Lecture 7

Engine Cycles for Subsonic Transport Aircraft

Objective: To outline the reasons for the choice of engine cycle.

Propulsion System Requirements

Optimum for Airframe Manufacturer:

- Sufficient Thrust to meet all Aircraft Requirements (Take-off, climb, Manoeuvre etc.)
- To use the minimum amount of fuel (low sfc, weight & drag)
- To have the lowest purchase price
- To have thrust growth for change in requirements

Optimum for Customer (Airline, Air Force etc.):

- *All of above, plus*:
- High Reliability
- Low Unscheduled removal rates
- Long time between overhauls
- Maintenance - low cost, easy to carry out & predictable.

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Choice of Engine Characteristics for Large Transport Aircraft

- Thrust capability → General sizing
- Specific fuel consumption
- Weight & Drag → Aircraft fuel burn / range
- Costs
  - Manufacturing
  - Maintenance

→ Aircraft operating costs

- Noise
- Emissions → Regulations and customer targets

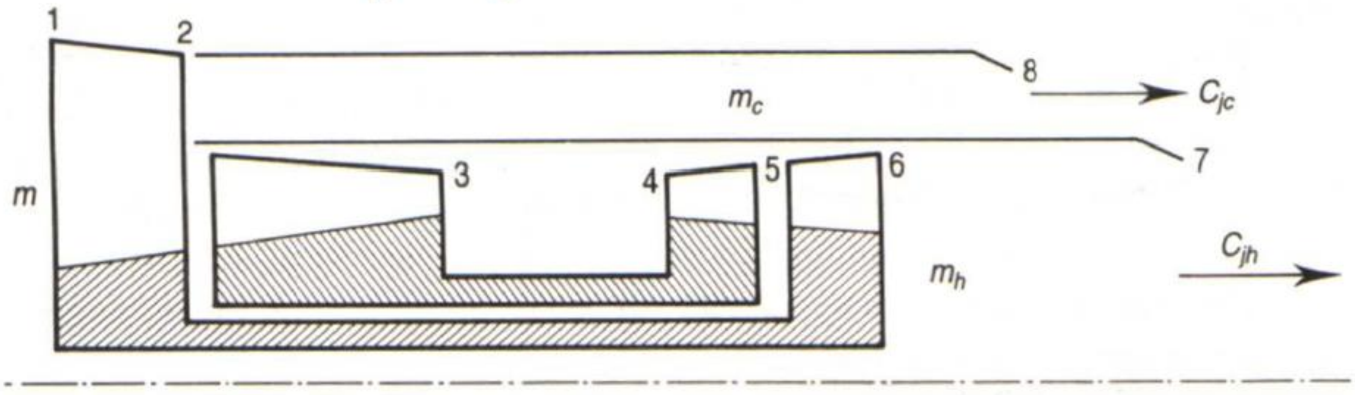
The headline parameter is Specific Fuel Consumption (SFC) but it is important to weigh the overall contributions of SFC PLUS weight & size to fuel burn, costs and environmental factors

Typical Engine Sizing Conditions

Subsonic Transport Aircraft

- **Take-off**
  - Sufficient thrust to meet take-off distance. Typically @ M = 0.20 - 0.25 at airfield altitude at ISA +15
- **En-route clearance**
  - Sufficient thrust to allow the aircraft to maintain altitude (typically 16,000 ft) with an engine failed at ISA +10
- **Climb**
  - Sufficient thrust to give the aircraft a rate of climb of 300ft/min at cruise altitude at ISA + 10 at a Mach Number ~ 0.2 less than cruise.
- **Cruise**
  - Sufficient thrust to allow the aircraft to sustain cruise Mach Number (M = 0.8 +) at ISA +10

Key Cycle Parameters

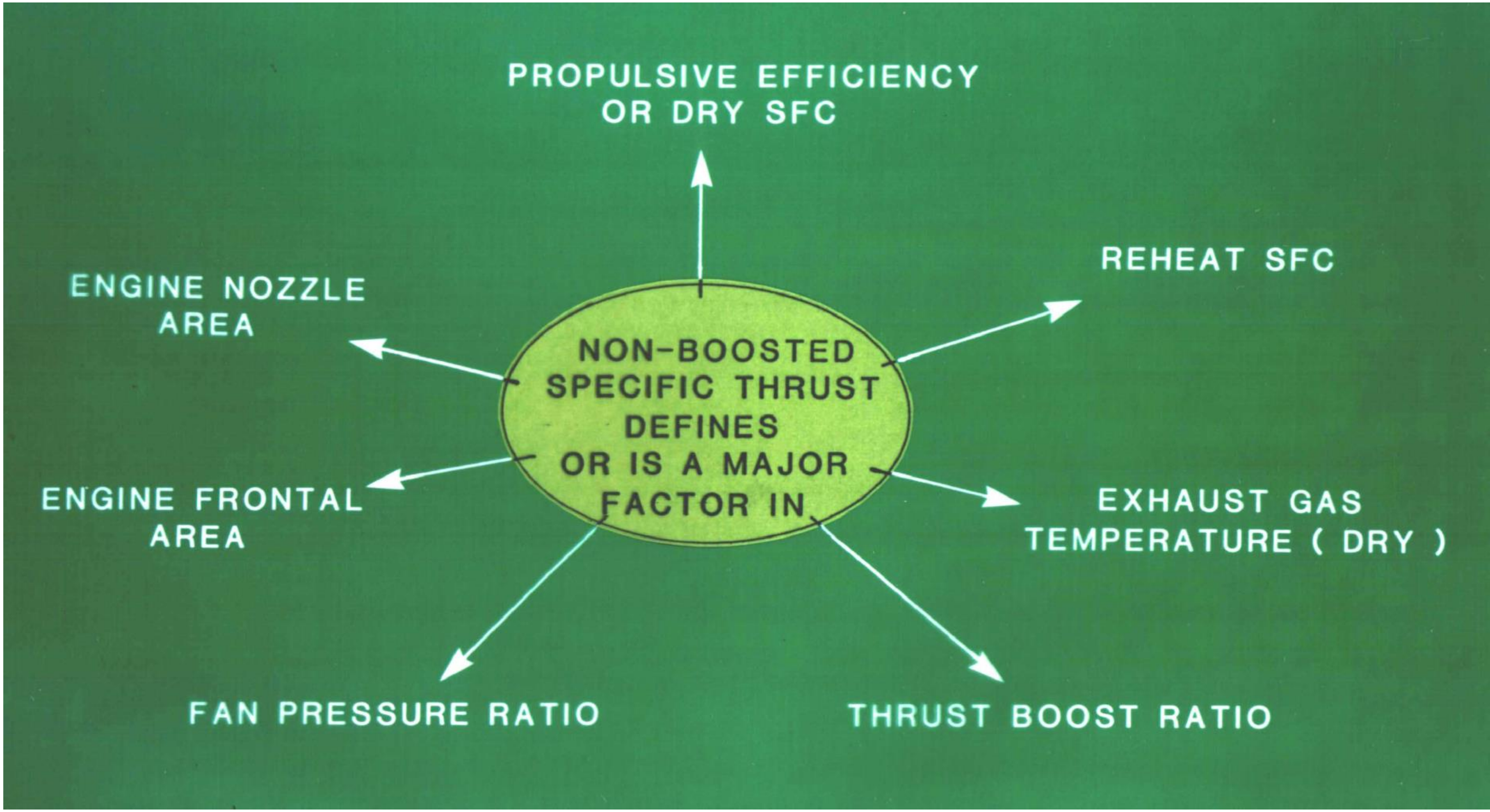


- Overall Pressure Ratio $OPR = P_{03}/P_{01}$
- Fan Pressure Ratio $FPR = P_{02}/P_{01}$
- Stator Outlet Temperature $SOT\ K = To_4$
- Specific Thrust $ST = F/\dot{m}$
- By-pass Ratio $\lambda = \dfrac{m_c}{m_h}$ (by-pass flow/core flow)

Note for mixed flow engines p_{sh}/p_{sc} is also important

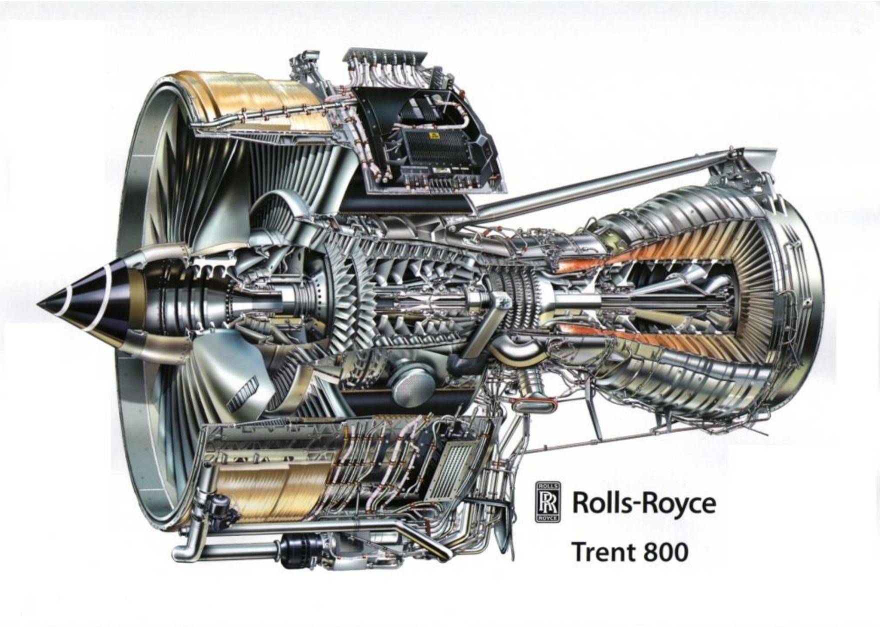
The above parameters are fixed at the Engine Design Point BUT vary at off-design conditions

