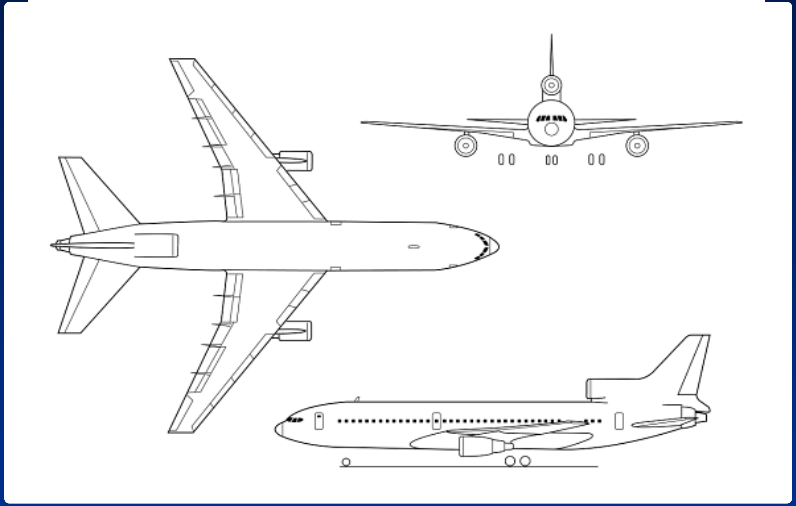
By JOHN M. LEE

Special to The New York Times

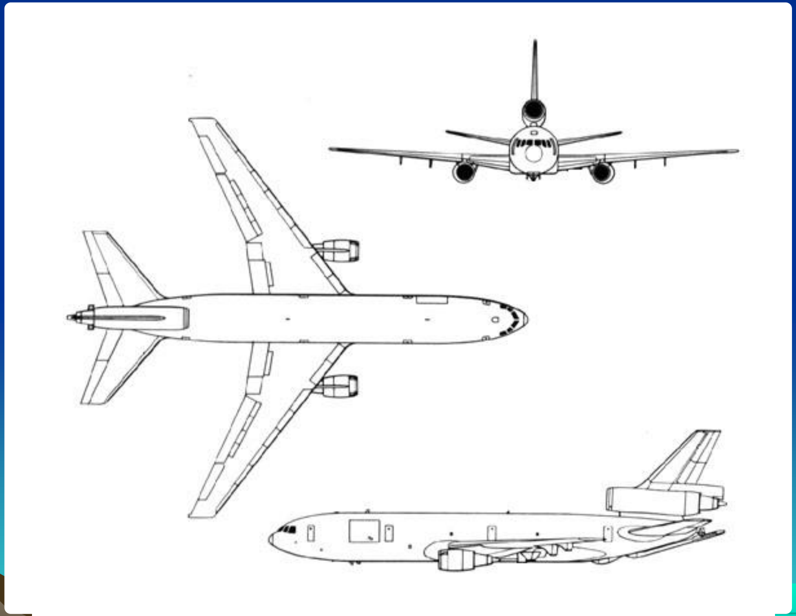
LONDON, Feb. 4—Rolls-Royce, Ltd., Britain's quality symbol for fine automobiles and sophisticated jet engines, declared bankruptcy today. The public reacted with conster-nation and politicians called

L-1011 vs. DC-10 Comparison

- Lockheed selected S-duct center inlet: lower drag, less weight but more difficult to design
- Douglas selected straight center inlet: smaller rudder size, engines closer to centerline, thus further forward[2]
- L-1011 had quad. hydraulics, DC-10 triplicate
- L-1011 had Cat IIIC Autoland, DC-10 did not
- DC-10 inlet area large enough for higher mass flow of JT-9D
- L-1011 galley under passenger floor



L-1011



DC-10

Sources:
[1] Francillon, R., “Lockheed Aircraft Since 1913”, Putnam, 1987
[2] Boyne, W., “Beyond the Horizons, The Lockheed Story”, St. Martin’s Press, 1998
[3] Anon, “Innovation with Purpose, Lockheed Martin’s First 100 Years”, Lockheed Martin, 2013
[4] Gray, R., “Rolls-Royce on the Rocks”, Panther, 1971

https://www.simpits.org/joinus/Misc_ClipArt.html

L-1011 vs. DC-10 Comparison

The McDonnell Douglas DC-10 has been involved in 55 accidents and incidents, including 32 hull-loss accidents, and 1,261 fatalities as of 2024-04.

The L-1011 has been involved in five fatal accidents, only one of which was due to a problem with the aircraft.

Lockheed L1011 Tristar

- Designed to AA requirement for LAX-ORD
- Capable of operation from LGA (7000 ft)
- 3 X R-R RB.211
- New production facilities at Palmdale, CA
- First flight Nov 1970
- Production ended in 1985 with 250 aircraft

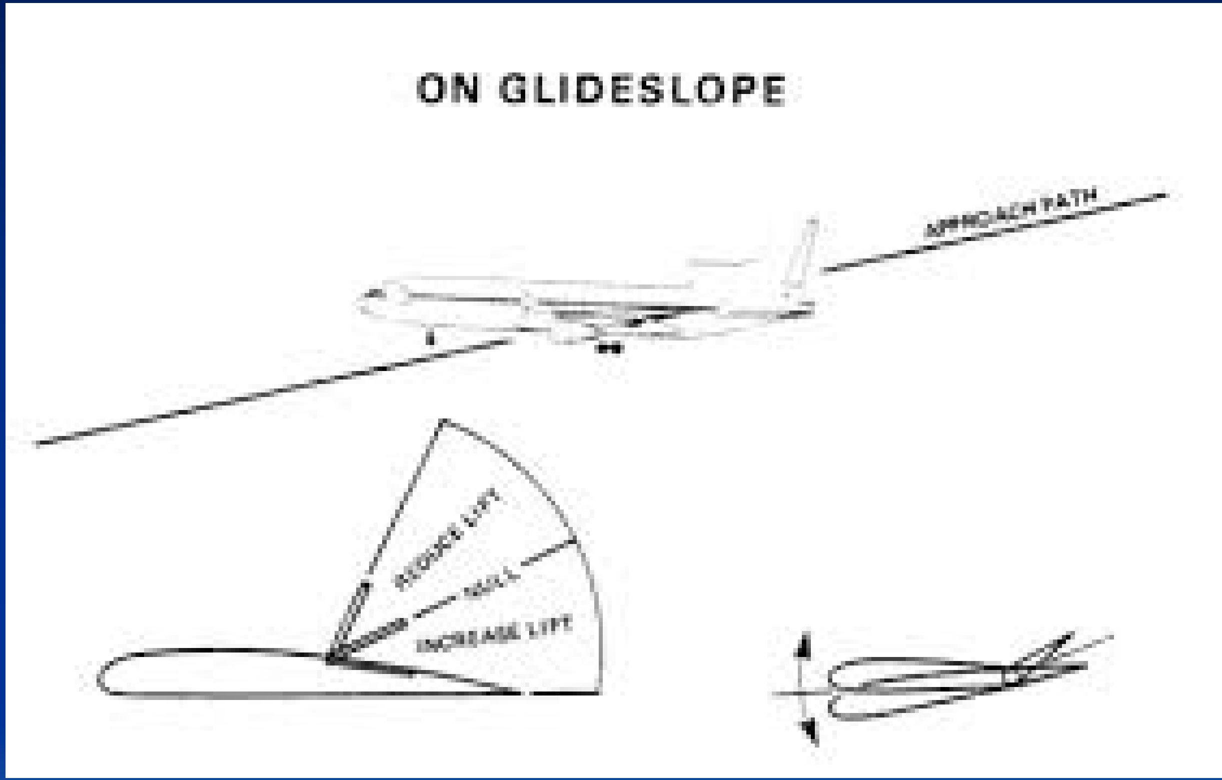
Flight test aircraft at Palmdale

L1011 Direct Lift Control (DLC)

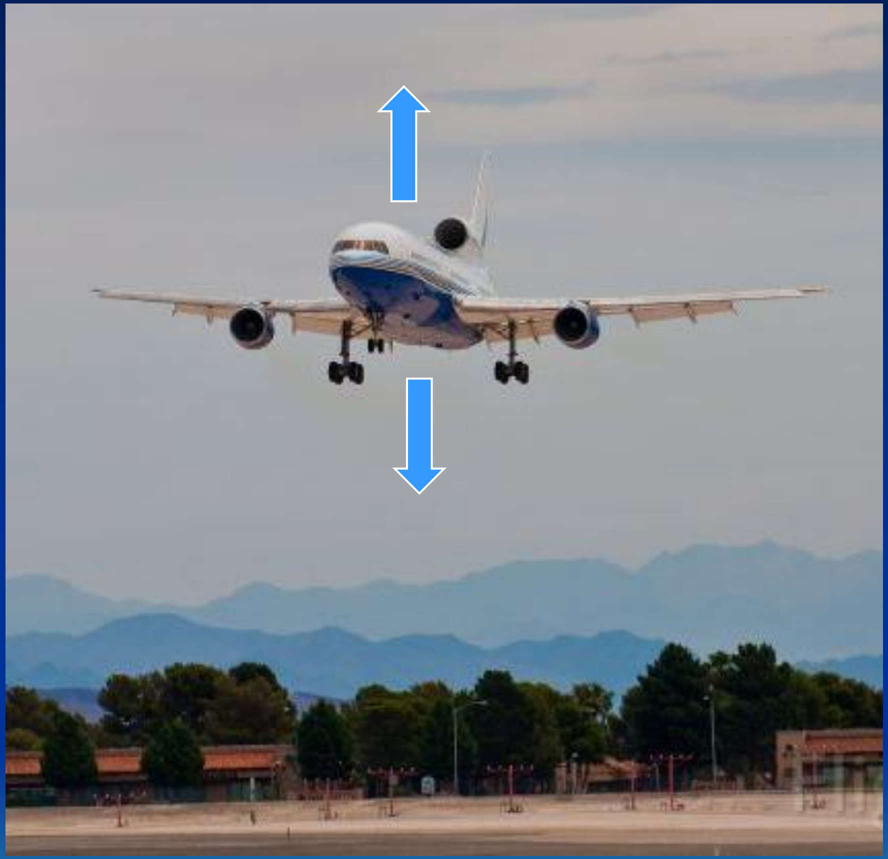
With landing flaps deployed, spoilers linked to control column for direct control of rate of descent

Source: © DIASpotter

L1011 Direct Lift Control



Direct control of rate of descent without changing pitch attitude



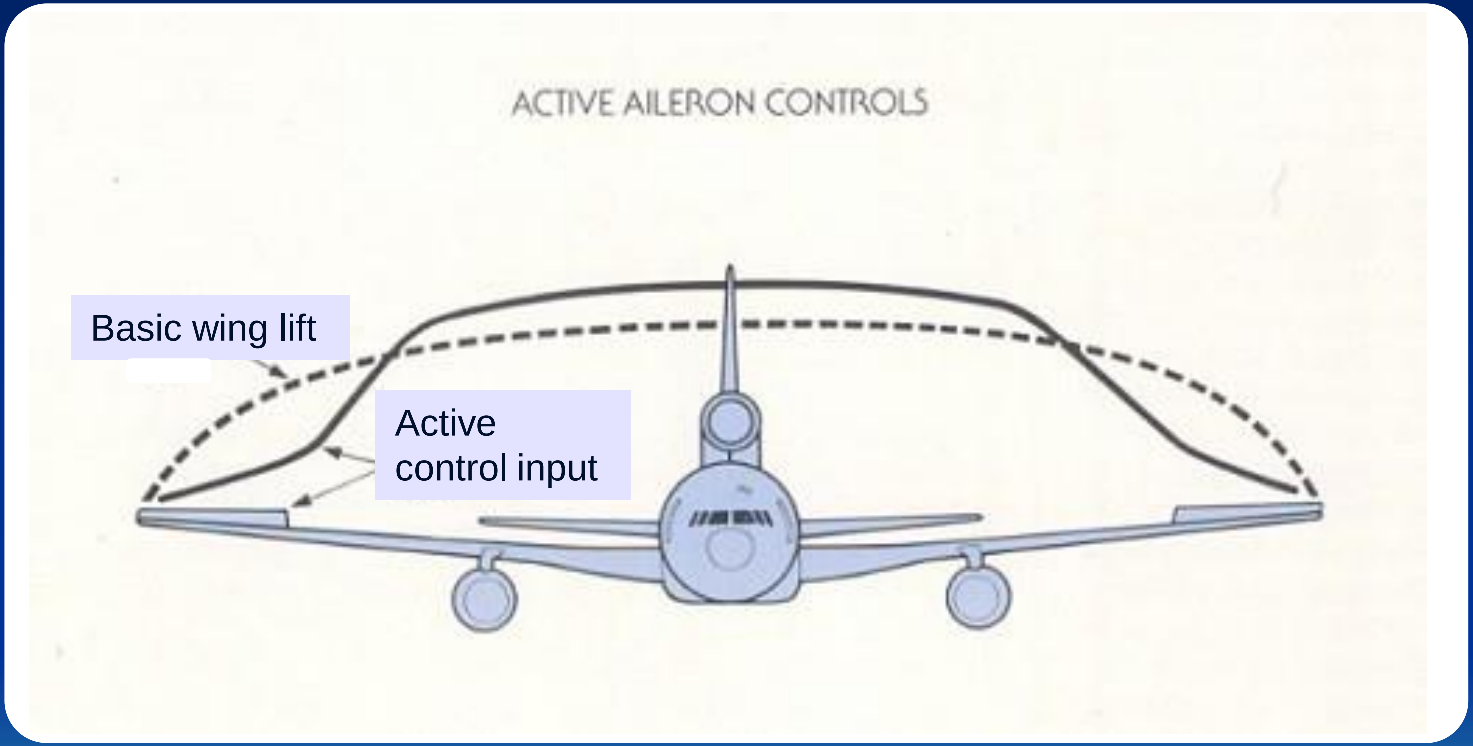
Source: www.flightaware.comr

L-1011 Maneuver Load Control/Gust Alleviation

Deflect ailerons t.e. up to reduce wing root bending moment during maneuver or gust

Overall lift unchanged

e is reduced

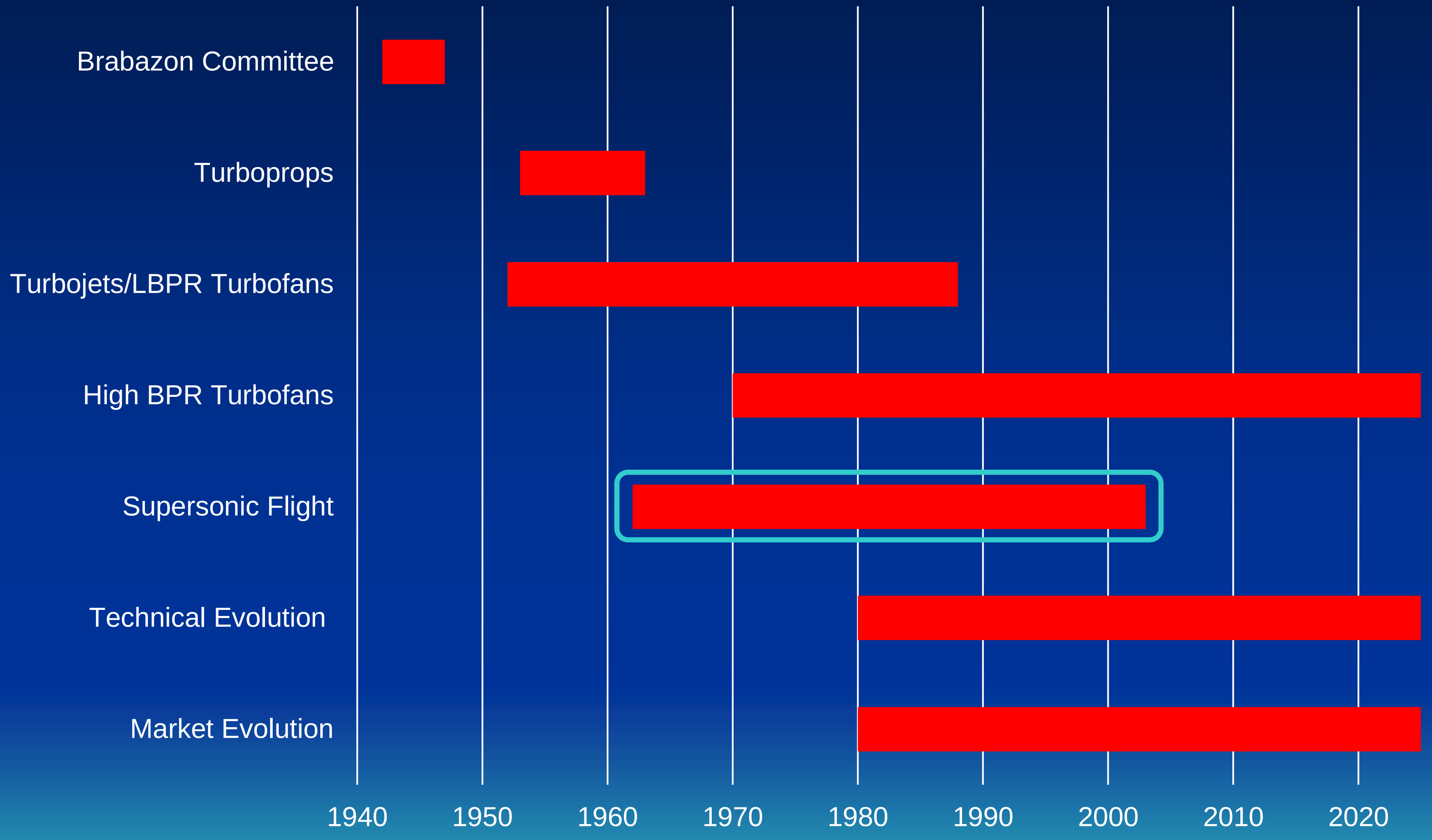


Source: Lockheed

Enables higher wing span (and reduced drag) for same maximum wing root bending moment

- Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
- Advent of high bypass ratio engines
- Supersonic flight
- Technical evolution
- Market evolution

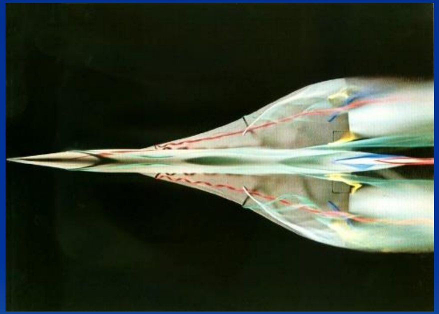
Commercial Aircraft Evolution



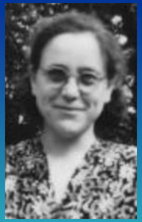
Early Studies in UK

- 1954 - Morien Morgan forms committee at RAE to study feasibility
  - Baseline similar to enlarged Avro 730
- Johanna Weber and Dietrich Küchemann at RAE Farnborough showed benefits of slender delta with ogive leading edge
  - Streamwise vortices produce enhanced lift at high C_L