Specific Thrust ~ the basic parameter



SPECIFIC THRUST (Thrust per unit Mass Flow) **=** $(C_j - C_a)$ **(Unit of velocity)**

Propulsion Systems for Transport Aircraft



High by-pass ratio Turbofan

Thrust ~2000 to 100,000 + lb

By-pass ratio 4 – 12

OPR ~ 40 +

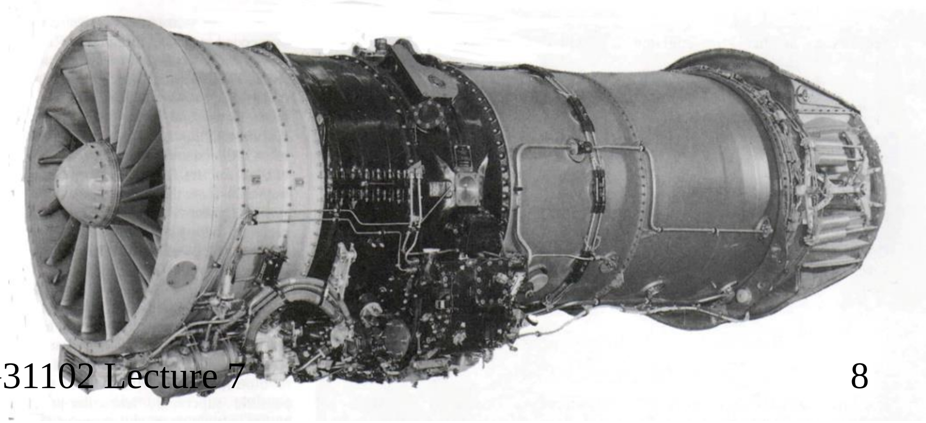
Fan PR 1.5 ~ 1.9

Specific Thrust SLS ~ 250 – 350 m/s (25 – 35 Lb/lb/sec)

The development of by-pass engines

The VC 10 on it's first flight

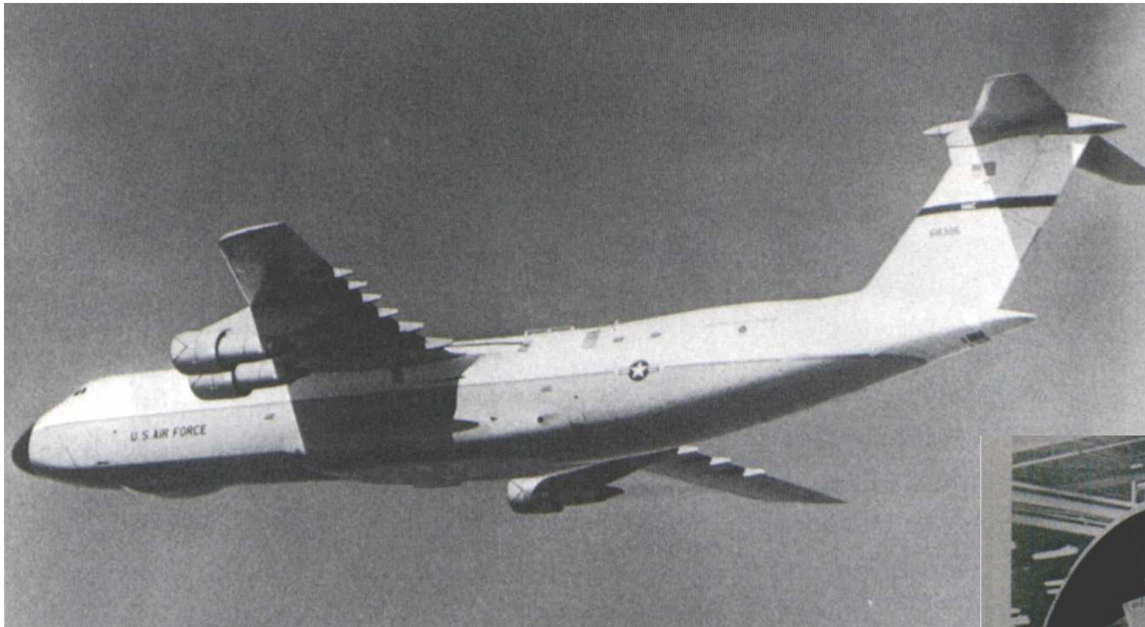
Entered service April 1964



Roll Royce Conway

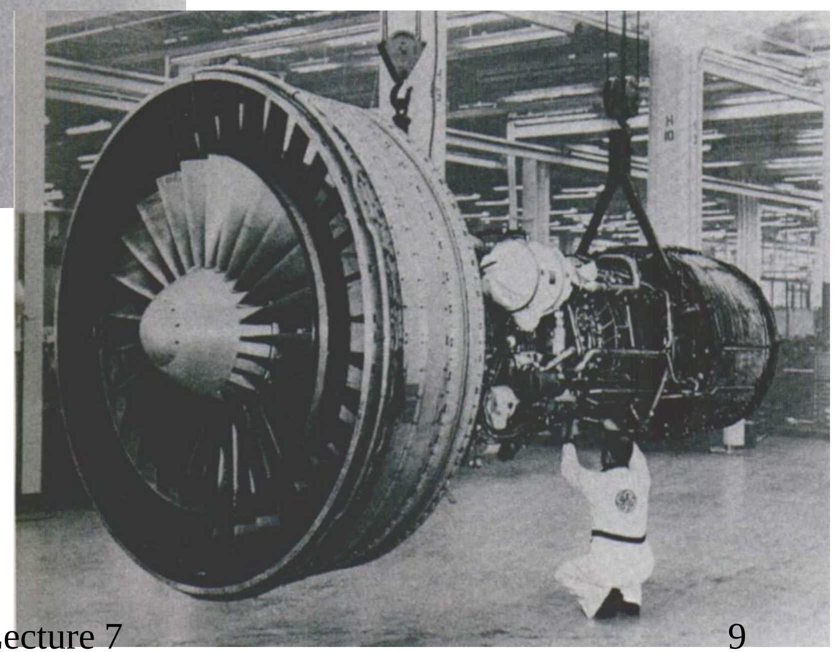
By-pass ratio ~ 0.3

The development of high by-pass ratio turbofans



GE TF39

First run 1965



Lockheed C5A

EIS 1970

The first wide-body Jets

Douglas DC10 ~ 1971

Boeing 747 ~ 1970

Lockheed 1011 ~ 1972

P&W JT9D	43,500 lbs	92 inch fan
GE CF6	40,000 lbs	86 inch fan
RB211-22B	42,000 lbs	85 inch fan
RB211-524B	50,000 lbs	85 inch fan

Fundamentals

SFC is improved by:

HIGHER PROPULSIVE EFFICIENCY and **HIGHER THERMAL EFFICIENCY**

Means - Reduced jet velocity

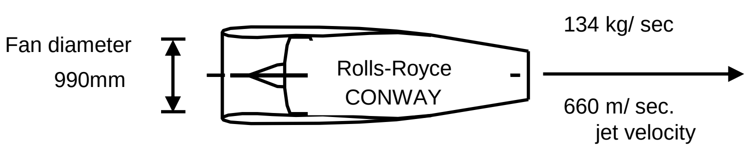
Larger fan moving more air at lower speed

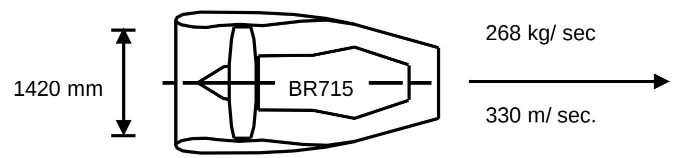
Increasing bypass ratio

Higher Overall pressure ratio (OPR)

Turbine temperatures (TET)

Component efficiencies





The Conway entered airline service in 1960.

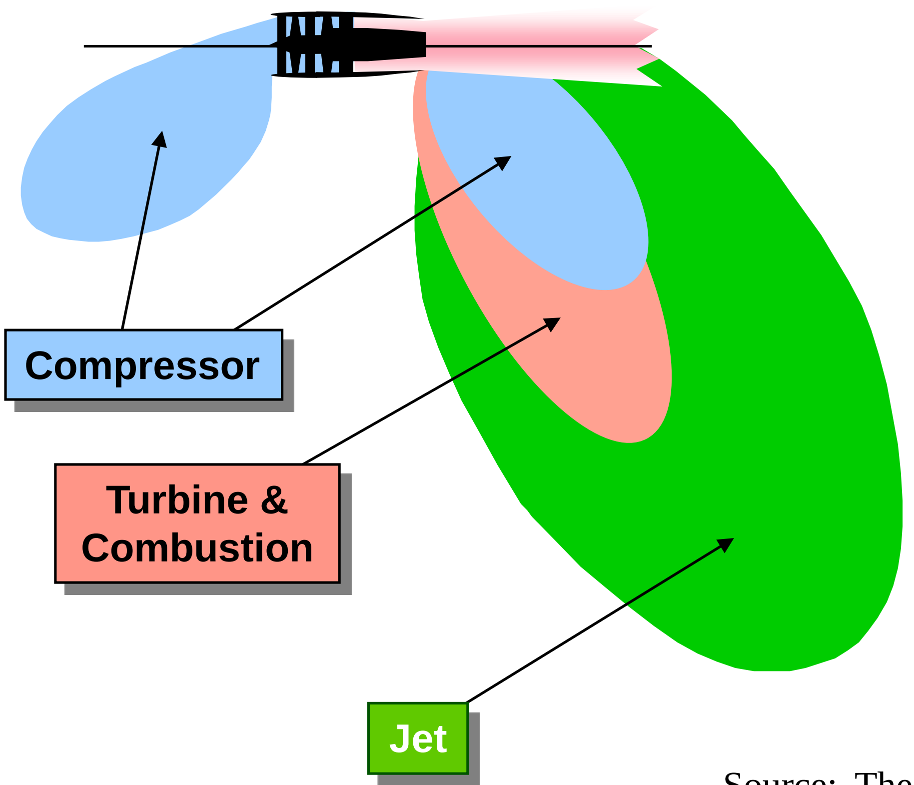
The BR 700 series entered service in 1996