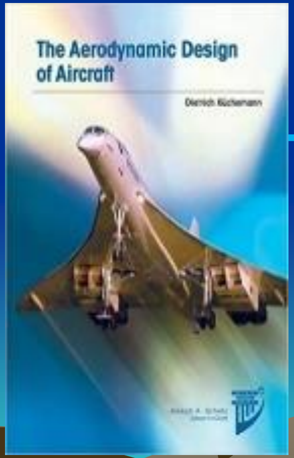
Avro 730 recce/ strategic bomber
Mach 2.5 @ 60,000 ft (1957)



https://www.pprune.org/tech-log/353898-strongest-wing-tip-vortices-when-slow-clean-heavy-but-why-2.html



https://en.wikipedia.org/wiki/Johanna_Weber#/media/File:Johanna_Weber_1948.png



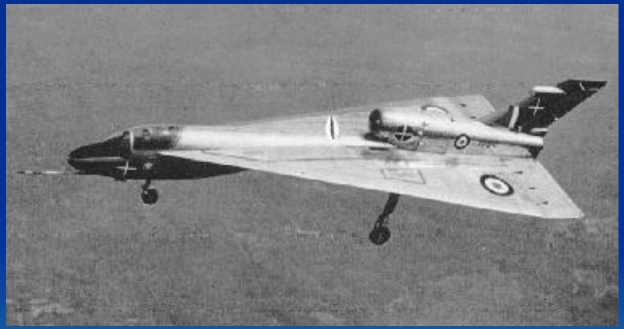
Dietrich Küchemann

Pub.: AIAA Education

Supersonic Technology Advisory Committee

- 1956-10 Supersonic Technology Advisory Committee (STAC) formed
  - Funded development of of Handley Page HP 115
  - Demonstrated safe handling down to 60 kt (111 km/hr)
- Believed economics similar to that of subsonic aircraft through higher utilization (but the Economist claimed profitability was optimistic)
- STAC proposed two SST models
  - Transatlantic range, 150 pax @ Mach 2
  - Shorter range, 100 pax @ Mach 1.2

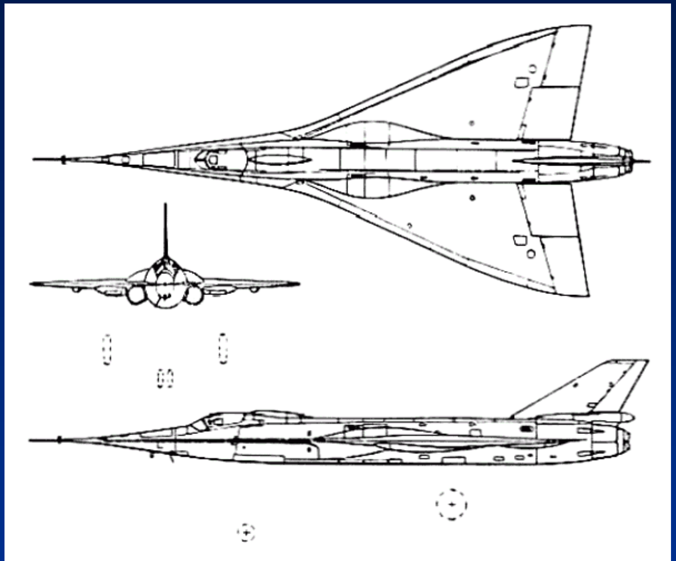
© Alex Christie   https://elpoderdelasgalaxias.wordpress.com/2018/12/12/handley-page-hp-115-low-was-the-new-high/



https://en.wikipedia.org/wiki/Concorde#/media/File:HP.115.gif

British Aircraft Corporation BAC 221

- Wind tunnel studies showed that ogive wing was preferred planform shape
- 1961 BAC converted Fairey FD2 to ogive wing with under-wing inlets
  - 6 ft fuselage extension for increased fuel capacity
  - Flight test up to Mach 1.6
- Flight testing from 1964 to 1971



https://hushkit.files.wordpress.com/2014/05/bac-221.gif

https://www.airliners.net/photo/British-Aircraft-Corporation/BAC-221/1019528

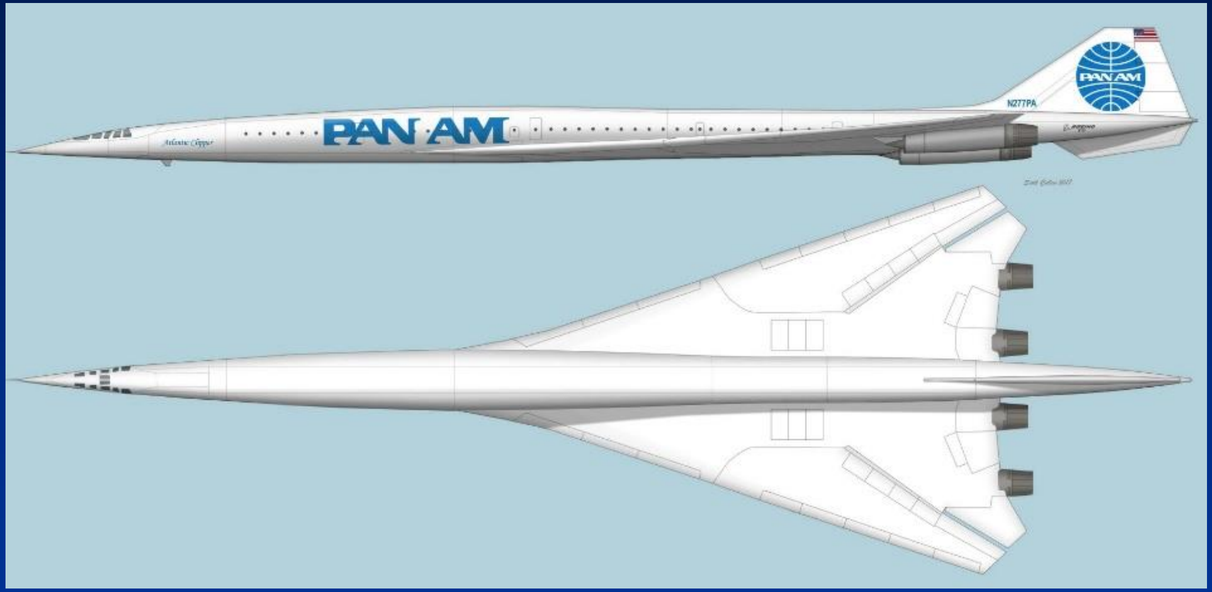
Anglo-French Teaming

- Sud Aviation performed similar studies that produced similar results as to optimum configuration
- Initial development cost estimate was £150 million
- UK cabinet not enthused, but believed that joint Anglo-French program would improve chances of overcoming President Charles de Gaulle's veto of UK entry to Common Market
- 1962-10 two countries signed treaty with heavy cancellation penalties

http://news.bbc.co.uk/2/hi/uk_news/2934257.stm

- Meanwhile, in the U.S.

SST Proposals to FAA



Boeing 2707

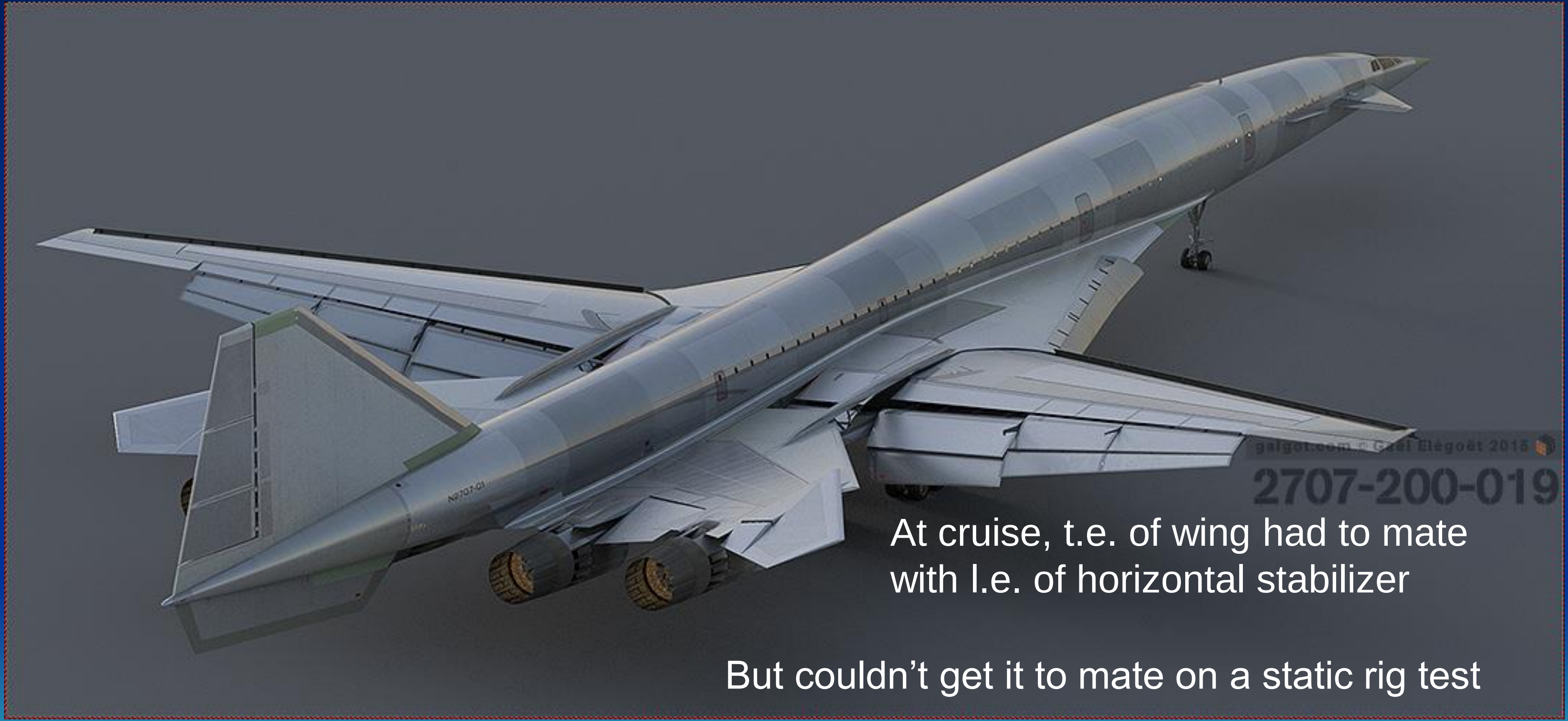
Lockheed L-2000

- 1963-08 FAA issues RFP for SST with M_{cruise} 2.7
- 1966-08 Boeing, Lockheed submit proposals

Existence of Lockheed YF-12A announced by President Johnson in 1964-02-29

Boeing 2707-200

1967-01-01 FAA selects Boeing design



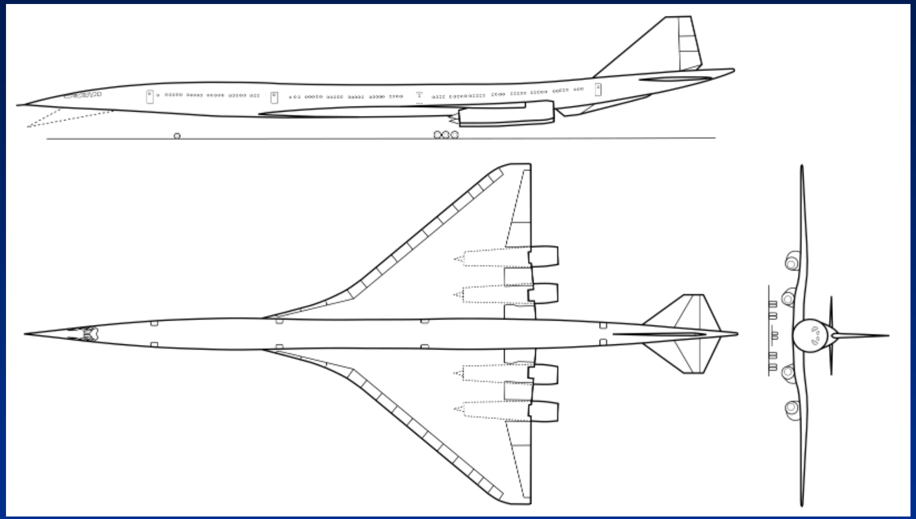
At cruise, t.e. of wing had to mate with l.e. of horizontal stabilizer

But couldn't get it to mate on a static rig test

www.airsoc.com

Boeing 2707-300

http://fantastic-plastic.com/Boeing2707-300.htm



By Nubifer - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=19969846

1969-07 Sonic boom, NO_x concerns raised
1969-10 Change design to delta wing with tail
GE-4 engine now too small for takeoff
FAA requested Lockheed provide L-2000 data

But engine development takes longer than airframe development

1971-01 U.S. Senate cancels funding
1971-05 U.S. House cancels funding
Boeing lays off 7,000 workers*
GE lays off 6,000 workers*

Boeing had 115 orders from 25 airlines

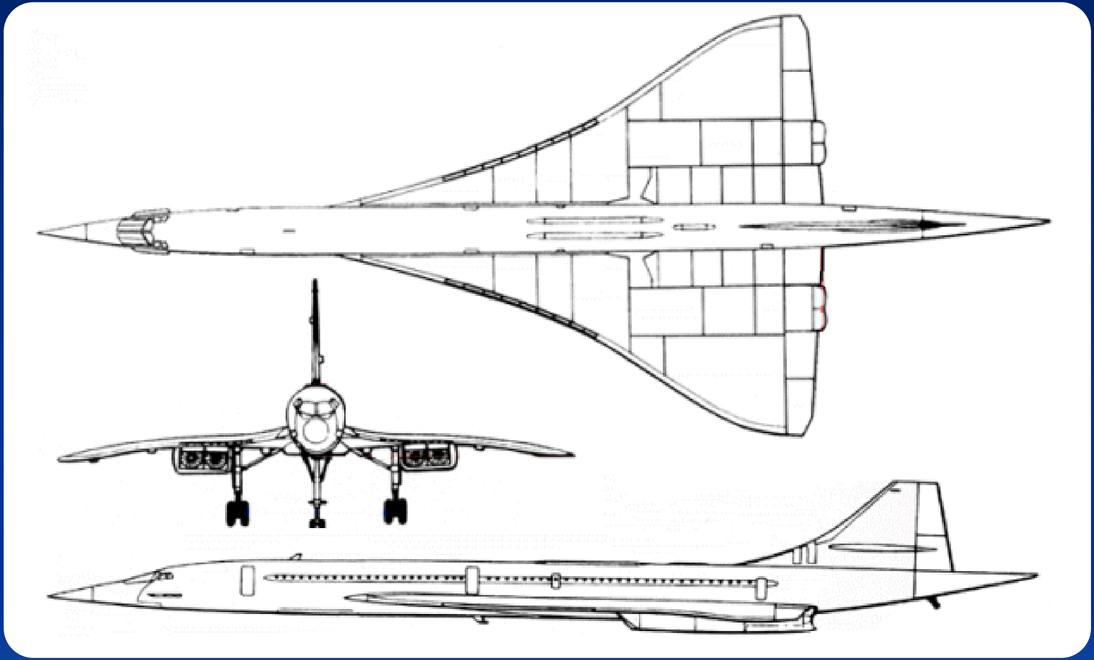
* Roughly the same time as 747, L-1011, DC-10, C-5 and Apollo became operational

- Back in the U.K.

Concorde Specifications

Why no area ruling? Supersonic area rule not the same as transonic area rule

- MTOGW: 185,065 kg (408,000 lb)
- EW: 78,700 kg (173,500 lb)
- Max P/L: 13,380 kg (29,500 lb)
- Length: 62.1 m (203.75 ft)
- Range (max fuel): 6,580 km (3,560 nmi)
- Range (max P/L): 6,230 km (3,365 nmi)
- M_{max}: 2.23
- M_{cruise}: 2.04 @ 51,300 ft
- Powerplant: 4 x RR/SNECMA Olympus 593 Mk 602 engines



http://www.aerospaceweb.org/aircraft/jetliner/concorde/

Bristol Siddeley Olympus Mk 593

- Olympus originally developed for Avro Vulcan and Handley Page Victor (but not installed on Victor)
- For Olympus 593
  - OPR: 15.5:1
  - Design thrust: 142 kN (32,000 lb) dry, 169 kN (38,050 lb) with A/B (production engine)
  - Twin spool axial compressor
    - 7 stage LP - 1 stage turbine
    - 7 stage HP - 1 stage turbine
  - Cannular combustion chamber (16 vaporizers)
  - Sfc: 33.8 g/kN-s (1.2 lb/lb/sec)