	Conway	BR 715
OPR	**15**	**32**
By-pass Ratio	**0.3**	**4.6**
TET	**1400K**	**1600K**
SFC lb/hr/lb	**~ 0.85**	**~ 0.6**

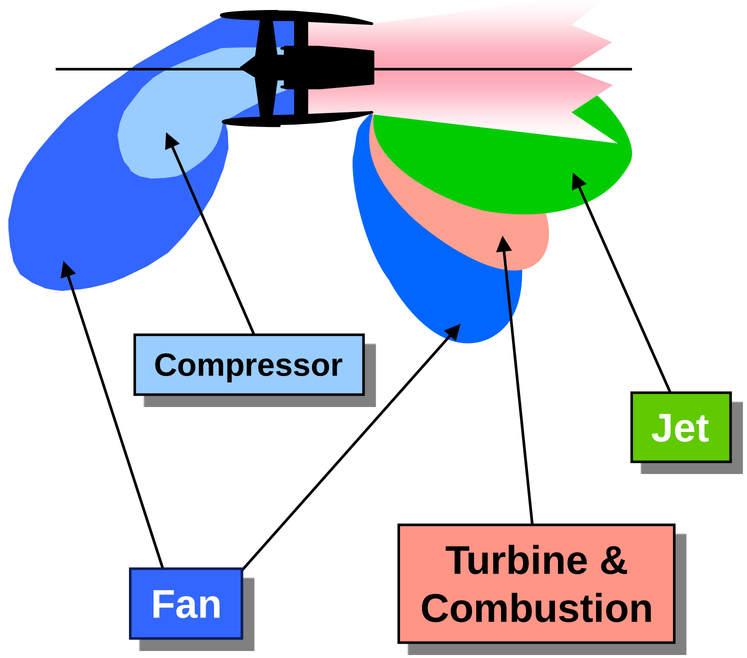
Gas Turbine Propulsion Systems

Comparison of Component Noise Sources

Typical 1960s Design

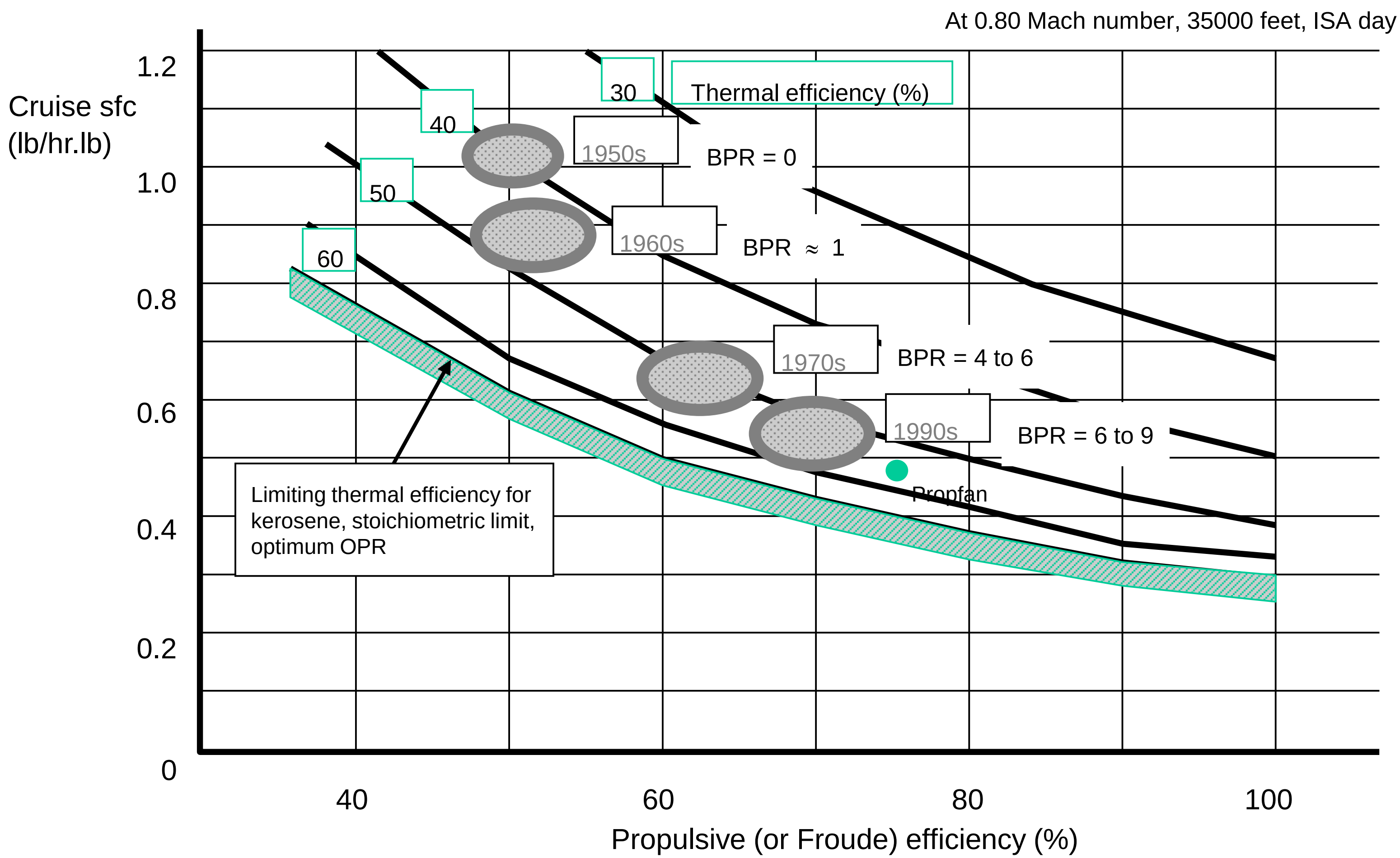


Typical 1990s Design



Source: The Jet Engine
Rolls-Royce plc

Cycle Efficiency Trends



Based upon Rolls-Royce plc Data

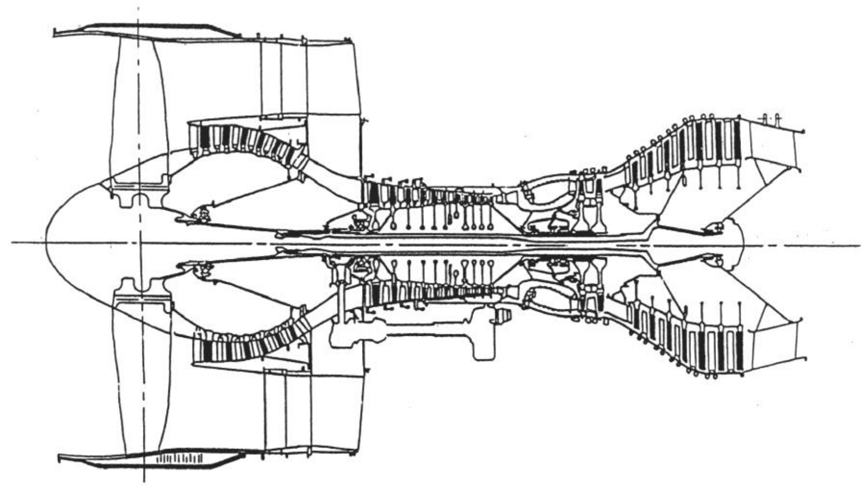
Cycles for Civil Turbofans

First, second & third generations

- Dominant requirements are for best fuel consumption, whilst meeting noise & emission requirements i.e. low specific thrust.
- The standard airframe configuration has underwing engines, hence engine diameter is an issue
- Fan pressure ratio is almost directly related to specific thrust
  - i.e. increasing fan pressure ratio (FPR) goes with specific thrust
- In order to minimise diameter & weight at a given level of thrust, the FPR tends to be as high as possible in a single stage
- Cycles for Civil Airliners:
  - Single stage fans with a FPR of ~ 1.9
  - High overall pressure ratio consistent with materials for HP compressors Compressor delivery temperature (T_3) limit
  - High Turbine Entry Temperatures to give good thermal efficiency, limited by HP Turbine Blade Materials.

The route to improvements in High By-pass Ratio Engines

Lower Specific Thrust
⇓
Larger Diameter Fan
⇓
Noise constraint means same fan tip speed



Pratt & Whitney 4084

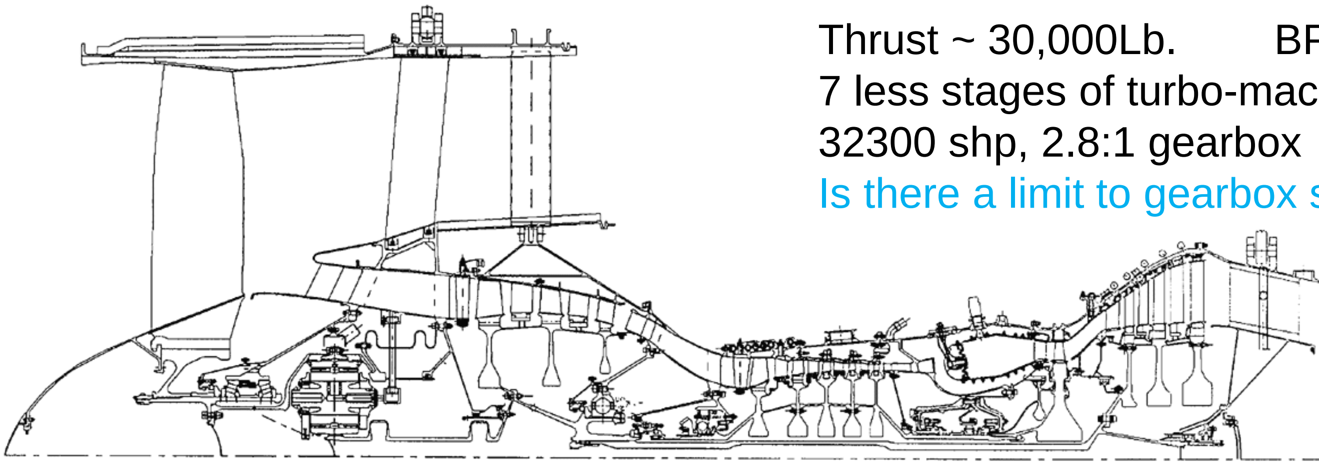
Either
Gearbox to separate fan from LP Shaft
⇓
Reliability & Maintenance issues

Or
Increased number of LPT & booster stages for efficiency
⇓
Increased mass, number of parts, cost etc.

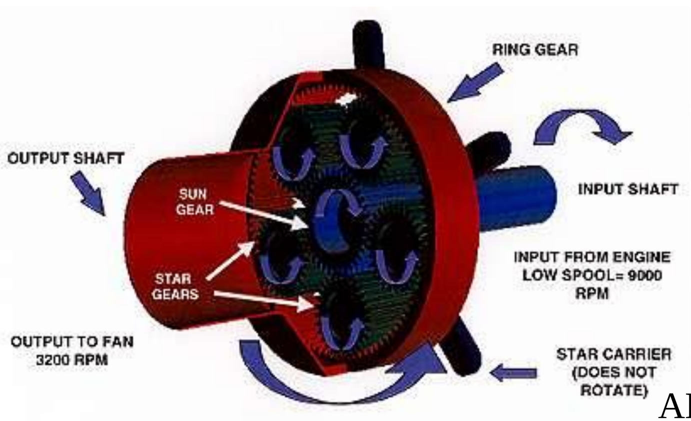
Improving propulsive efficiency

Geared fan – PW8000

Reducing specific thrust → Increasing bypass ratio



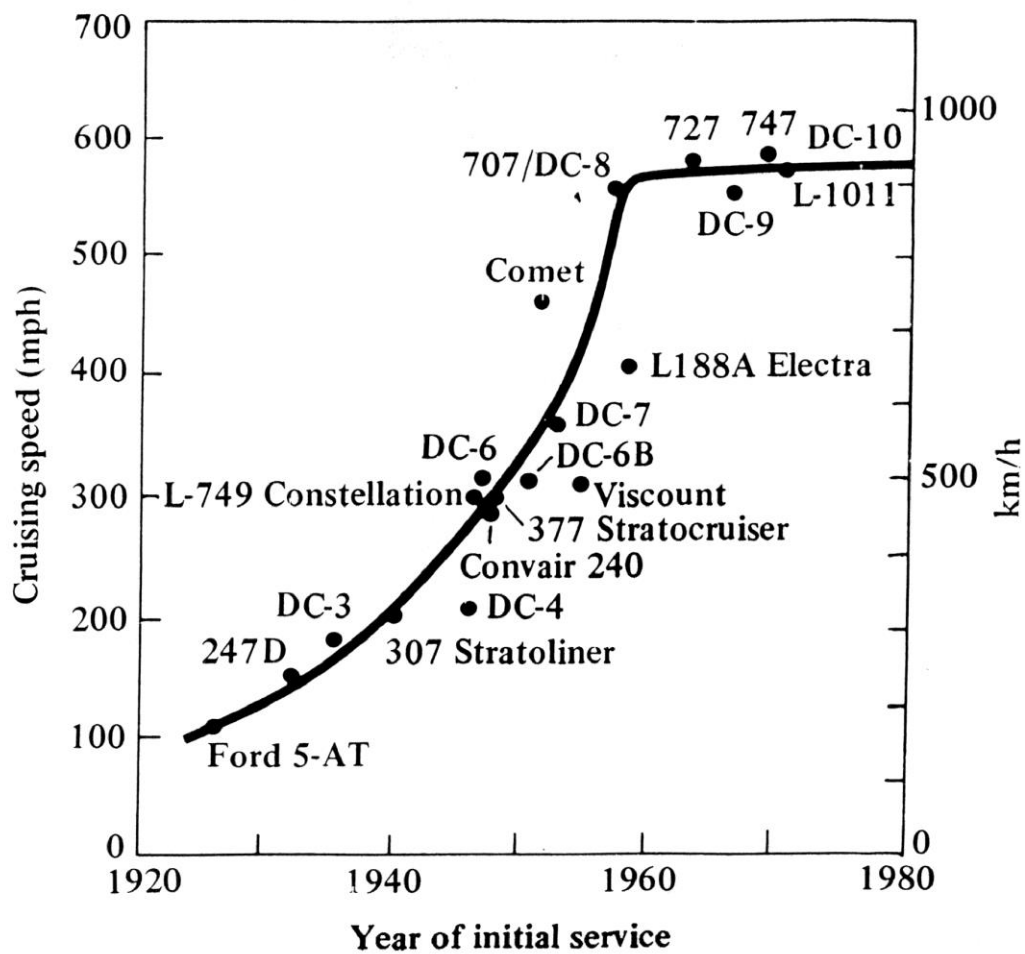
Thrust ~ 30,000Lb. BPR = 11:1
7 less stages of turbo-machinary
32300 shp, 2.8:1 gearbox
Is there a limit to gearbox size?



Ref: Pratt & Whitney develops geared turbofan, Christopher Hess.

Commercial Transport Aircraft

The Development of speed from the 1920's to the 1990's



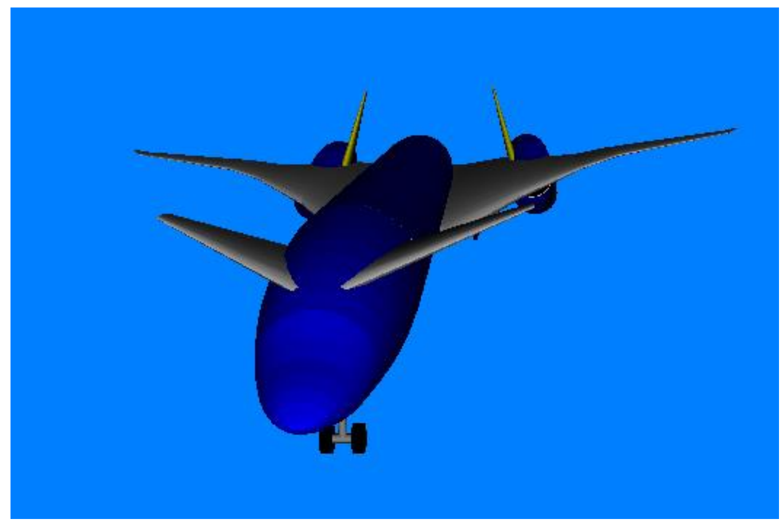
Source: "What makes Airplanes fly" P Wegner

Boeing Sonic Cruiser

Double Delta Canard

Propulsion Requirements for Transonic Design:

- Noise, Emissions & Fuel Burn key drivers
- Close to today's High BPR Engines
- Derivative approach