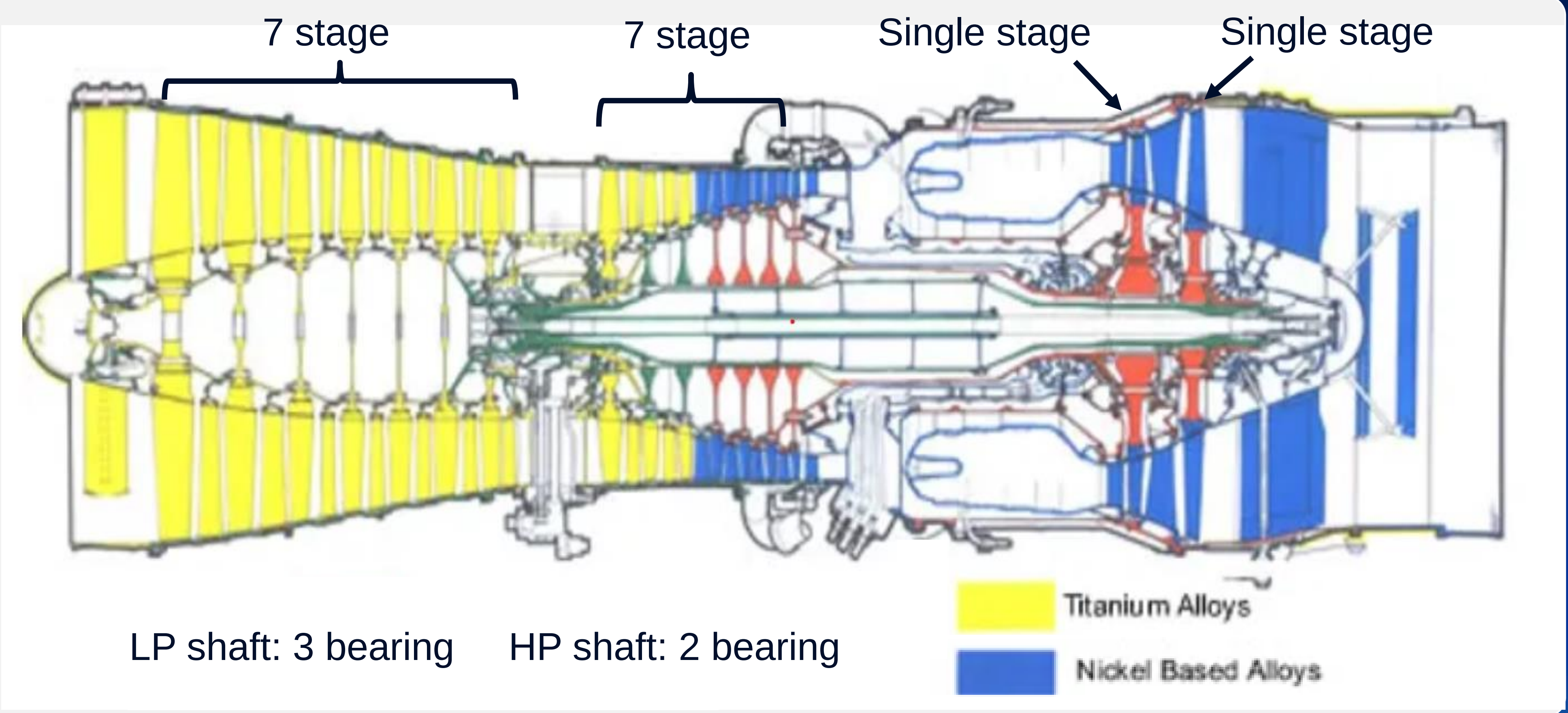
Vulcan flying test bed (FTB) with spray rig for icing test, and testing subsonic envelope

https://avrovulcan.com/vulcan/engine-test-beds

Bristol Siddeley Olympus 593

https://www.gracesguide.co.uk/Rolls-Royce_Engines:_Olympus

Bristol Siddeley Olympus 593 Mk 610



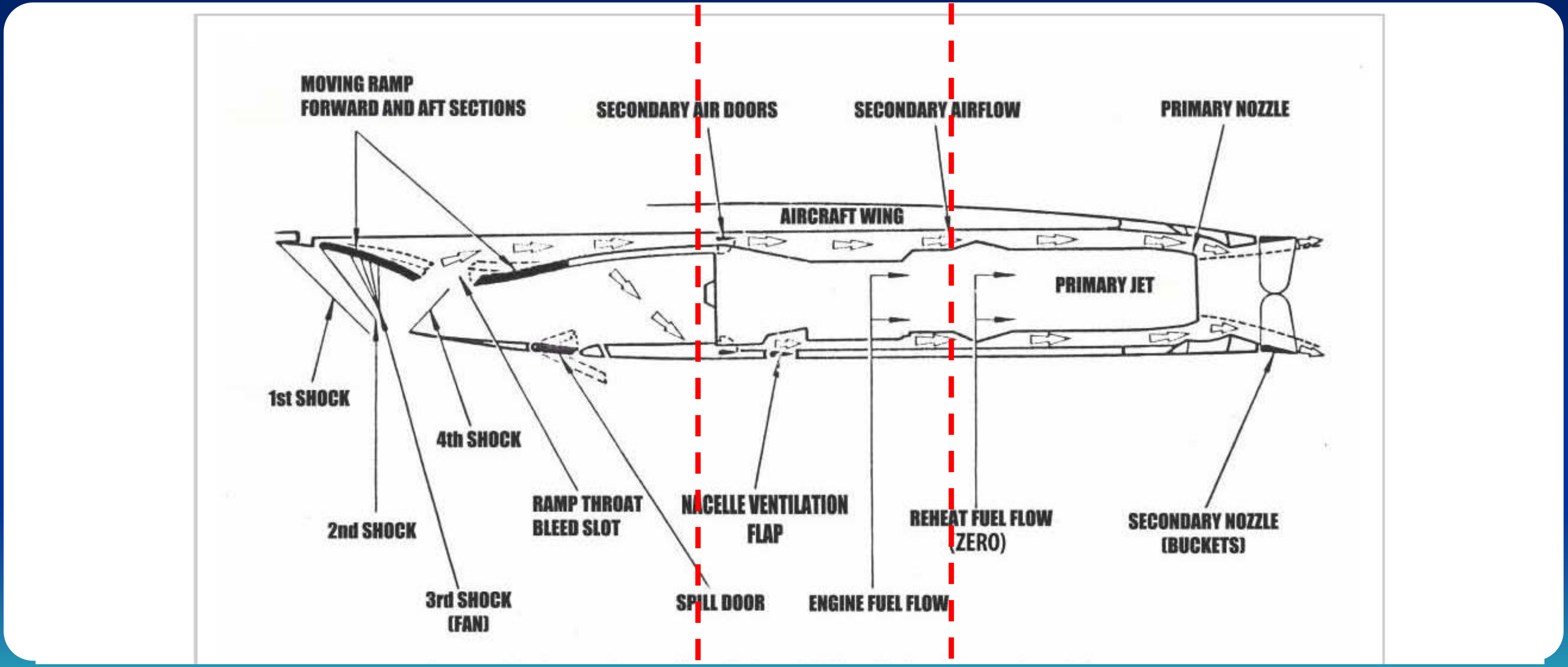
Source: https://www.heritageconcorde.com/concorde-olympus-593-mk610-engines

Concorde Nacelle

British Aircraft Corporation (BAC)

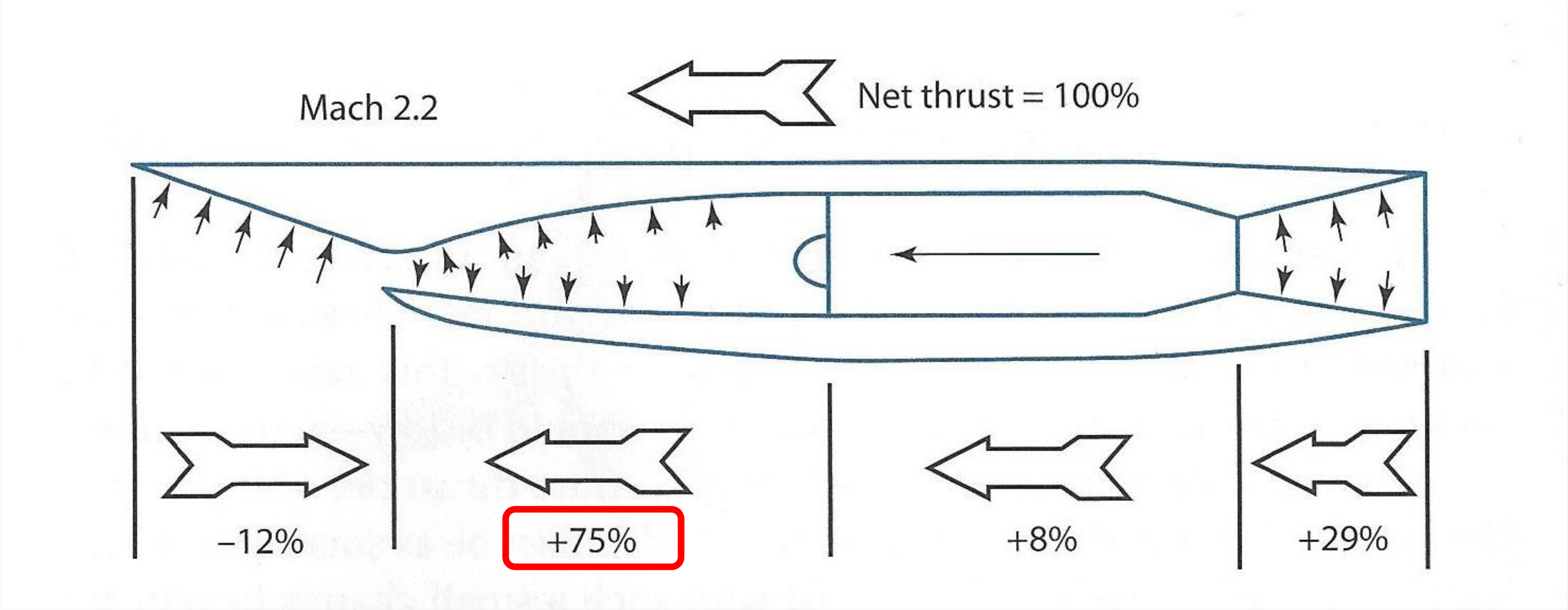
Bristol Siddeley (now Rolls-Royce)

Société Nationale d'Études et de Construction de Moteurs d'Aviation (SNECMA)



Source: Leeham News

Nacelle Thrust – Drag Accounting



North American A-5 with GE J79 turbojets

Source: Raymer

- The inlet pushes the airplane along
- The engine reduces the pressure at the aft end of the inlet

Operational History

- 1976-01-21 enters service London-Bahrain and Paris-Rio de Janeiro (via Dakar)

24 years

- 2000-07-25 AF 4590 suffered catastrophic fire resulting in crash. Loss of 100 pax, 9 crew
- 2003-04-10 BA, AF announce forthcoming retirement
- 2003-10-24 Last commercial flight (by BA)
- BA and AF each had 7 aircraft, but some were kept in storage and not flown

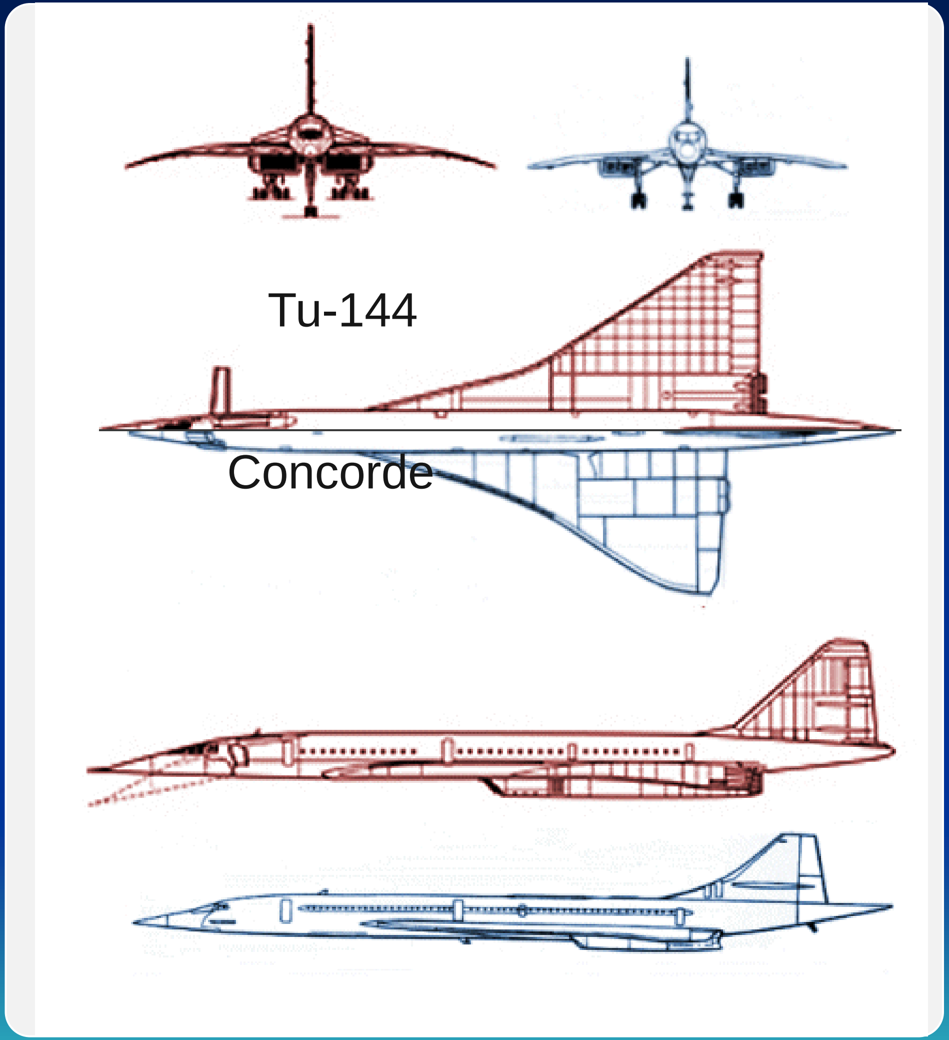
https://commons.wikimedia.org/w/index.php?curid=5810282

https://worldwarwings.com/crash-concorde-sky-flames/

Concorde Handicaps

- Development cost 6X original estimate
- Flown supersonically only over water
- 1973 oil shortage deterred buyers
- 15.8 pax miles/gal, compared with B707 33.3 mpg, B747 46.4 mpg, DC-10 53.6 mpg
- Banned from operation at some airport because of perceived noise
- In July 2000, AF Concorde crashed at CDG due to fuel leak/engine fire
- Withdrawn from service 2003

Tupolev Tu-144

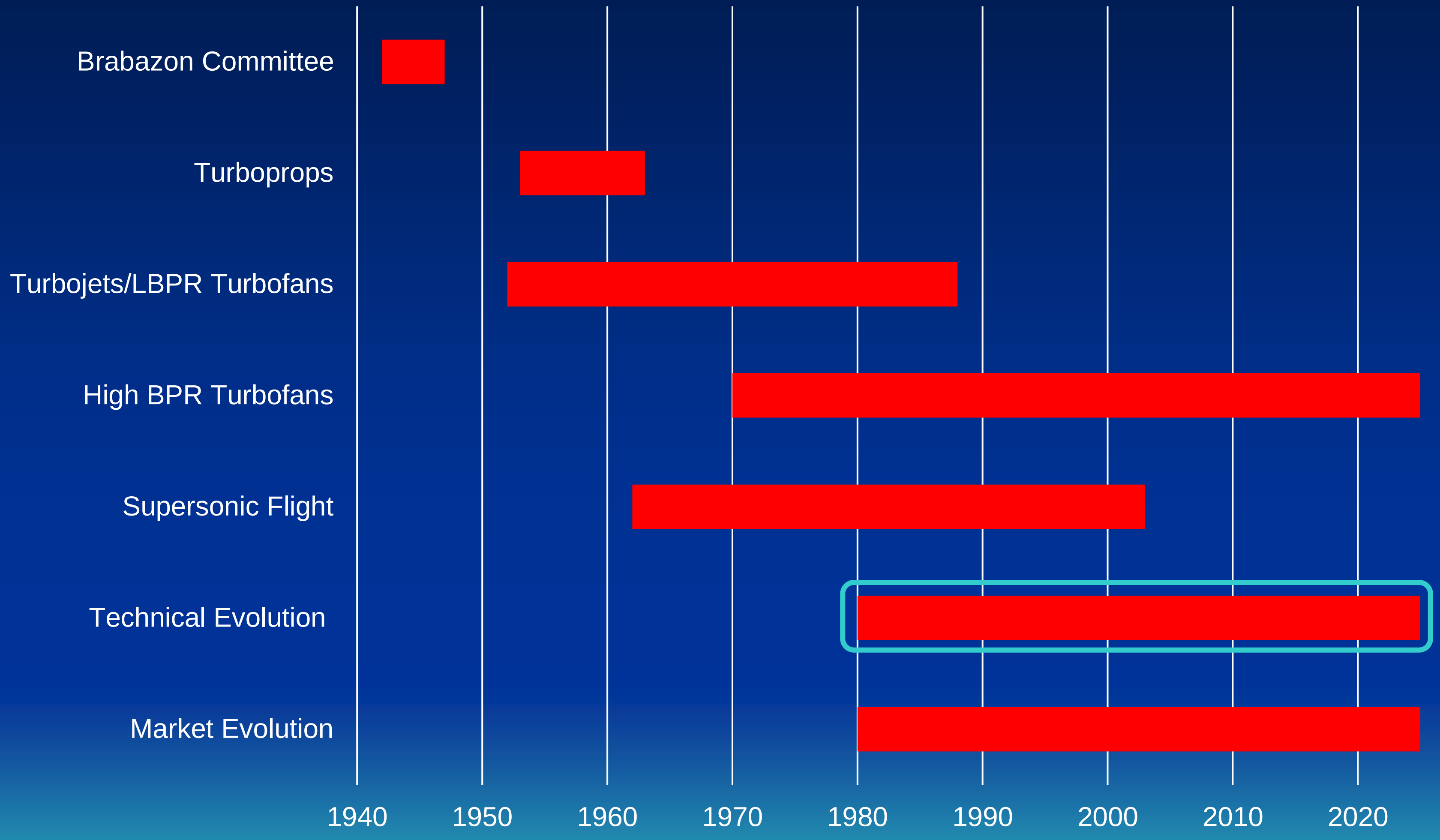


https://en.wikipedia.org/wiki/Tupolev_Tu-144

- 1968-12-31 First flight
- 1973 Crash at Paris Airshow
- 1977-11-01 Entry into service
- 1978-04 Crash on test flight during delivery
  - Retired from pax service
- 1999 Retired from service
- Number built 16

globalsecurity.org

Commercial Aircraft Evolution

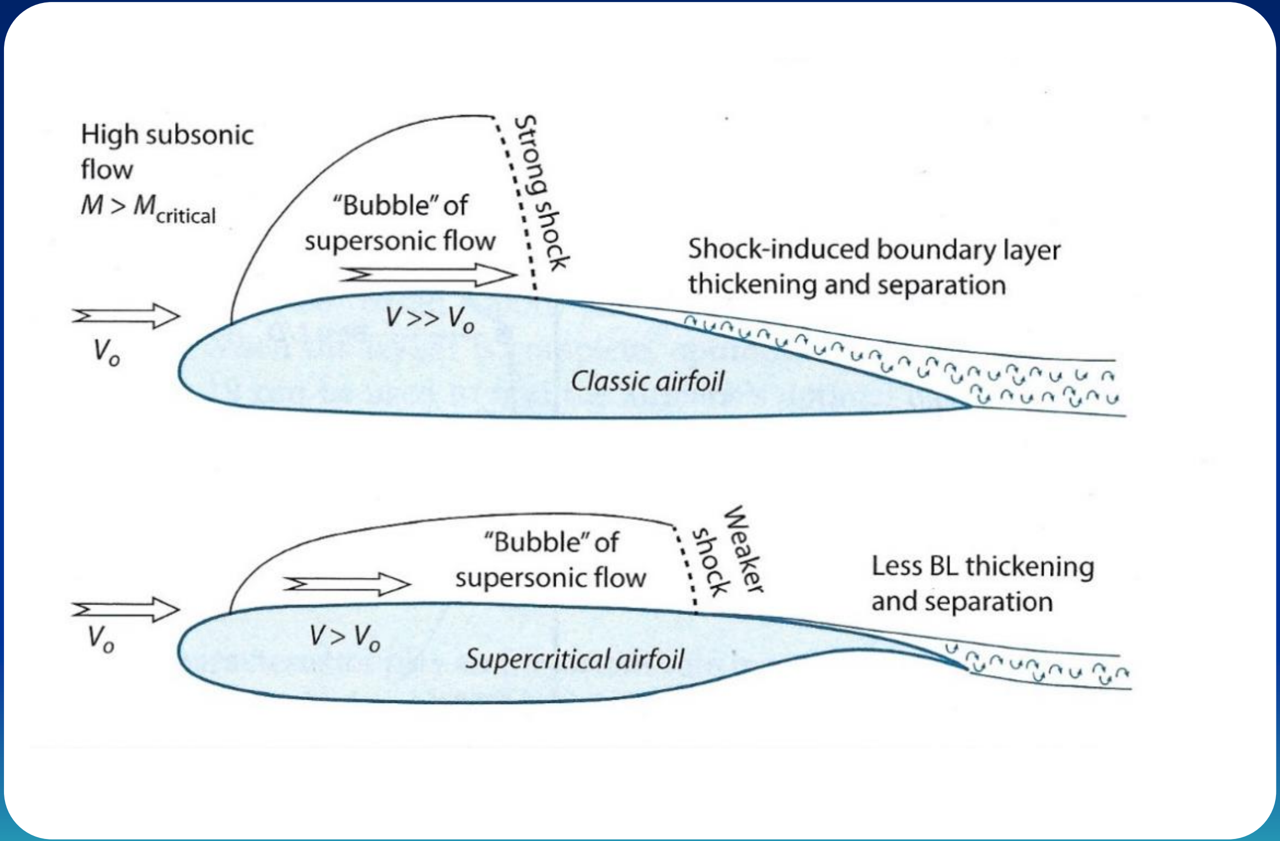


Technical Evolution

- Supercritical airfoil
- Fly-by-wire
- Glass cockpit
- Composite airframe structure
- Geared turbofan

Conventional and Supercritical Airfoils

- Proposed in Germany in early 1940s
  - Developed at Hawker Siddeley Hatfield in 1959-65, and by Richard Whitcomb in US in 1960s
- Supercritical airfoil reduces shock strength on upper surface
- Produces more uniform chordwise lift distribution



Raymer Fig. 4.8

Vickers VC10 (U.K.)