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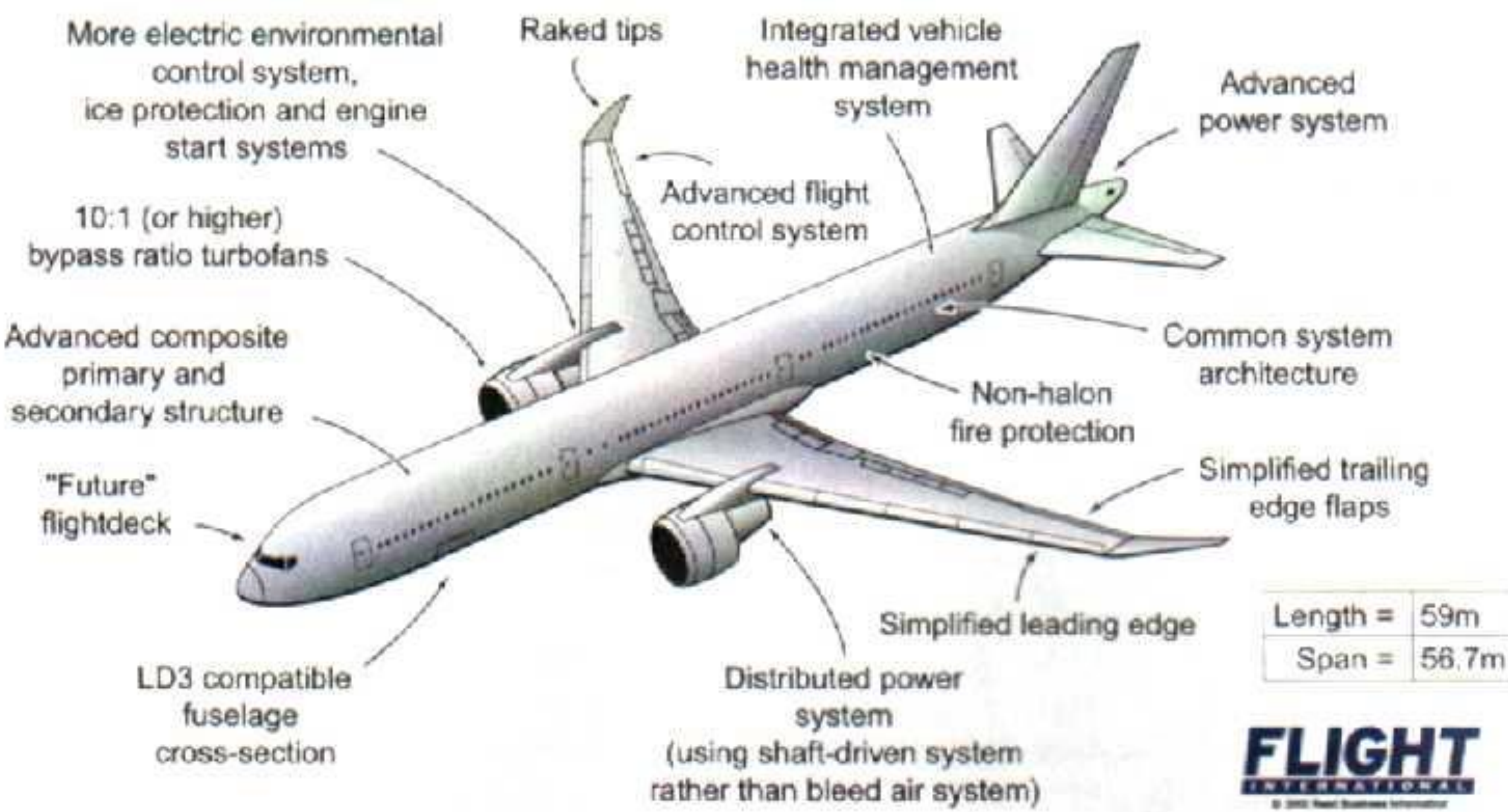
Boeing Super Efficient Aircraft Concept



Boeing 787

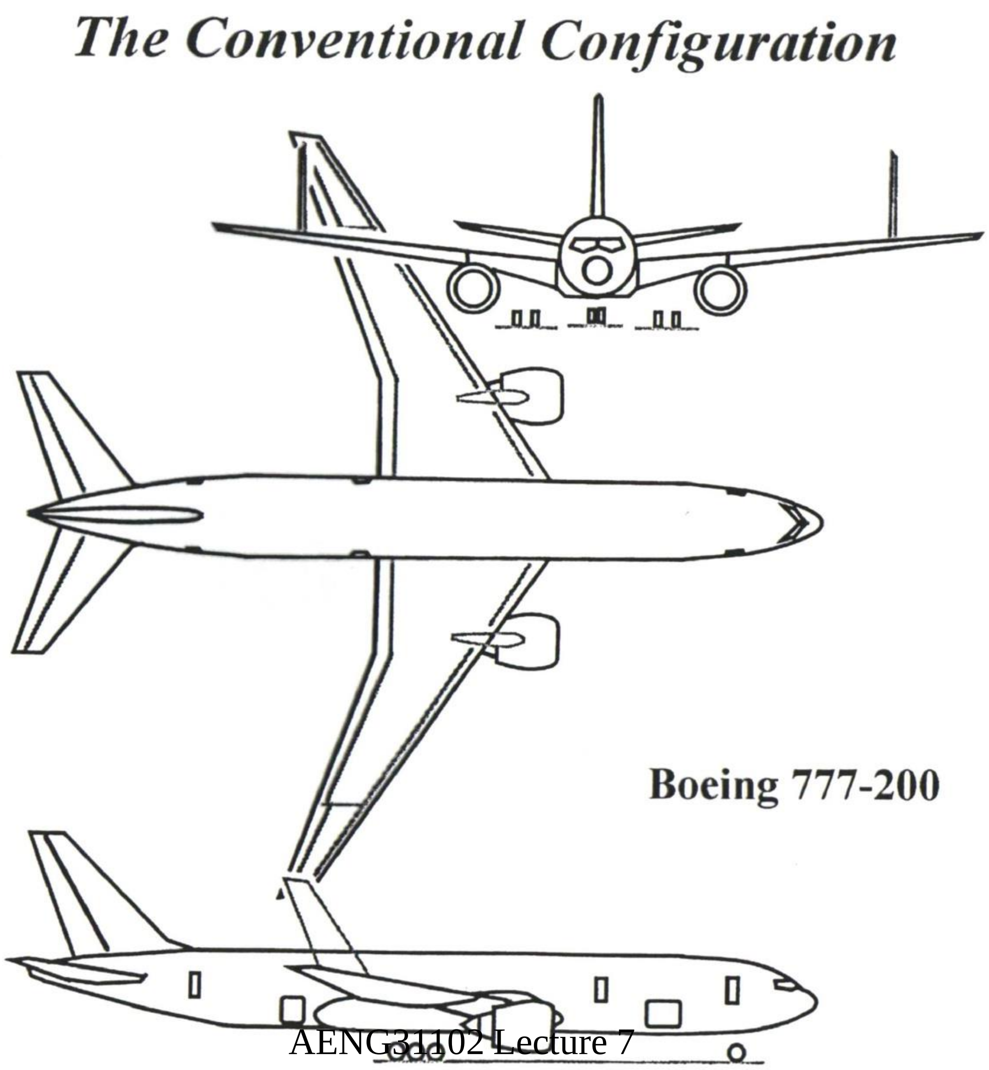
Wind Tunnel Model

Composite Fuselage Section

Airbus 350


A321
A320
A319
A340
A3XX
A310
A300
A330
BRITISH AEROSPACE
Airbus

Subsonic Commercial Transport Aircraft



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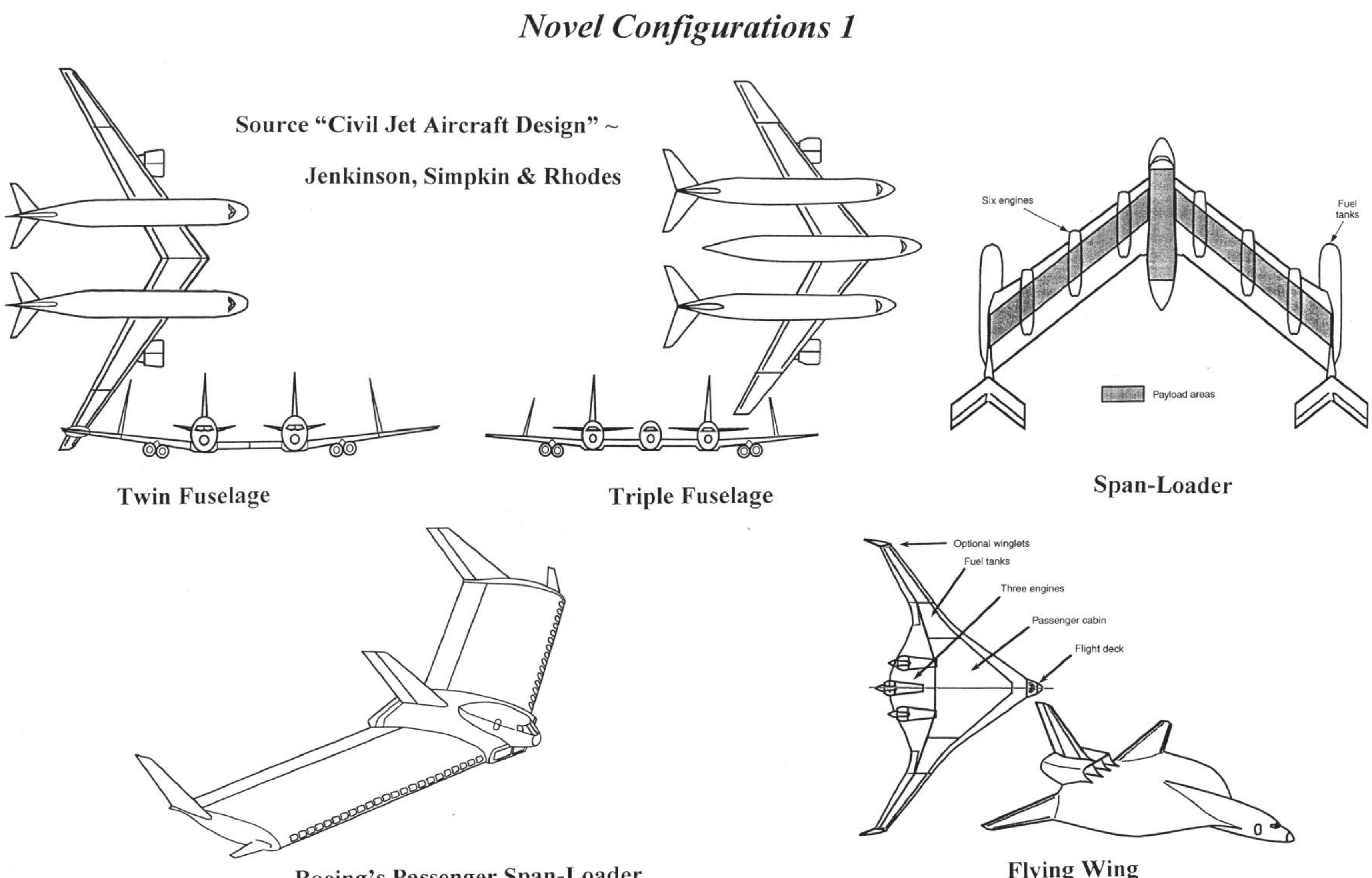
A NASA View

Quote* from Dennis Bushnell, Chief Scientist NASA Langley **Subsonic Commercial Transport Aircraft** on subsonic transport systems:

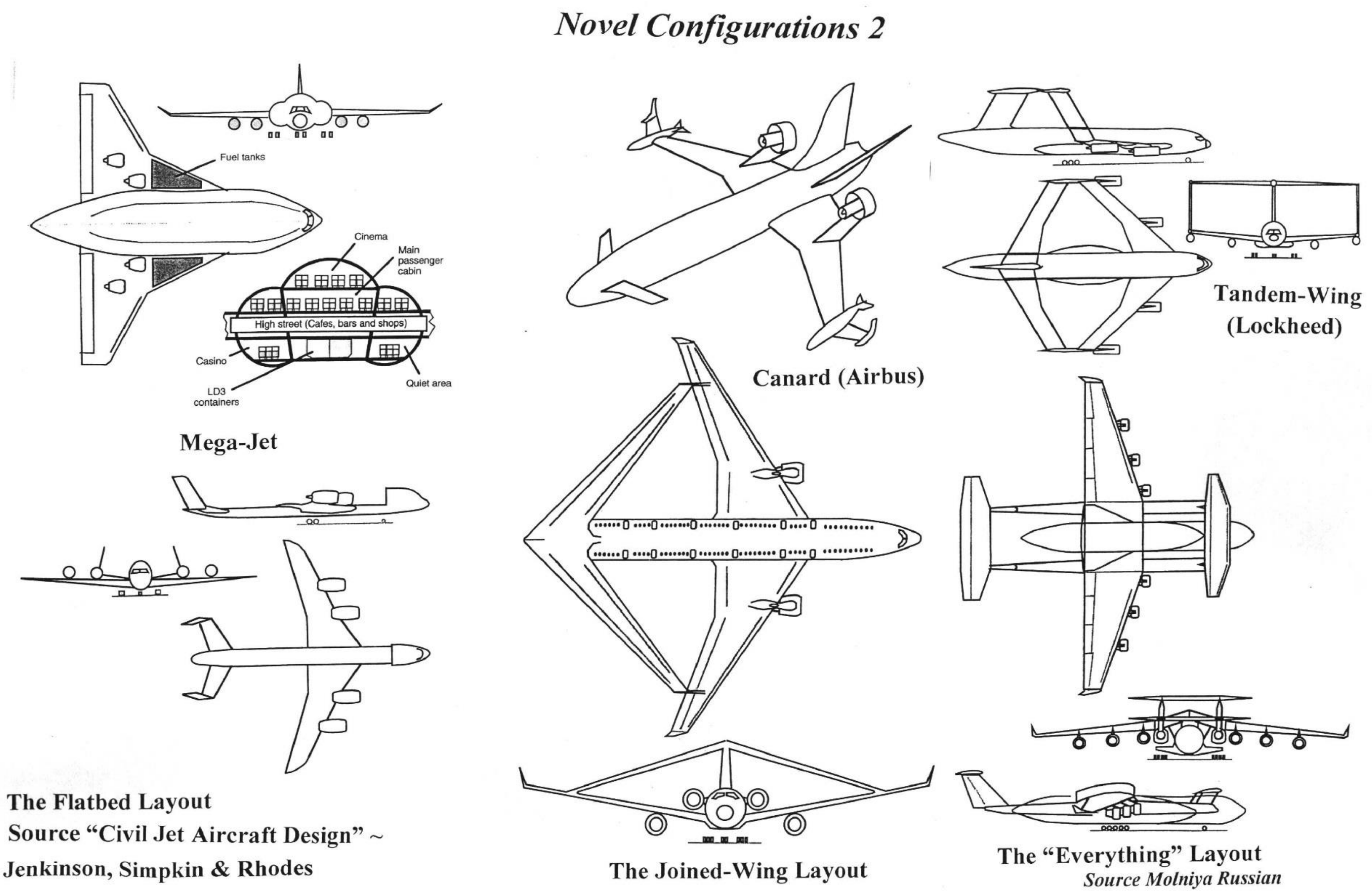
“Most of the improvements over the past 40 years have been as a result of propulsion technology, primarily higher by-pass ratios and turbine inlet temperatures, nearly tripling seat miles per gallon. Advanced configuration concepts have, in general not been investigated in depth nor implemented”

*1998 Wilbur & Orville Wright Lecture - Aerospace Journal January 1998.

Subsonic Commercial Transport Aircraft *1*



Subsonic Commercial Transport Aircraft 2



Cycles for Civil Turbofans

Situation in the early 2000's

- The standard airframe configuration with underwing engines was beginning to be questioned. Were there a more efficient layouts?

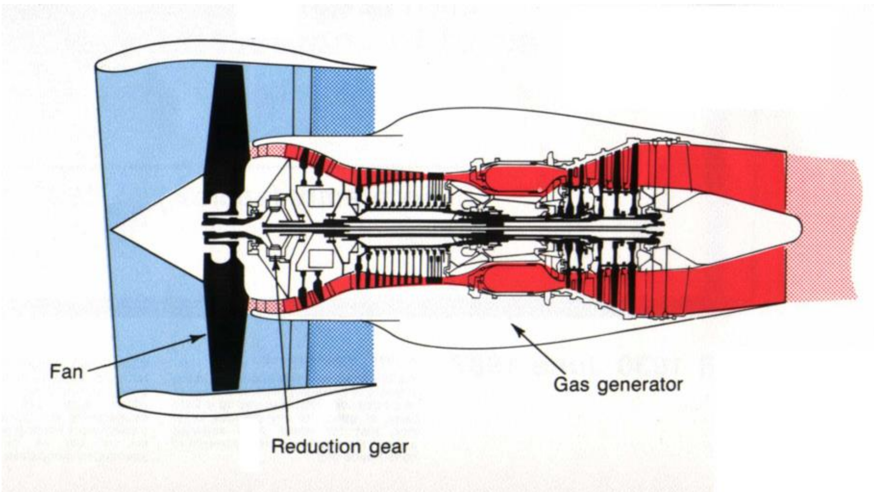
- After the launch of the A 350 & B787, the big challenge was a replacement for the 150 seat airliner i.e. the A320/B737. Airbus & Boeing studied many options:
  - Advanced turbofans including Geared Turbofans
  - Propfans
  - Turbo-props

- ***Airbus launched the A320 (NEO) & Boeing the B737 Max.***

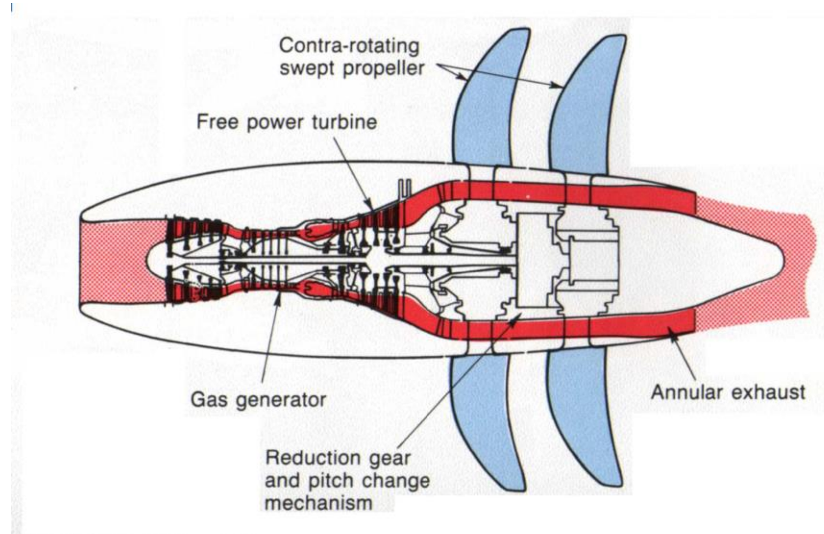
Future Cycles for Civil Turbofans

- In only 10 years the market has changed dramatically
- Climate change has become the dominant issue for future commercial airliners.
- The contribution of NOx to global warming not well understood but it accepted as a contributor
- Low fuel consumption is key to reducing CO_2.
- Hence is lowering of specific thrust (increasing fan diameter or a propeller) the key to driving down fuel burn & emissions CO_2?