- M_{CR} = 0.866
- M_{MO} = 0.886
- M_{NE} = 0.94

https://www.pprune.org/tech-log/9304-vc10-mach-94-a.html

Source: wikimedia

Technical Evolution

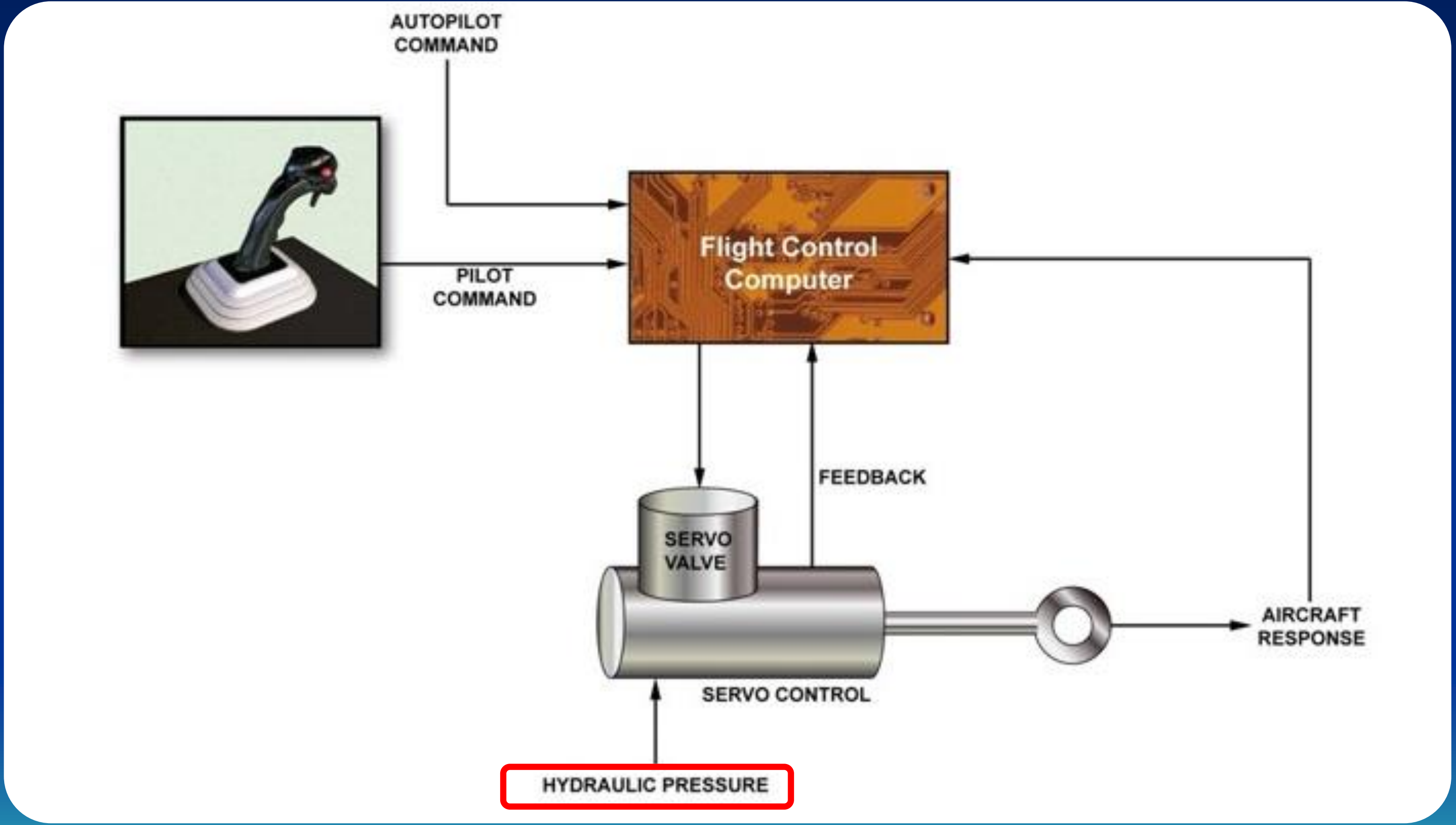
- Supercritical airfoil
- Fly-by-wire
- Glass cockpit
- Composite airframe structure
- Geared turbofan

Fly-by-wire

- Concorde: analog fly-by-wire with mechanical backup
- A320: digital fly-by-wire with mechanical backup (first flight 1987-02-22)
- Boeing 777 followed (first flight 1994-06-12)

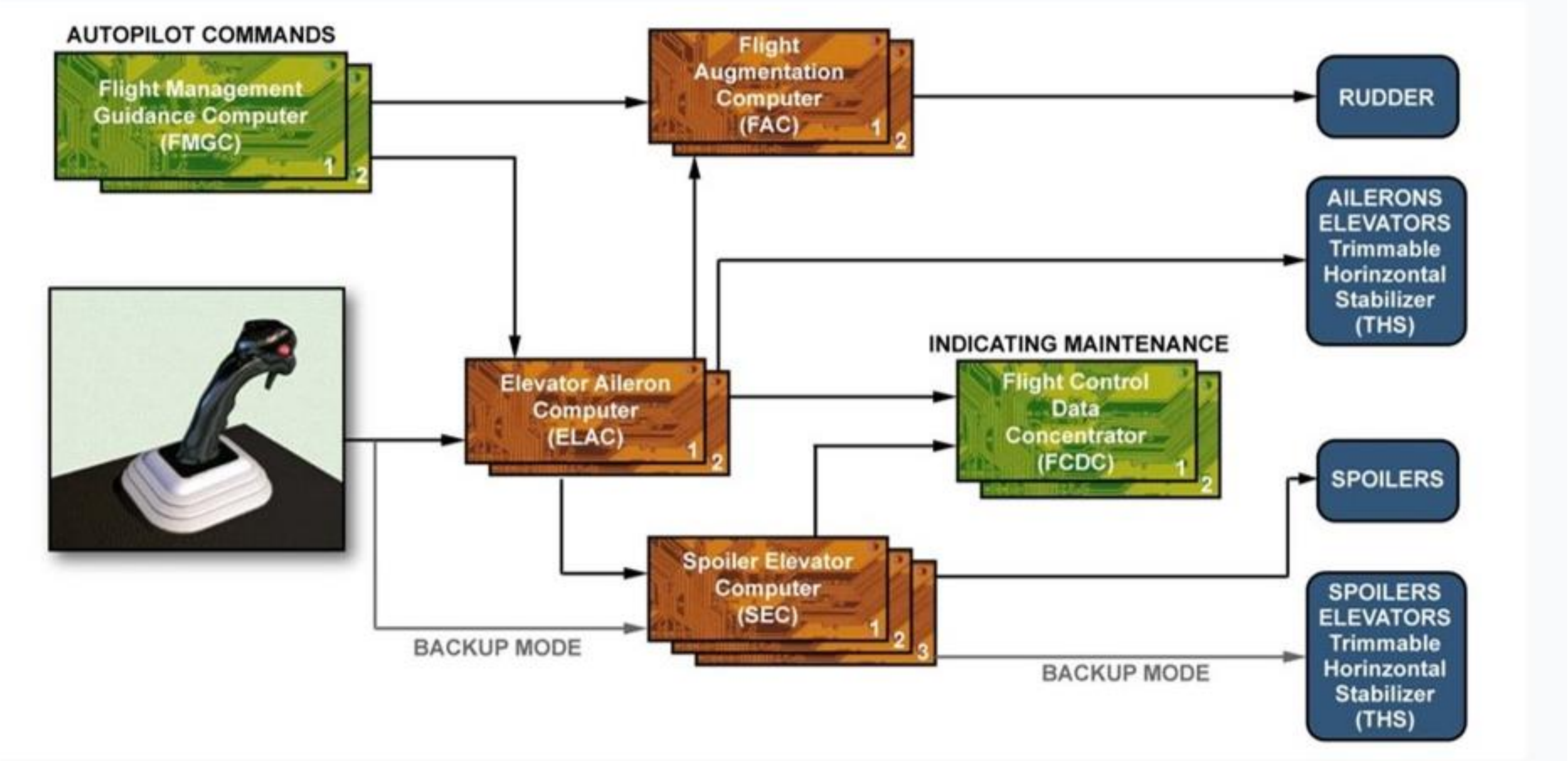
Fly-By-Wire Concept

- Control cables replaced by wired connections controlling (usually via flight control computers) hydraulic actuators



https://aviationnuggets.com/blog/41/a320-enhanced-electric-rudder

Fly-By-Wire Concept



https://aviationnuggets.com/blog/41/a320-enhanced-electric-rudder

Technical Evolution

- Supercritical airfoil
- Fly-by-wire
- Glass cockpit
- Composite airframe structure
- Geared turbofan

Concorde Flight Deck

- View from flight engineer's seat
- All displays and input devices (knobs, buttons, switches) must be available simultaneously

A320 Cockpit

- A320 was first commercial aircraft with glass cockpit and fly-by-wire (entry into service 1998-04-08)
- Replaced analog displays with CRT (early configuration) or LCD
- Pilots have some control over what is displayed on each screen

https://medium.com/@ciaranoshea66/how-to-land-an-airbus-a320-c202fcb60b74

B.787 Flight Deck

- Alaska Airlines used HUD on 737 for Cat III operations (can allow for operations in low visibility conditions)

- Boeing 787 was first commercial aircraft with HUD as standard equipment

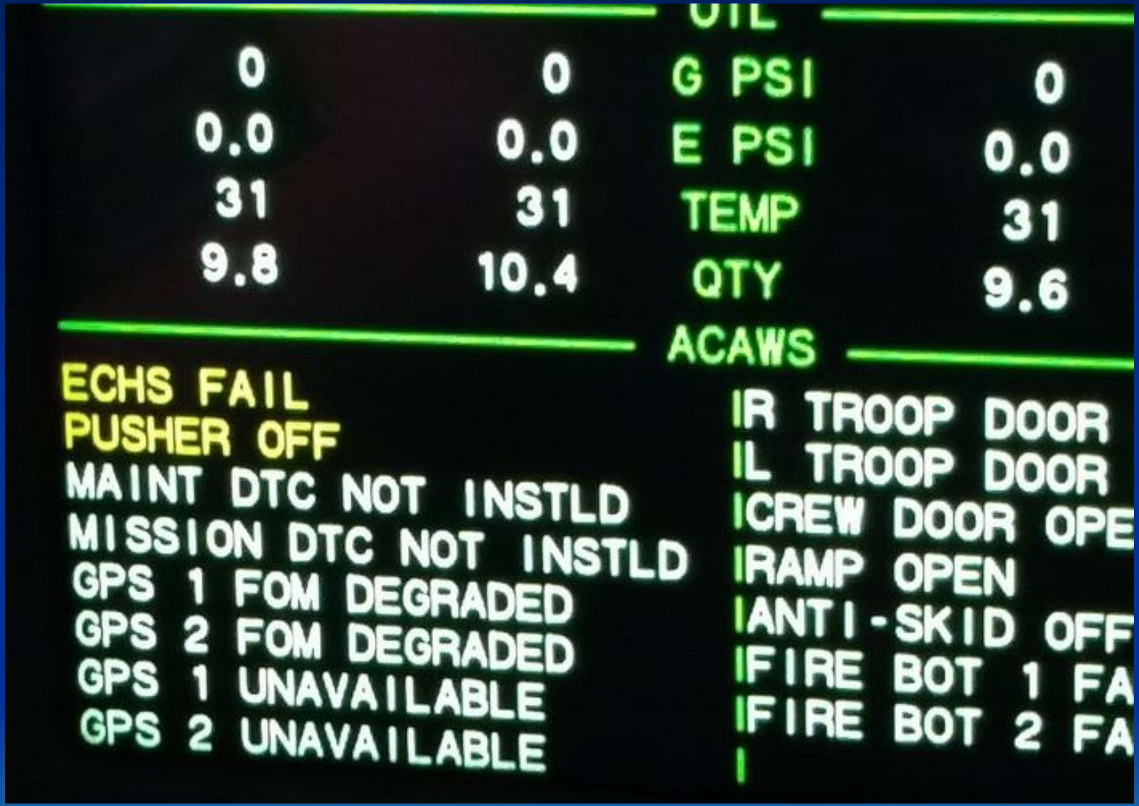
- Also available on A330, and will be available on A320, A340

HUD

https://www.reddit.com/r/aviation/comments/147efco/787_flight_deck/

C-130 ACAWS

- Advisory, Caution, And Warning System
- Display shows pilots what has failed, and often the procedure required to correct it



White text= Advisory
Yellow text = Caution
Red text = Warning

Technical Evolution

- Supercritical Airfoil
- Fly by wire
- Glass cockpit
- Composite airframe structure
- Geared turbofan

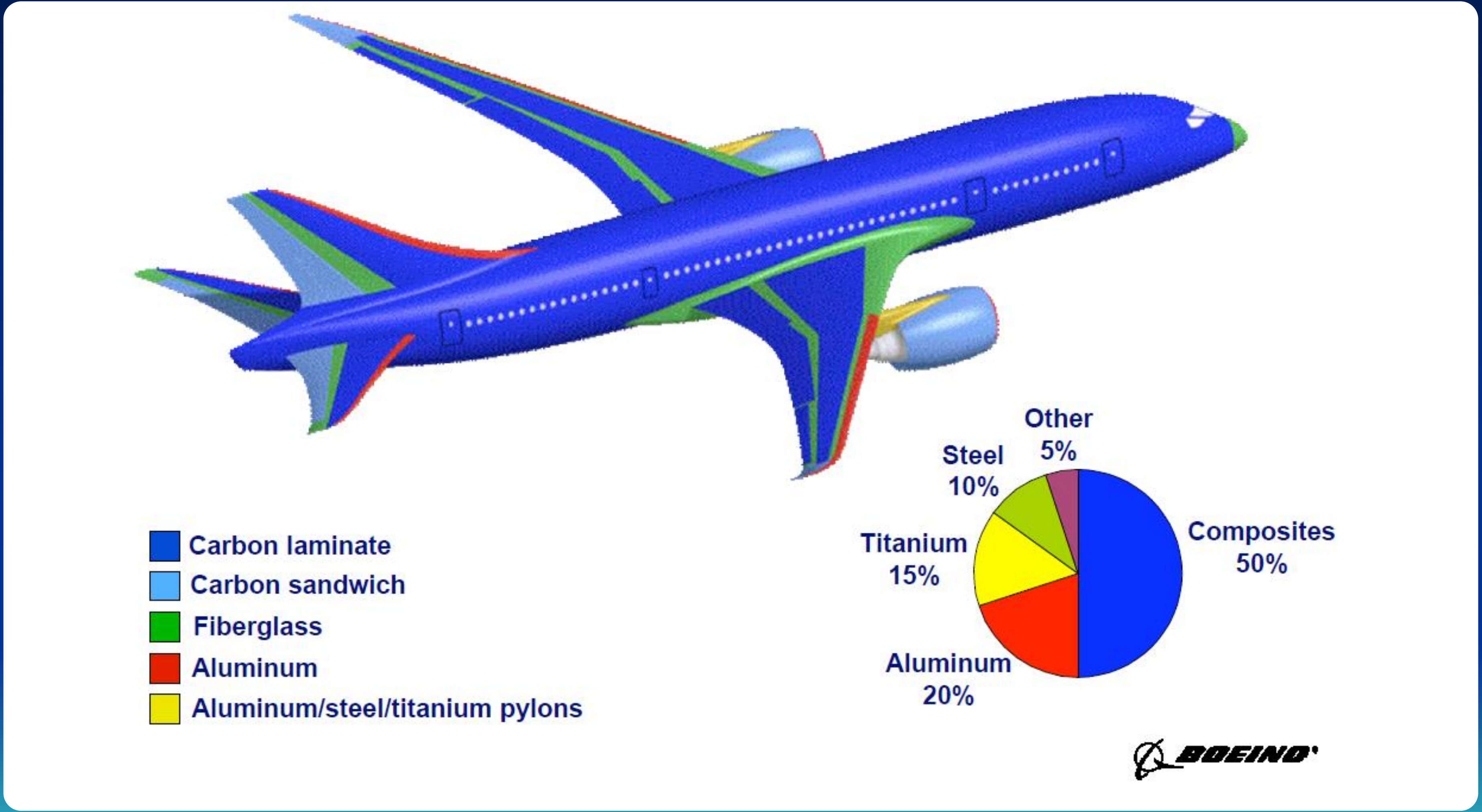
Boeing 787

https://samchui.com/2018/10/02/united-orders-more-boeing-787-9-dreamliners/#.XZn6l0YzaGI

Specs. for 787-9

- First flight: 2009-12-15
- MTOGW: 254,011 kg (560,000 lb)
- Pax: typ. 290, max. 406
- Range: 14,140 km (7,635 nmi)