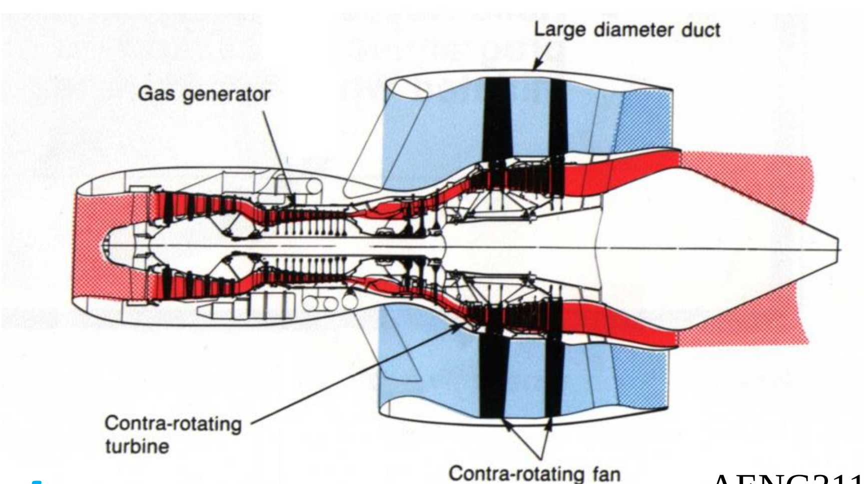
New Propulsion Concepts for Transport Aircraft



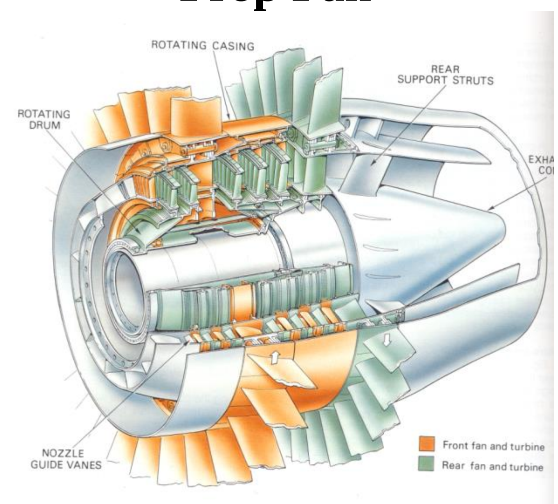
Geared Fan



Prop Fan



Contra Fan



A380

How far can Fan Diameter be increased?

Airbus A350

Boeing 787

Airbus A320 NEO

Boeing 737 Max

Improving propulsive efficiency

Unducted fan (open rotor)

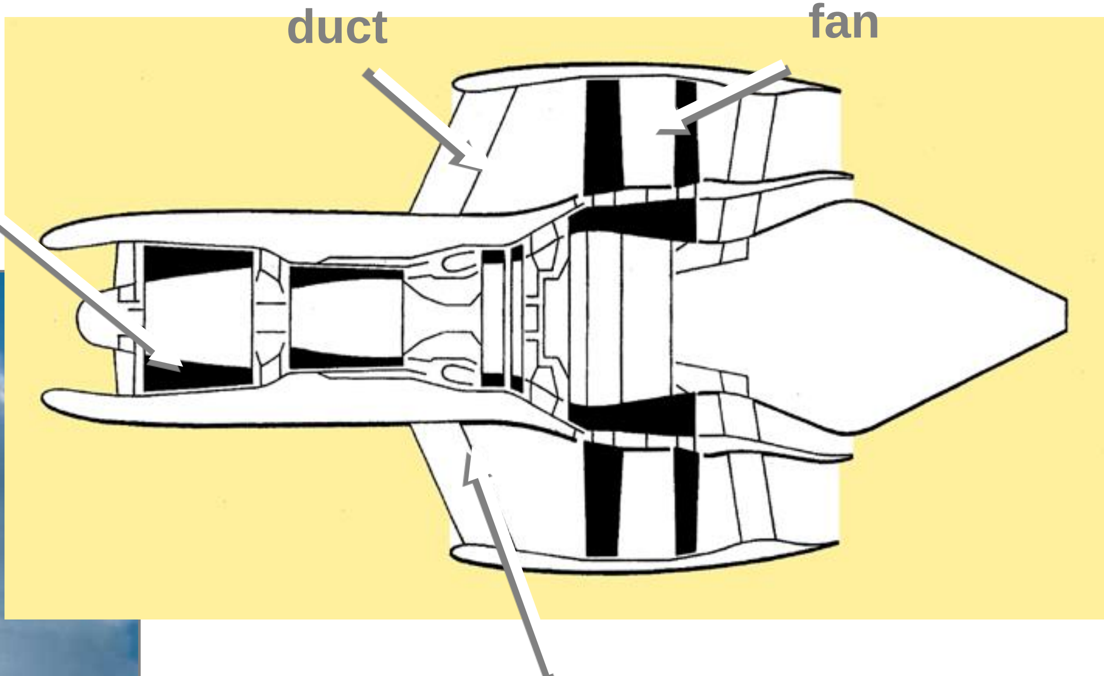
General Electric GE36

NASA research fan


Antonov An70


EasyJet engine design !

Future Aircraft Configurations



Flying wing

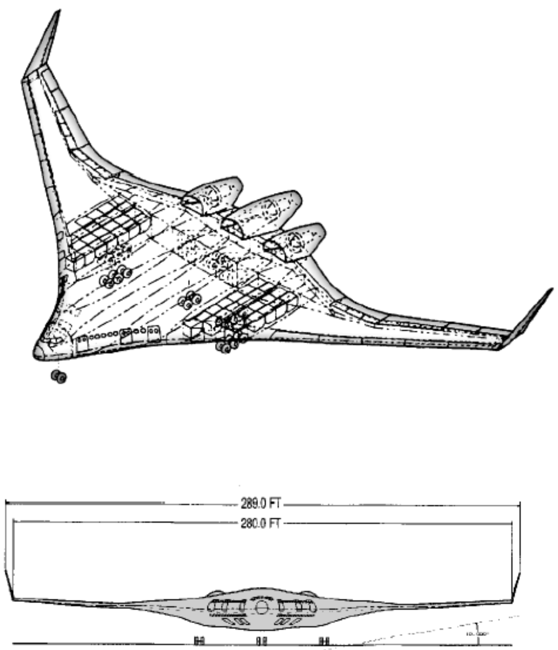
Blended wing aircraft may offer up to 30% reduction in fuel consumption - 40% if combined with electric engine concepts

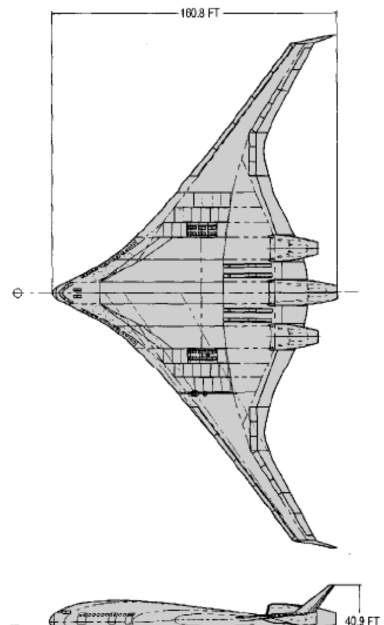
Blended Wing Body (BWB)

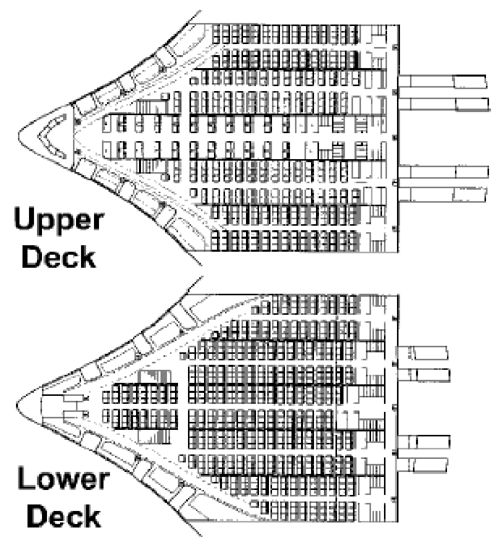
- The fuselage is also a wing.

Northrop YB-49 (1948)

B-2 (1989)



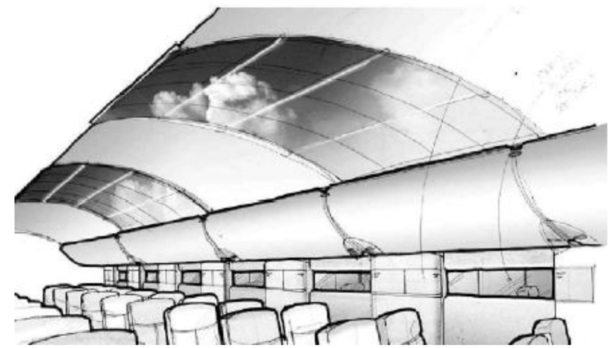


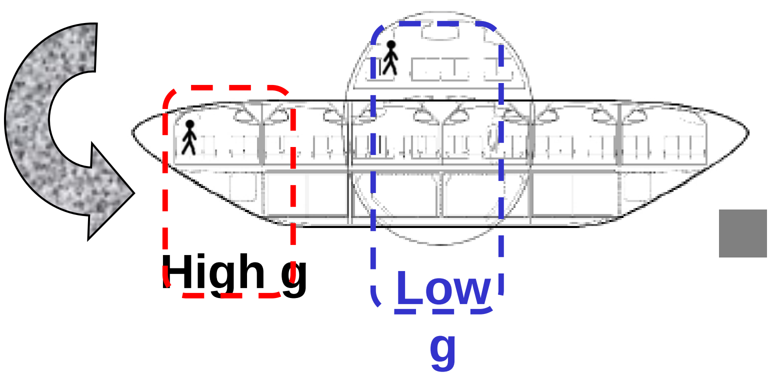


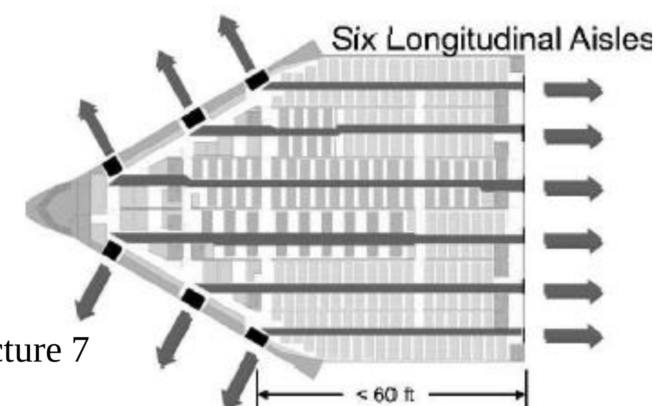
BWB challenges

- Non-tubular pressure vessel
- Engine access
- BWB/airport integration

- Passenger evacuation (90s)
- G-forces experienced in lateral positions
- Passenger acceptability







Factors affecting choice of Specific Thrust

- On "conventional" underwing designs, nacelle diameter is a key factor in terms of layout ground clearance, undercarriage length etc.
- Airframe defines geometric constraints & hence has a key role in setting of specific thrust.
- Final choice a compromise between environment (emissions & noise), fuel burn, installation issues, cost etc.

Specific Thrust Variation

Sea Level Static ISA+15

- **Thrust =** 150 kN (33,700 Lb)
- **Mass Flow =** 500 kg/s (1100 lb/s)
- **Specific Thrust =** 300 m/s (30.6 Lb/lb/s 984 ft/s)

Top of Climb M=0.8, 35,000ft ISA

- **Thrust ~** 0.2 Take-off Thrust (approx.)
- **Mass Flow =** Same flow function $W\sqrt{T_o}/P_o$
- **Specific Thrust =** 155 m/s (15.8 Lb/lb/s 508 ft/s)
- **Jet Velocity =** 392 m/s (1286 ft/s)
- **Jet Velocity/Flight Velocity =** 1.65

Top of climb Specific Thrust ~ half of Take-off Specific Thrust

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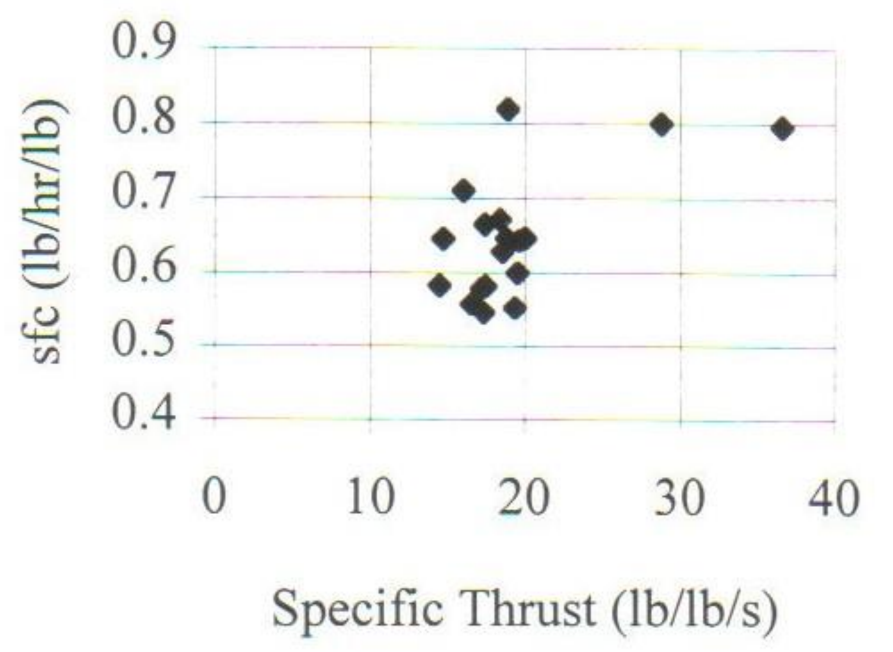
Specific Thrust as a key parameter

To a first order Specific Thrust determines:

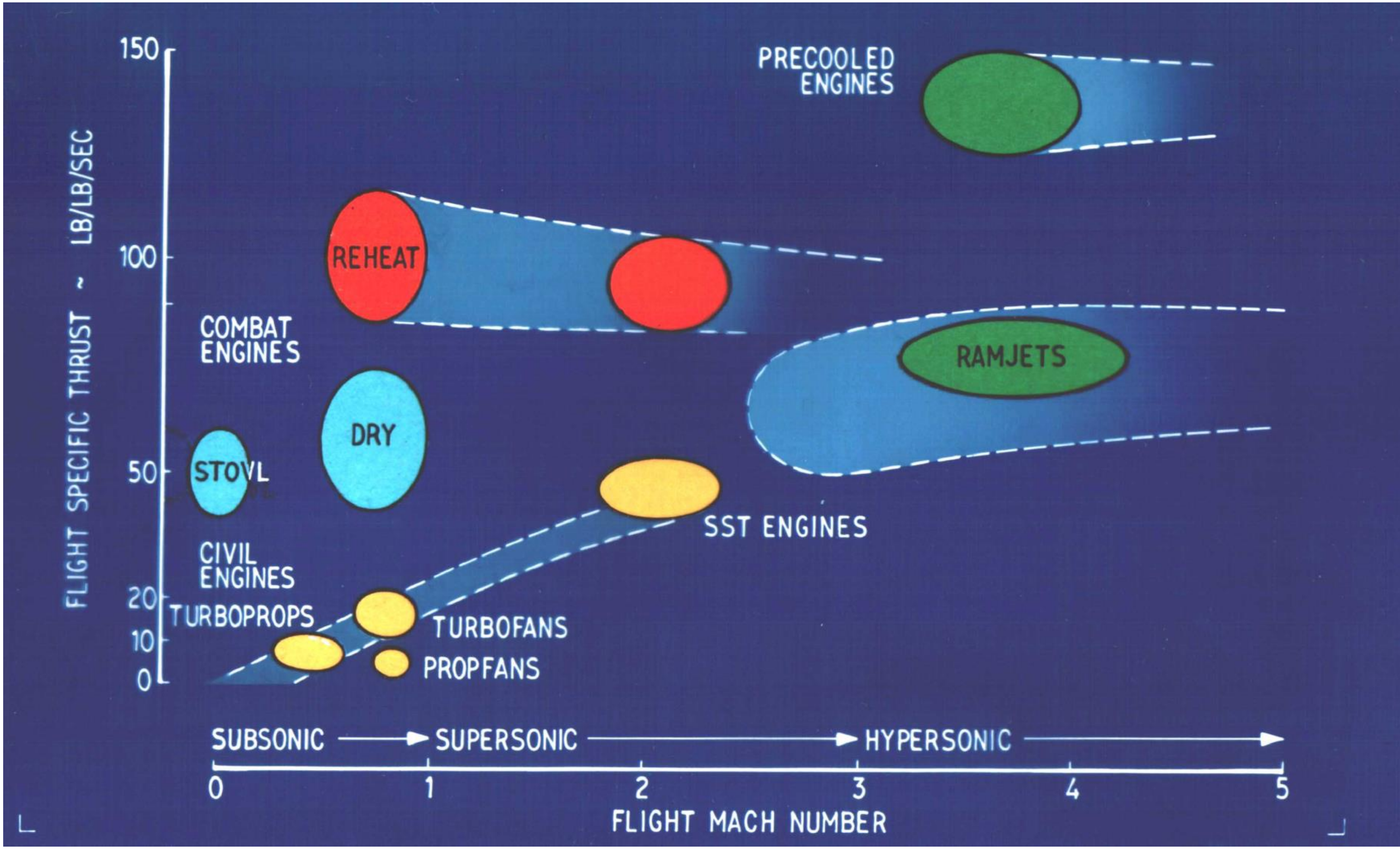
- Mean speed of jet.
- Fan diameter for a given thrust.
- Engine geometry, mass & cost.
- Nacelle envelope, mass, drag.

Current turbofan engines at cruise



Specific Thrust at cruise conditions, typically M = 0.8 at 35,000ft

Specific Thrust - Variation with design flight speed



Optimisation of Gas Turbines & Aero Engines

- **Work by Dr A Guha (papers on Blackboard)**

- **Optimisation of aero gas turbine engines ***

  The Aeronautical Journal July 2001

- **Optimum Fan Pressure Ratio for Bypass Engines with Separate or Mixed Exhaust Streams**

  Journal of Propulsion & Power Vol 17 No 5 October 2001

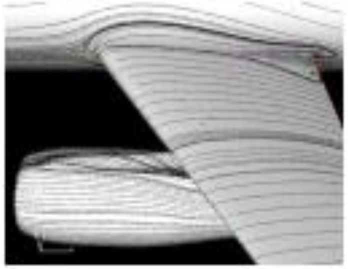
- **Performance & optimisation of gas turbines with real gas effects ***

  Proc Inst Mech Engrs Vol 215 Part A

(* Paper on Blackboard)

Fuel burn – the final arbiter ?

Drag



Engine Fuel Burn

SFC

Weight

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Or should the final arbiter be Overall life-cycle cost ?

Key Lessons from Lecture 7

- Choice thermodynamic cycle for low specific thrust engines a function of many inter-related variables.
- Specific Thrust is the key parameter in setting engine cycle.
- There is a "theoretical" optimum cycle for a given level of specific thrust but this is relatively insensitive to small changes in other parameters.
- Many other factors e.g. powerplant installation (position & drag), mass, mechanical issues (e.g. stability, need for a gearbox, engine layout etc.) all influence the final choice.
- For any specific manufacturer its design style, level of technology, use of existing cores etc. all influence the final choice.

Cycle Choice ~ Military & Supersonic Transports

Objective ~ Lecture 8

To outline the reasons for the choice of engine cycle for Combat Aircraft & Supersonic Transport Aircraft.