787 Materials



Airbus A350

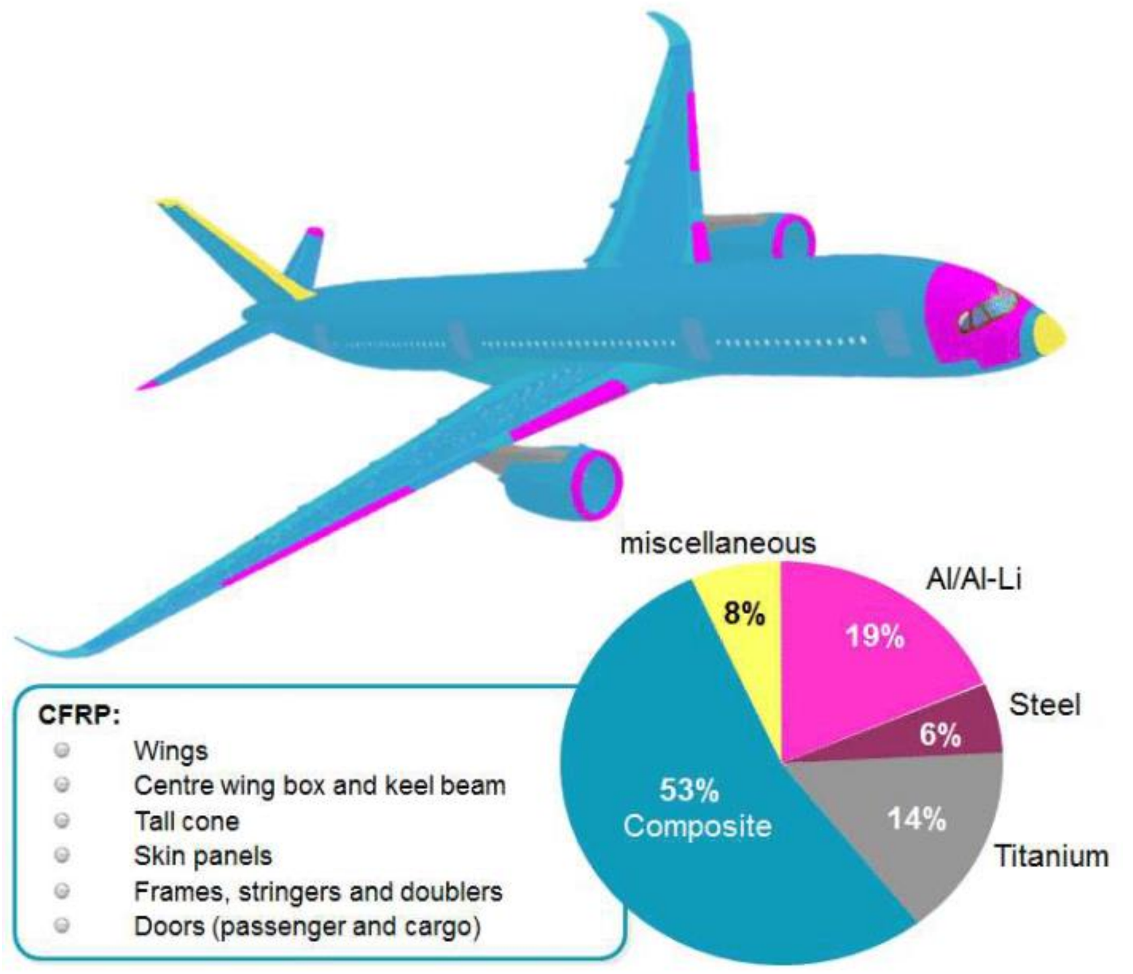
Specs. for A350-1000 (stretched version)

- First flight: 2016-11-24
- MTOGW: 322,000 kg (710,000 lb)

- Pax: 350-480
- Range: 16,500 km (8,900 nmi)

Airbus A350

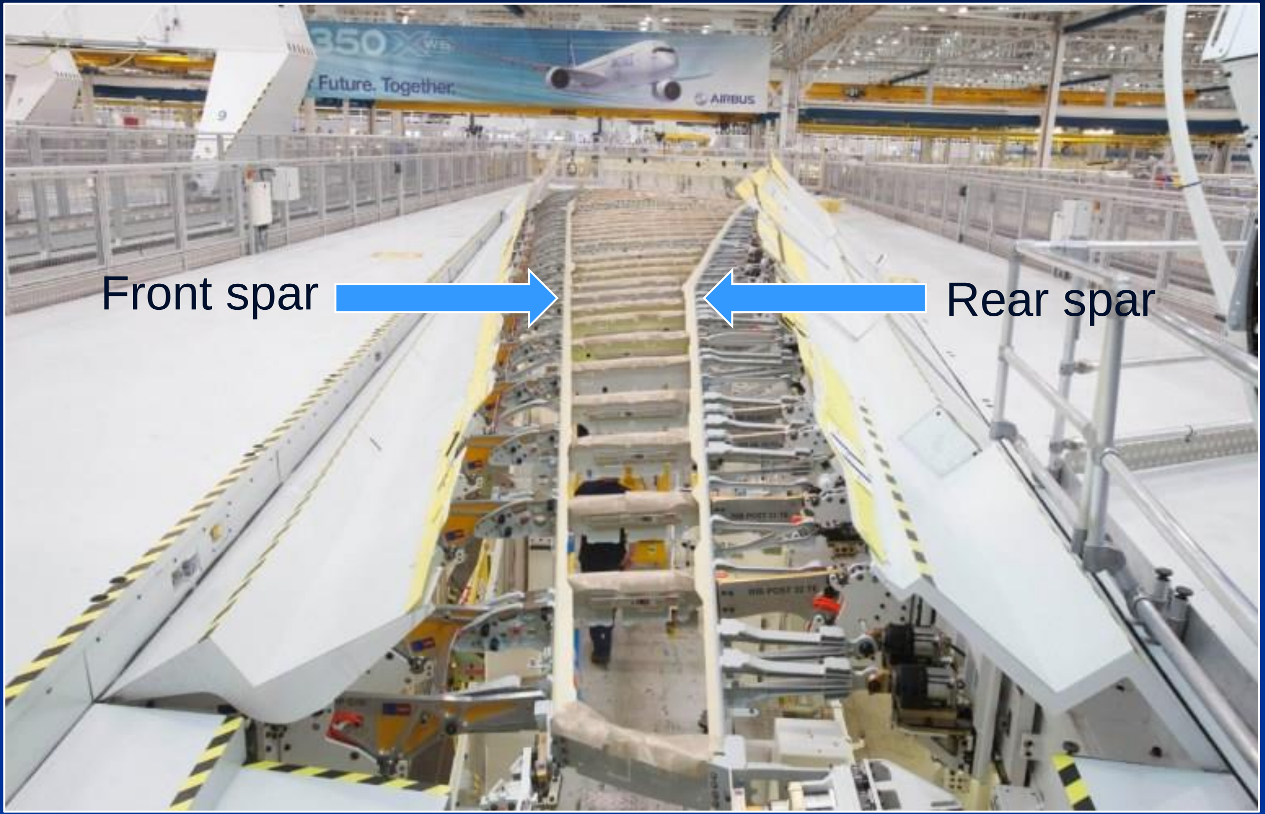
CFRP:
Carbon Fiber Reinforced Plastic



Materials used in a modern aircraft, the Airbus A350 XWB [5]

https://www.researchgate.net/figure/Materials-used-in-a-modern-aircraft-the-Airbus-A350-XWB-5_fig6_318923824

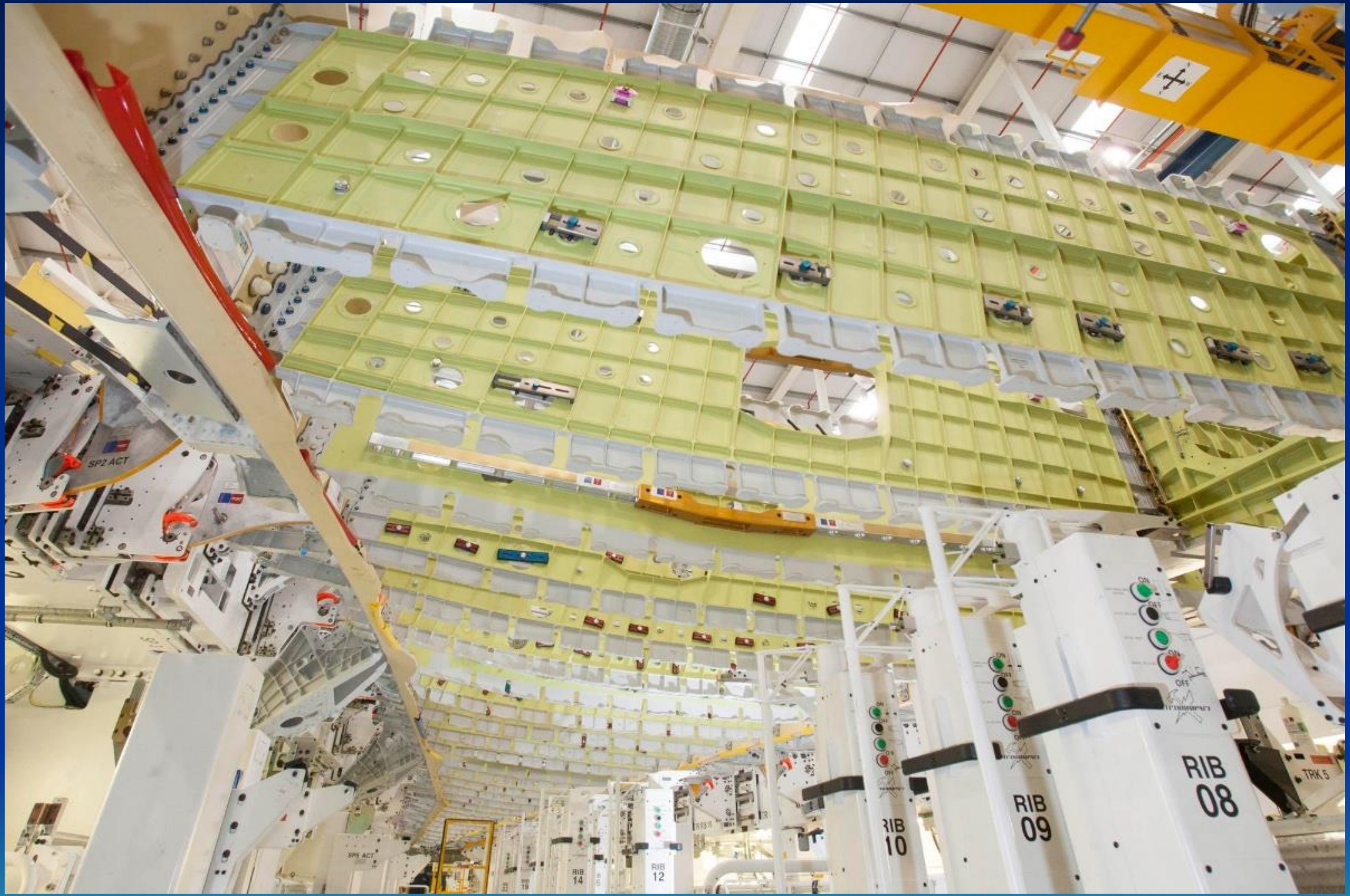
Airbus A350-100 Composite Wing



https://www.compositestoday.com/2015/08/work-starts-at-airbus-on-the-largest-carbon-fibre-wings-in-civil-aviation/

Designed at Airbus facility in Filton, Bristol
Manufactured in Broughton, North Wales

Airbus A350-100 Composite Wing Ribs



https://www.compositestoday.com/wp-content/uploads/2015/08/Airbus-wings-3.jpg

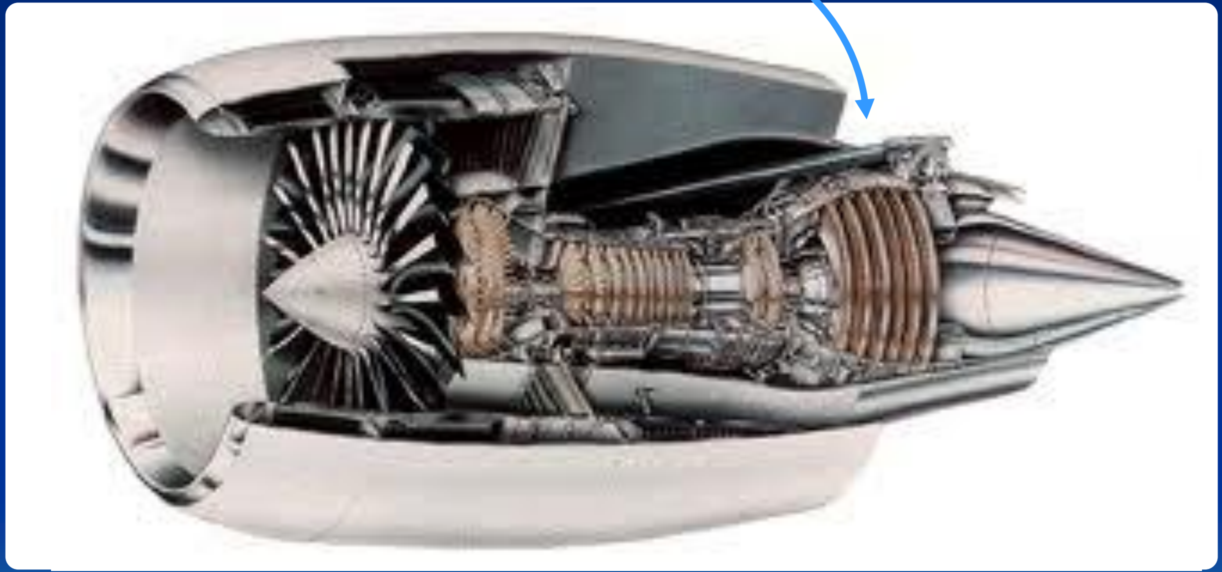
Technical Evolution

- Supercritical Airfoil
- Fly by wire
- Glass cockpit
- Composite airframe structure
- Geared turbofan

High Bypass Ratio Turbofan

- GE90
  - Twin spool
  - Composite fan blades
  - Thrust from 74,000 lb to 115,000 lb
  - BPR = 9, OPR = 40
  - IOC 1995
  - T/W = 5.6
  - Installed on B777

- LP turbine rpm limited by fan tip speed
- Turbine rotor must be large (and heavy) to optimize turbine efficiency

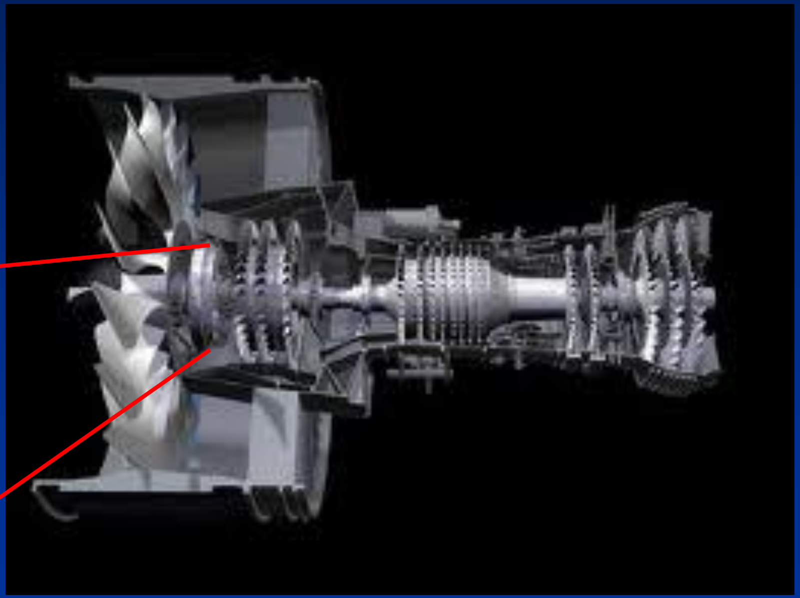


LP turbine connected directly to LP compressor and fan

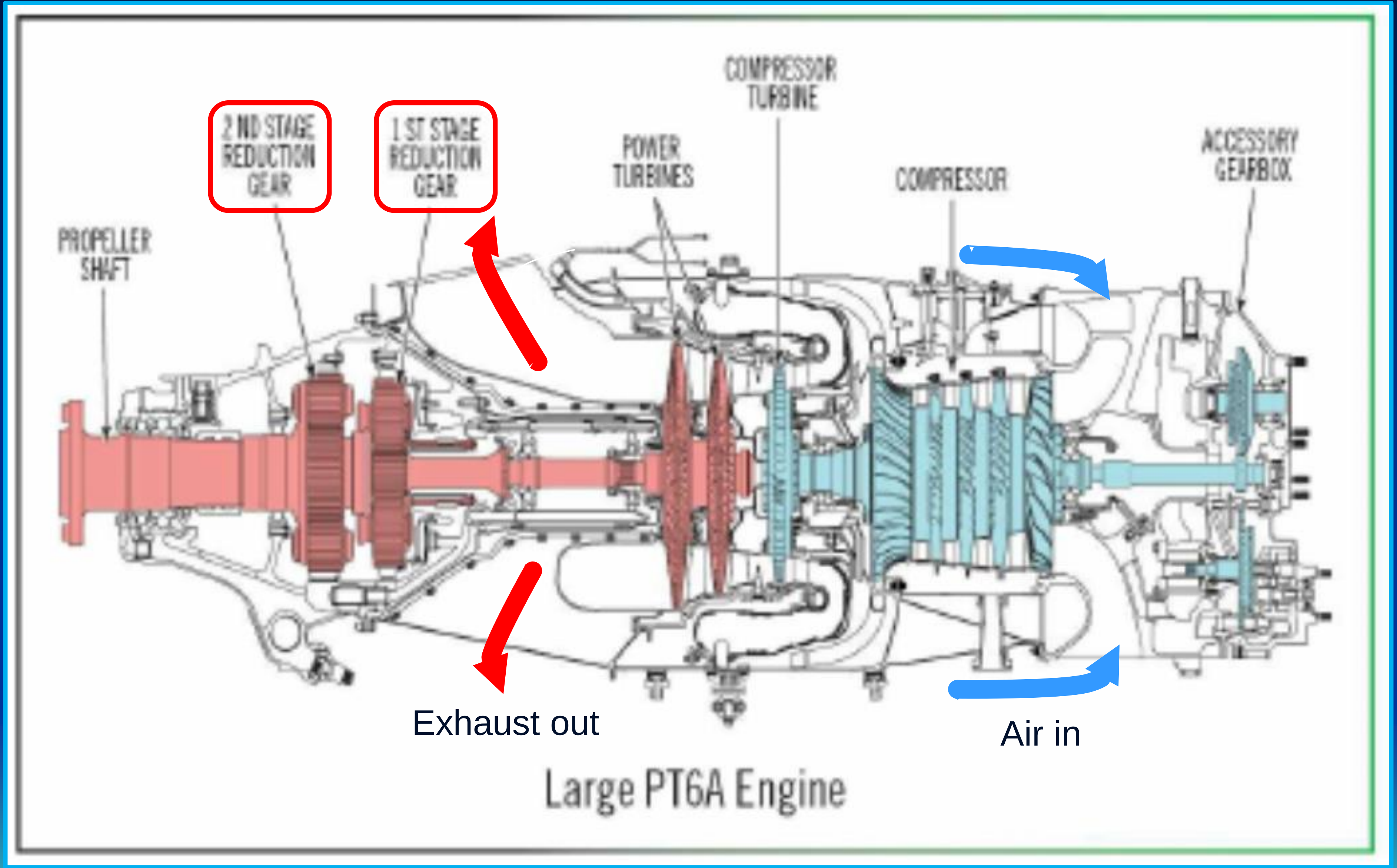
Geared turbofan

- PW-1000 series
  - Planetary gearbox is compact and light (similar to PT6 reduction gearbox)
  - First test run in 2007
  - Certified in 2013

Planetary carrier not shown



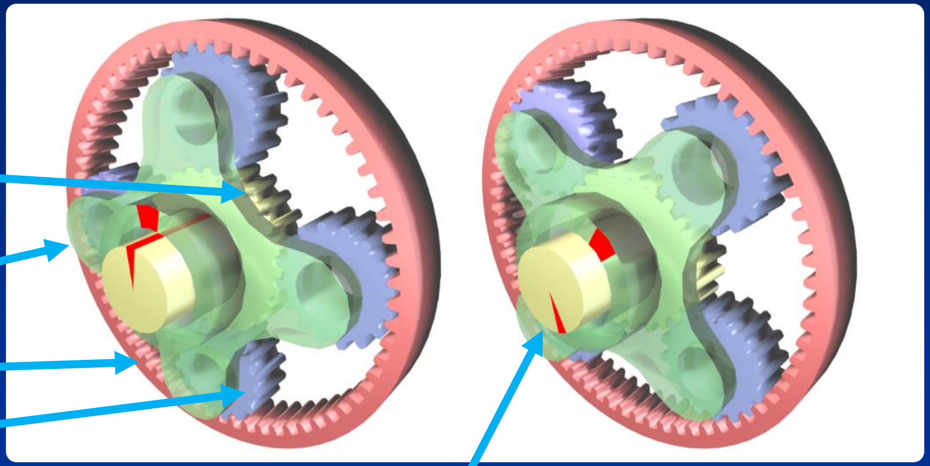
Powers: Airbus A220, A320neo, Embraer E-Jet E2, Yakovlev MC-21



64,000 PT6s sold, with one billion accumulated flying hours since 1963

Planetary Gearbox

- Gear reduction
  - Turbine shaft power input at sun gear (yellow)
  - Fan attached to the planetary carrier (green)
  - Ring gear fixed (pink)
  - Planetary gears (blue)

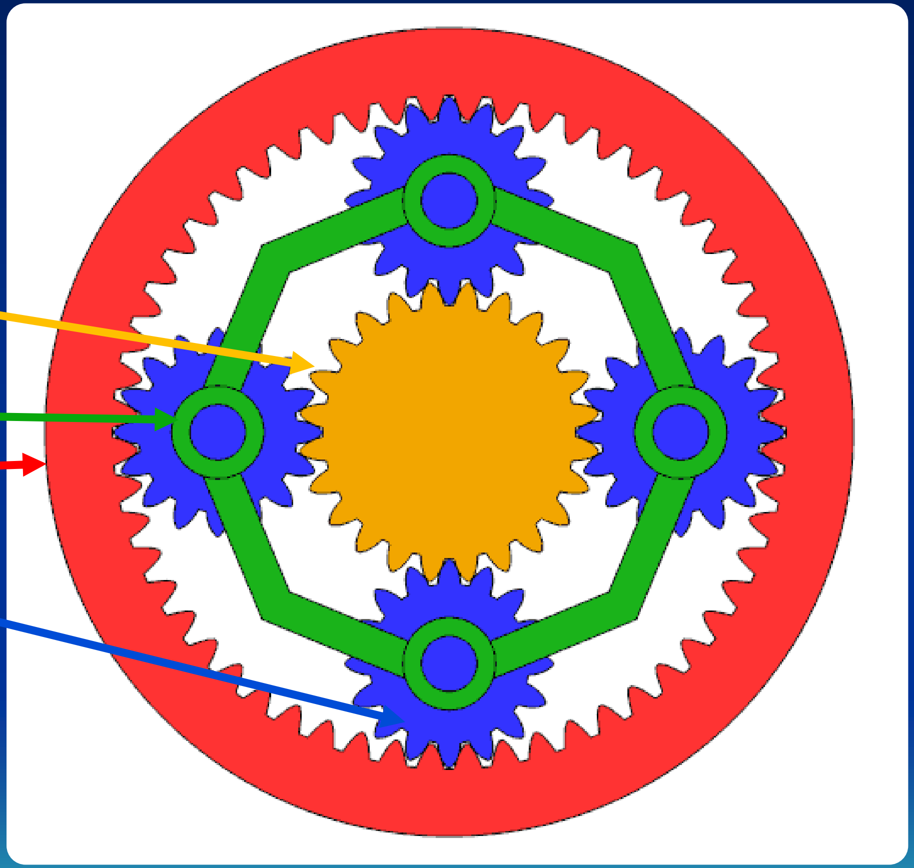


Gear ratio with equal diameter gears is ~ 4:1 (see red markers)

Invented around 1800 by William Murdoch, an employee of James Watt (inventor of the Watt steam engine in 1776)

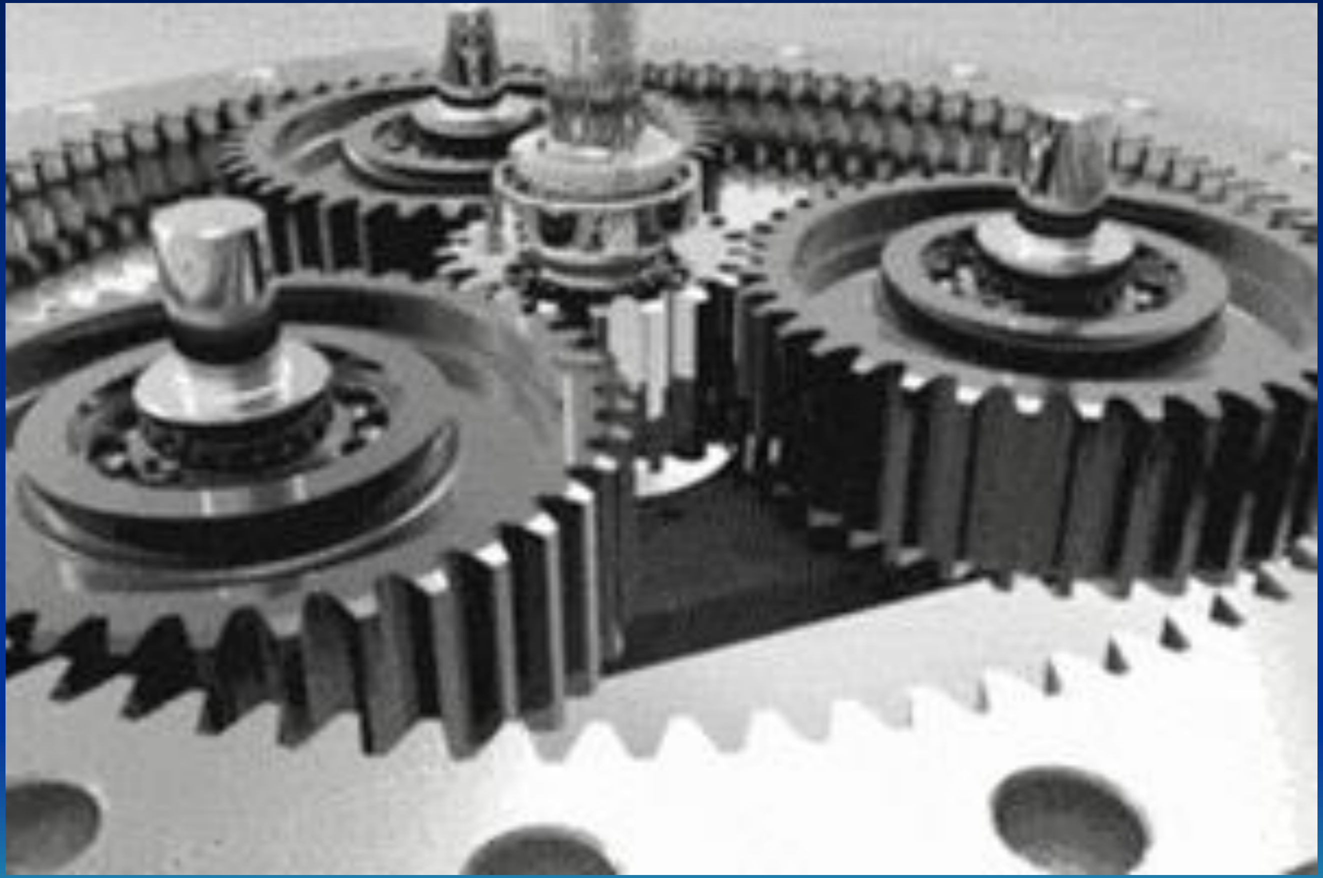
Planetary Gearbox

- Gear reduction
  - Turbine shaft power input at sun gear (yellow)
  - Fan attached to the planetary carrier (green)
  - Ring gear fixed (red)
  - Planetary gear (blue)
  - Typically 4:1 reduction
- Spur gears are most common, but helical gears may also be used



Planetary Gearbox

Also possible to fix planetary carrier and take output from ring gear (typically 3:1 reduction), but not used in current engine designs

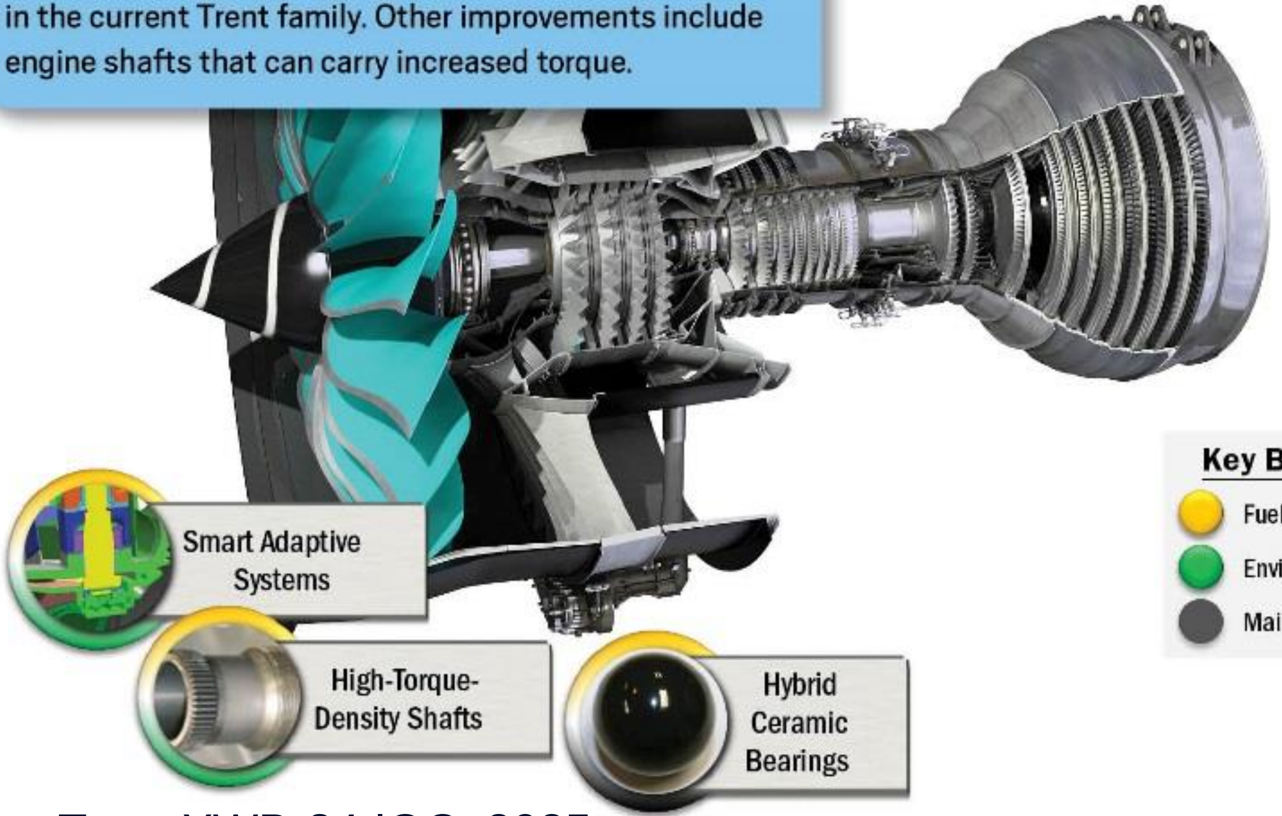


Rolls Royce **Advance**

AVIATION WEEK

4 Advance's new lighter core will be supported by hybrid ceramic bearings located farther aft in cooler, more benign locations away the hotter ones used for bearings in the current Trent family. Other improvements include engine shafts that can carry increased torque.

Note large diameter turbine disks



Key Benefits

- Fuel Burn
- Environment
- Maintenance

BACK HOME NEXT

Trent XWB-84 IOC: 2025
Trent XWB-97 IOC: 2028

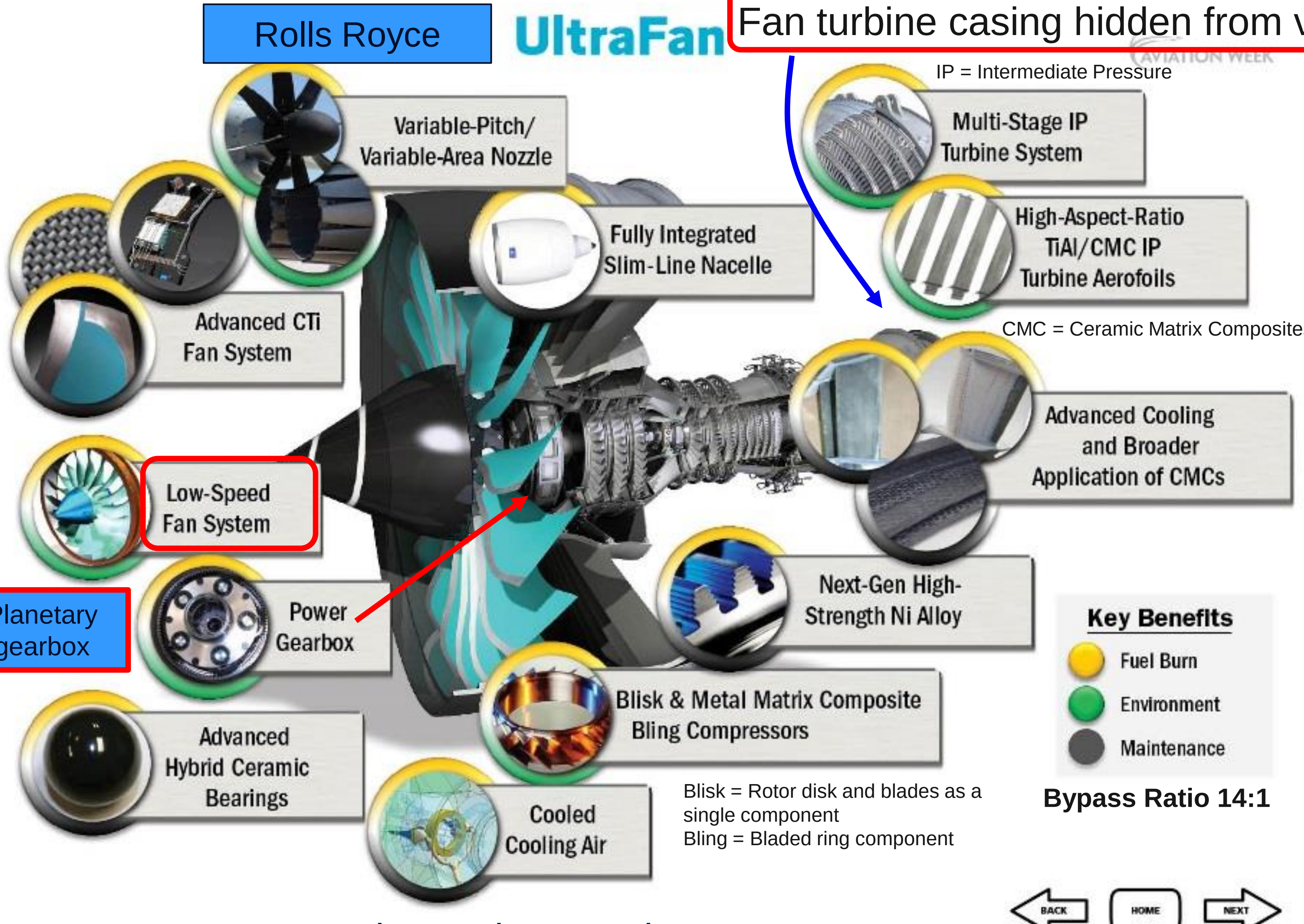
Source: Rolls-Royce

Rolls Royce

Fan turbine casing hidden from view

IP = Intermediate Pressure

CMC = Ceramic Matrix Composites



Planetary gearbox

Blisk = Rotor disk and blades as a single component
Bling = Bladed ring component

Bypass Ratio 14:1

Source: Rolls-Royce

Expected entry into service: 2030

Technical Evolution

Extinct or Evolving

- VTOL Airliner
  - HS.133/141
- Unducted fan
  - GE36
- 2nd generation supersonic transport

- Blended wing body
- Boom Supersonic
  - 3rd generation supersonic transport

Technical Evolution

Extinct or Evolving

- VTOL Airliner
  - HS.133/141
- Unducted fan
  - GE36
- 2nd generation supersonic transport
  - High Speed Civil Transport

VTOL Regional Airliner

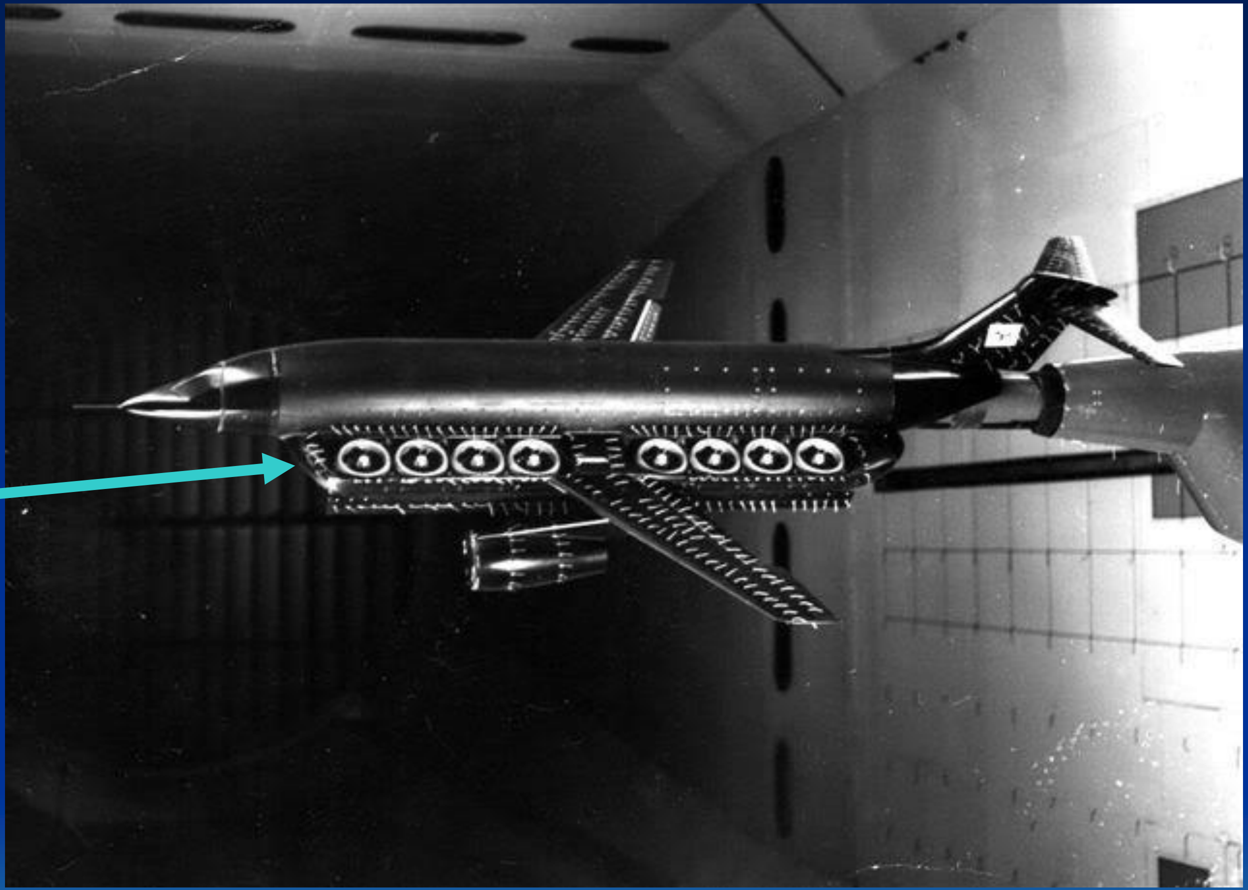
- HS.141 VTOL airliner
  - 2 x RR Speys for propulsion
  - 16 x RB.202 lift fans (BPR: 10)

ROLLS-ROYCE aero engine data — RB.202

AERO ENGINE DIVISION

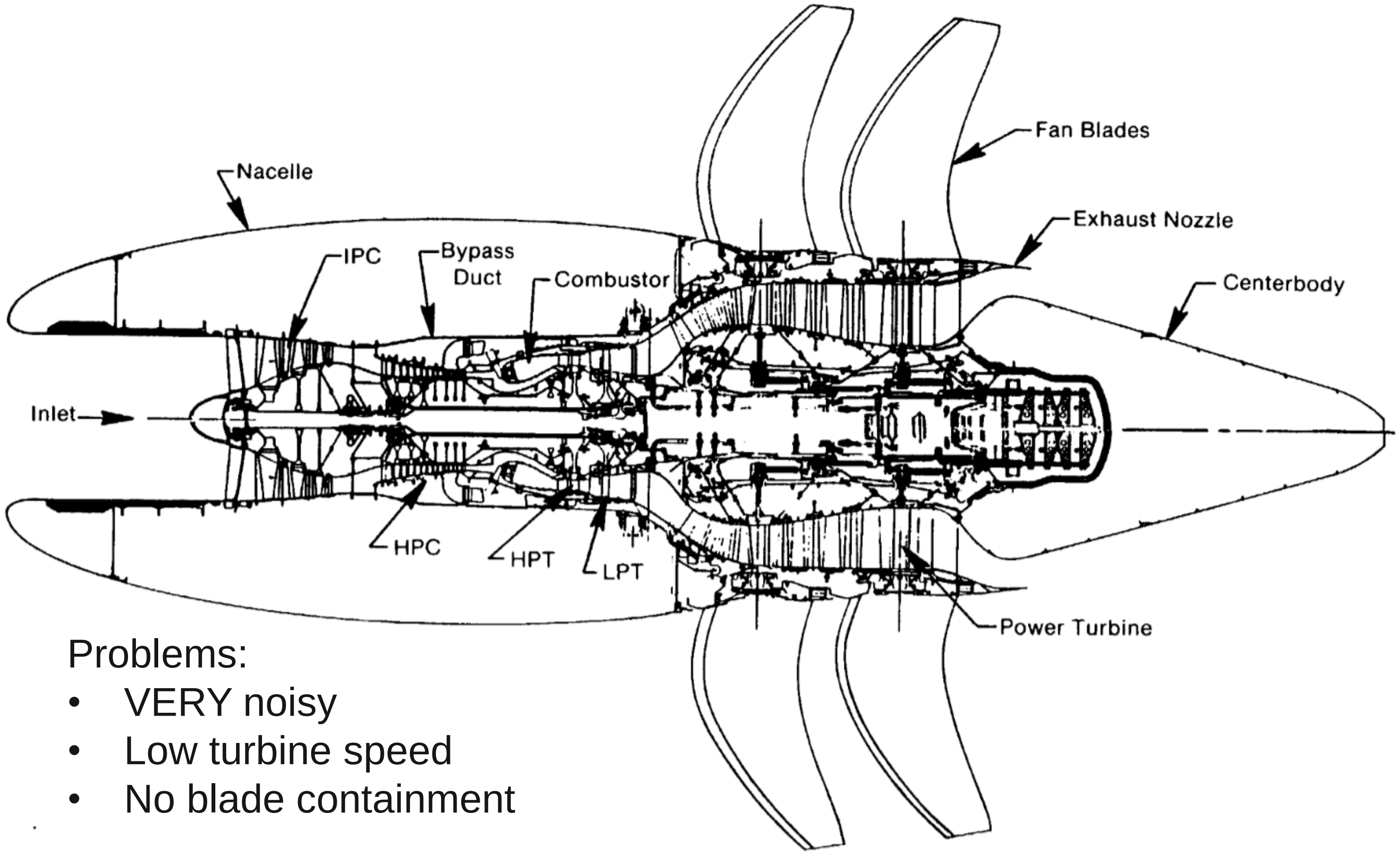
TWO-SHAFT LIGHTWEIGHT TURBOFAN

DERIVATION:	The first lift fan designed to meet the low noise level requirements of future commercial STOL and VSTOL aircraft operations. A logical development of the RB 162 and the Rolls-Royce/Allison XJ99 pure jet lift engines.
PERFORMANCE:	**Take-off thrust range:** 10,000-20,000 lb. (44-89 kN)
BASIC FEATURES:	**Rotor System:** Single-stage fan without I.G.V., driven by multi-stage L.P. turbine. Gas-generator multi-stage H.P. axial compressor driven by single-stage H.P. turbine with air-cooled blades. **Combustion System:** Fully annular. **Bypass Ratio:** 10:1 Extensive use of composite materials. Engine swivels for thrust vector angle control.
STATUS:	Project design phase.



Operational aircraft would have had doors on RB.202 inlet and exhaust

Unducted Fan (UDF)



Problems:
- VERY noisy
- Low turbine speed
- No blade containment

https://en.m.wikipedia.org/wiki/File:UDF-cross-section.png

Unducted Fan (UDF)

1986-08-20 First flight on Boeing 737

1987-04-05 Installed on McDonnell Douglas MD-80

1987-05-18 First flight on MD-80

1988-09-04/-11 Farnborough Air Show

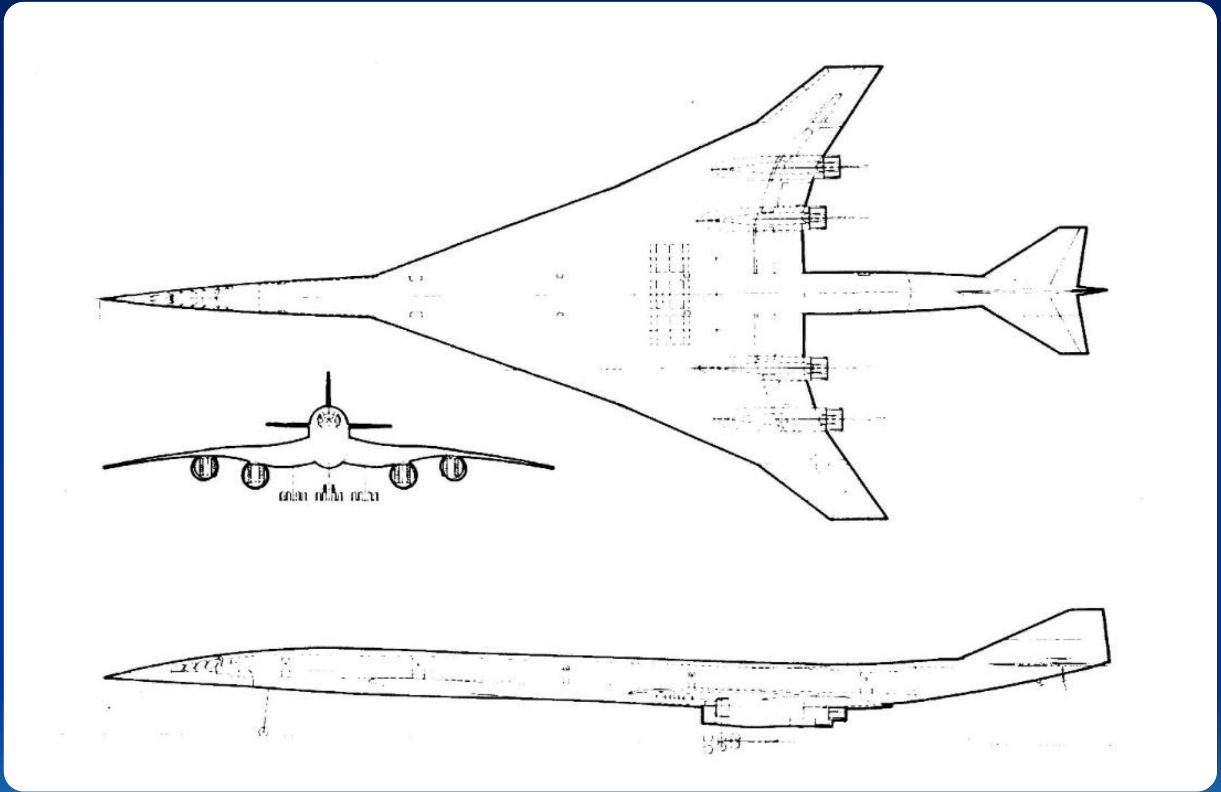
1989 Program cancelled

1991 Engine donated to Smithsonian Air & Space Museum

Lockheed CL1627-1 High Speed Civil Transport

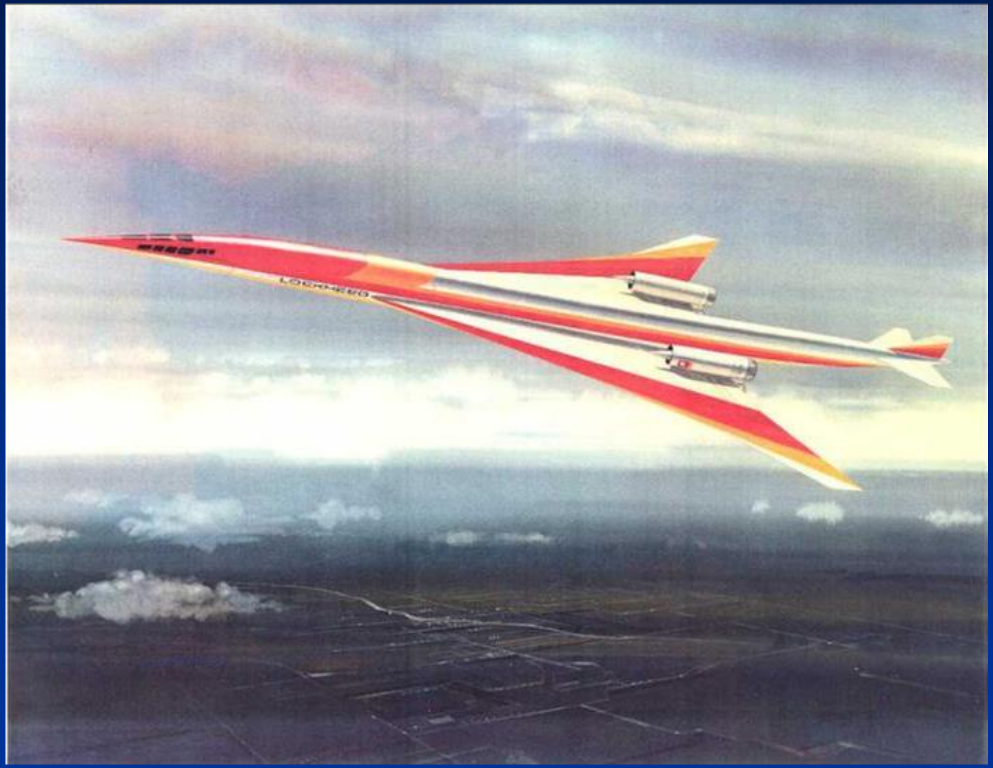
Study performed for the International Civil Aviation Organization (ICAO) by
- United States
- United Kingdom
- France
- Soviet Union

- MTOGW: 269,483 kg (594,109 lb)
- Payload: 23,247 kg (51,250 lb)
- Range: 7000 km (3,780 nmi)
- M_{cr}: 2.2
- TOFL: 3,505 m (11,500 ft)



Clauss, J.S., Hays, A.P., Wilson, J.R., The Common Case Study, NASA CR-158935, 1978

Lockheed Over-Under Engine Concept



CL1611

Over/Under Engine Concept in
Low Speed Wind Tunnel

Market study suggested that with 7000 km range, routes were limited to North Atlantic and North-South America, with likely sales under 20 aircraft

Technical Evolution

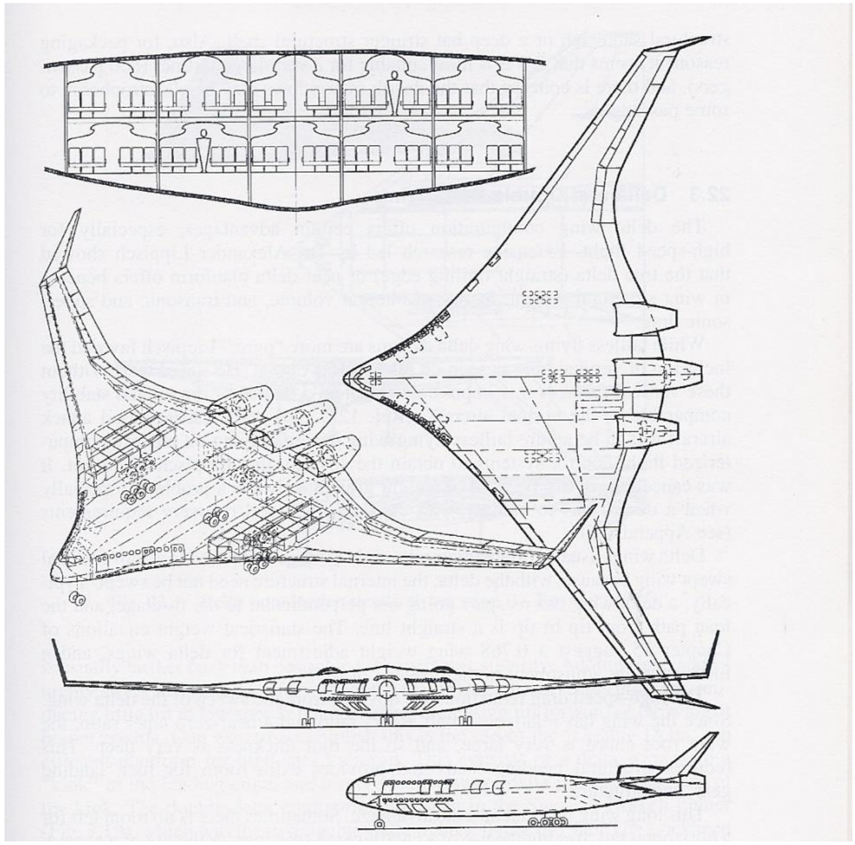
Extinct or Evolving

- Blended wing body
  - MDD/Boeing
  - Airbus
  - JetZero
- 3rd Generation SST

    Boom Technology

Blended Wing-Body

- Advantages
  - Higher L/D
  - Noise shielding of jet engines
- Disadvantages
  - Increased weight of non-cylindrical passenger cabin
  - Difficult passenger access/egress



Source: Raymer

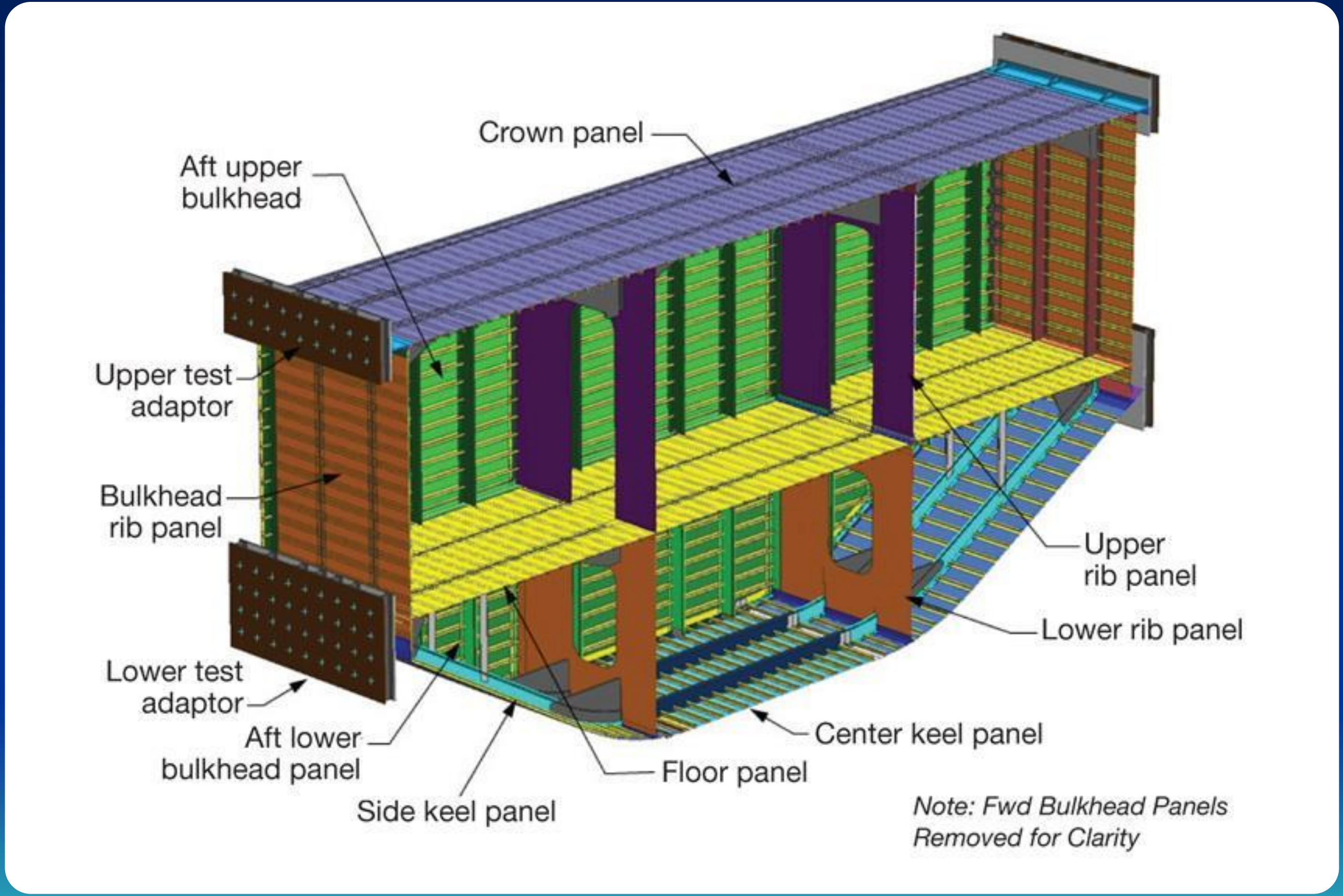
Blended Wing Body (BWB)

By Tony Landis for NASA https://commons.wikimedia.org/w/index.php?curid=1478722

- Studies and test flights from 1920s
- Boeing X-48B first flight 2007-07-20
  - Wingspan 21 ft (6.4 m)
- Where to put MLG on full-scale aircraft?

Blended Wing-Body

- NASA contract to Boeing to evaluate non-circular pressurized structures
- ~ 2008



www.compositeworld.com

Blended Wing Body (BWB)

- Airbus BWB, unveiled in 2020, part of ZEROe program
- 200 Pax
- LH_2 fuel

JetZero Blended Wing Body (BWB)

- $235M from US DoD Defense Innovation Unit
- Z4 - 170-290 pax
- Z3 - 100-170 pax
- Z5 - 290-370 pax

Where to install main landing gear (MLG)?

Rotating nose landing gear strut permits MLG to be well aft of c.g.

Airframe structural weight will be critical to program success

Watch:

https://www.youtube.com/watch?v=LSsxb_R1ZdA

https://www.youtube.com/watch?v=nOVtmSJujc4&ab_channel=AviationFederation

https://www.youtube.com/watch?v=1HxJ7CDwI7A&ab_channel=UCIrvineEngineering

Technical Evolution

Extinct or Evolving

- Blended wing body
  - MDD/Boeing
  - Airbus
  - JetZero
- 3rd Generation SST

  Boom Technology

Boom Technology - Overture SST

https://techcrunch.com/2022/08/16/american-airlines-to-buy-20-jets-from-boom-supersonic/

- Development cost ~ $6 – 8 billion ← Boom estimate, but note:
  - Concorde development cost about $20 B (in current dollars)
  - Boeing 787 development cost about $16 B
- Must amortize development cost over small production run
- Total funding $700 M (2024-05)
- Claimed DOC to be 25% that of Concorde
- GE / P&W / R-R not supporting program

https://www.seattletimes.com/business/boeing-celebrates-787-delivery-as-programs-costs-top-32-billion/

Other Airliner Manufacturers

- Russia
  - Tupolev
  - Yakovlev
  - United Aircraft Corporation
  - Sukhoi
  - Mikoyan
  - Ilyushin
- Brazil
  - Embraer
- China
  - COMAC

Embraer

- Founded in 1969
- E170
  - 66-78 pax 3,982 km (2,150 nmi)
- E175
  - 76-88 pax 4,074 km (2,200 nmi)
- E190
  - 100 pax 4,535 km (2,450 nmi)
- E195
  - 116 pax 4,815 km (2,600 nmi)

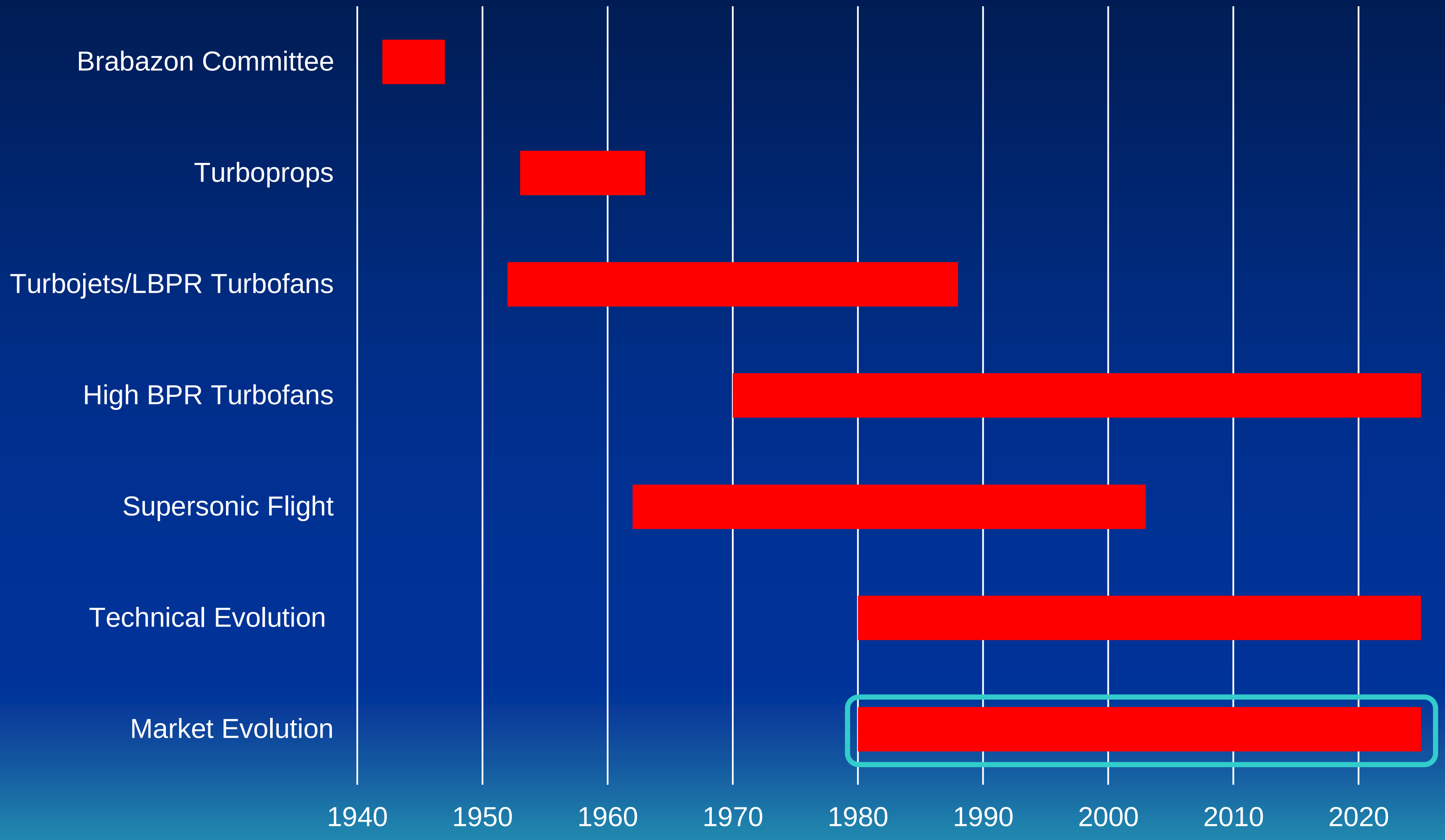
Fuselage diameter 3.01 m (9 ft 11 in)

- Republic Airways flies E170 & E175 for AA, DL, and UA
- LOT flies E190
- Porter, Azul and KLM fly E195

COMAC

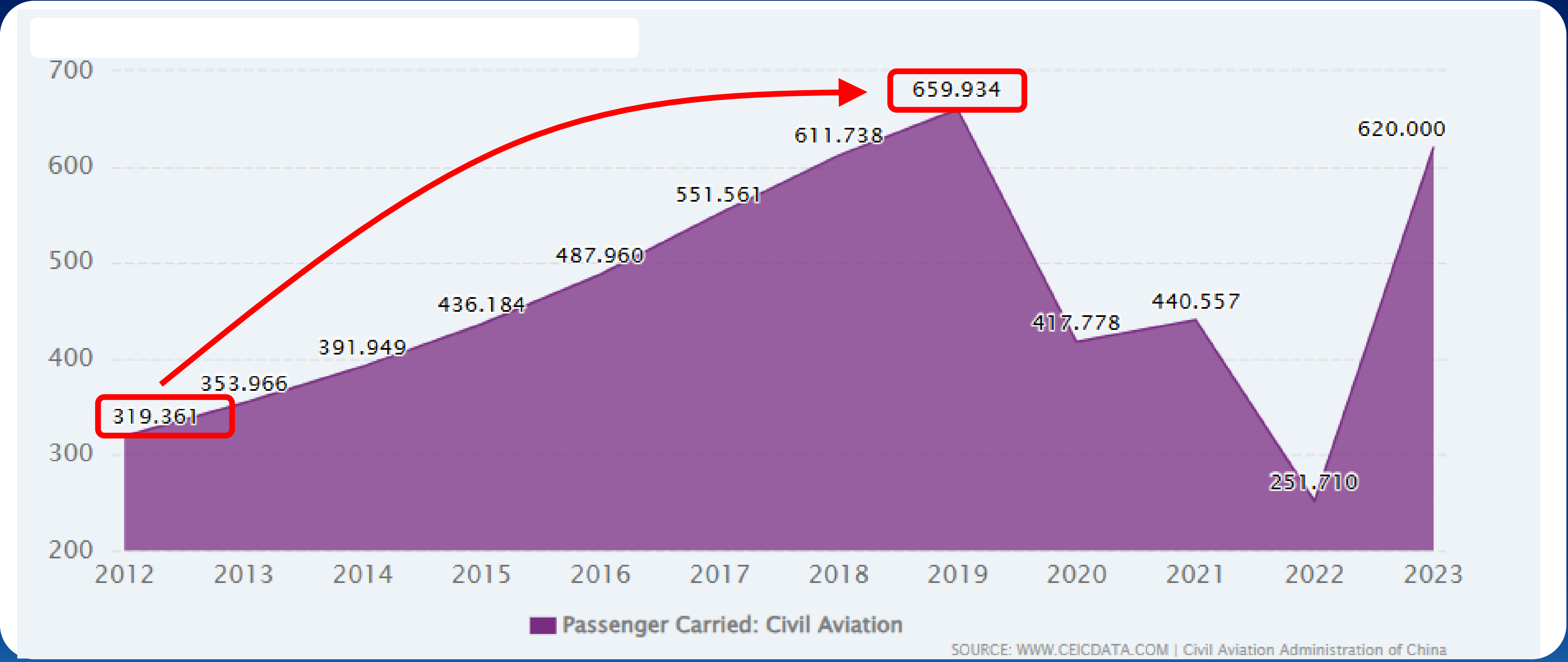
- COMAC ARJ21
  - Pax: 78-90
  - First flight: 2008-11-28
- COMAC C919
  - Pax: 158-192
  - First flight: 2017-05-05
- COMAC C929
  - Pax: 258-320 (3-class seating)
  - First flight: 2025
- COMAC C939
  - Pax: 280-400
  - First flight: 2028?

Commercial Aircraft Evolution



- Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
- Advent of high bypass ratio engines
- Supersonic flight
- Technical evolution
- Market evolution

China – Growth in Passengers Carried



https://www.ceicdata.com/en/china/air-industry-overview

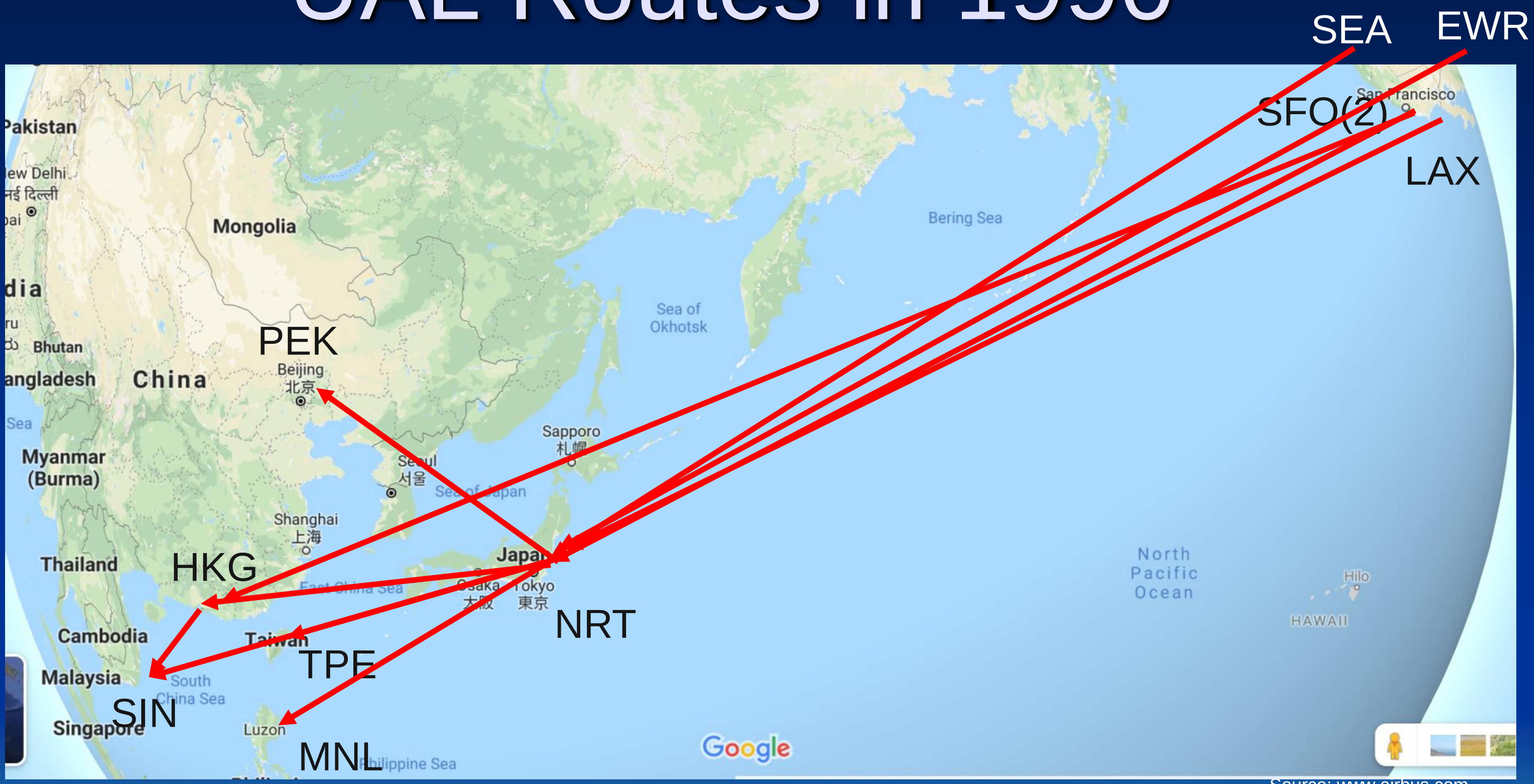
Passengers carried more than doubled in 7 years

UAL Routes in 1985

Source: www.airbus.com

All routes flown by 747-200 (later 747-400)

UAL Routes in 1990

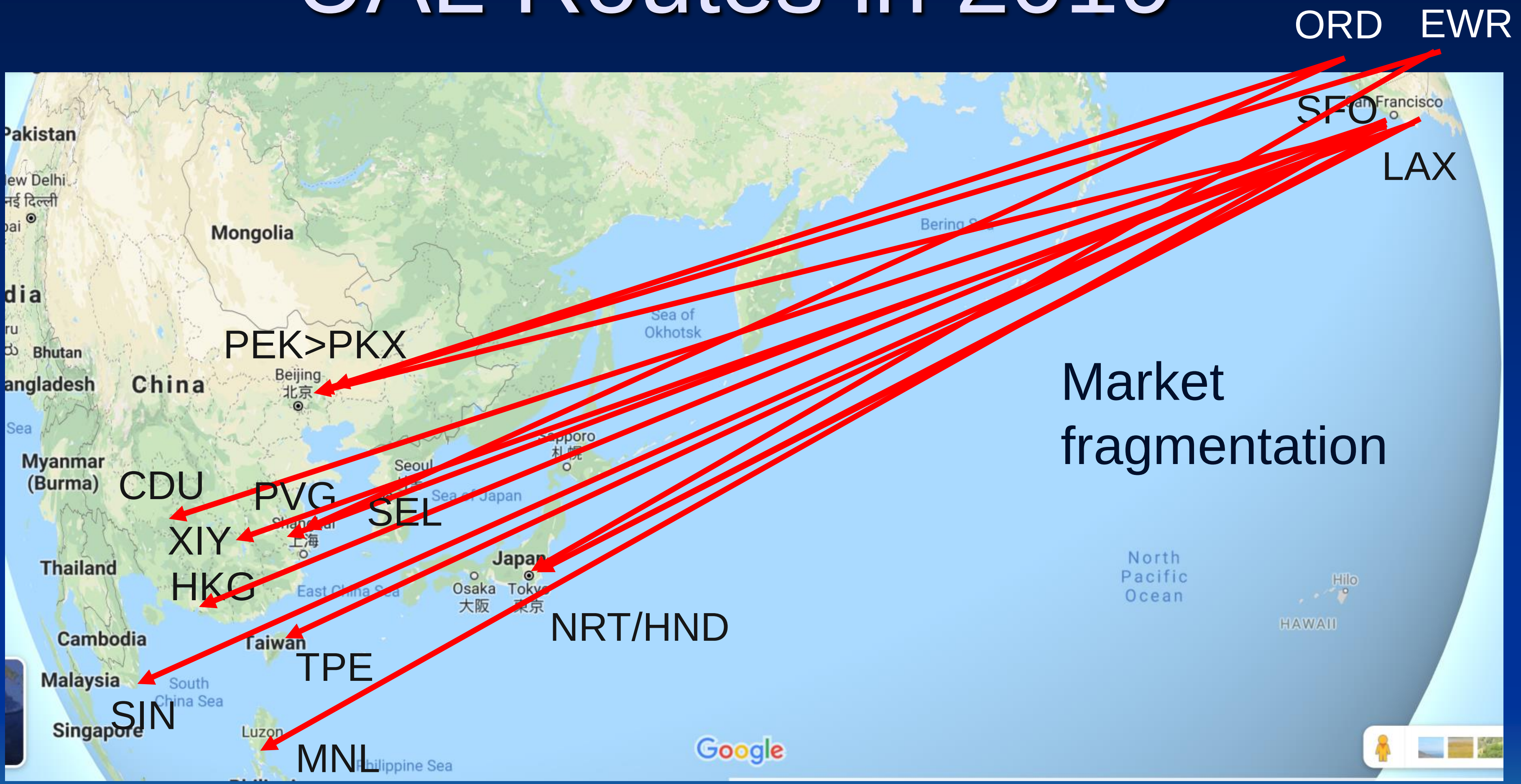


Source: www.airbus.com

All routes flown by 747-200 (later 747-400)

ADAC Aircraft Design & Consulting

UAL Routes in 2019



Nearly all routes flown by 787 (but now several routes flown by 777)

ADAC
Aircraft Design & Consulting

- Who lost out?

Airbus A380

https://airwaysmag.com/industry/analysis-the-weak-a380-aftermarket/

- First flight: 2005-04-27
- MTOGW: 575 t (1,268,000 lb)
- Pax: typical 575, max. 853
- Range: 14,800 km (8,000 nmi)

- Planned production: 750 aircraft
- Actual production: 254 aircraft
- Production ended: 2019-02

https://simpleflying.com/airbus-return-of-a380-not-ruled-out/

What We Covered

- UK Planning for post-war civil aircraft design
- First generation of turboprops
- First generation of turbojets/turbofans
- Advent of high bypass ratio engines
- Supersonic flight
- Technical Evolution
- Market Evolution

Thanks for your interest

A pdf of this presentation will be posted on adac.aero