Chapters 10 and 13
Propulsion and Fuel Systems Integration
Secondary Power

Chapters 10 and 13

Propulsion and Fuel Systems Integration

Secondary Power

Breguet Range Equation Design Drivers

For given speed of sound, a, and initial weight, $W_{initial}$

$$R = \frac{a}{C}\left[M\left(\frac{L}{D}\right)\right]\ln\left(\frac{W_{initial}}{W_{final}}\right)$$

Propulsion

Aerodynamics

Structures and Materials

Source: Musée de lAir

Propulsion System Choices

- What kind of engine to select

- Where to install it

$\eta = \eta$

Engine Cycle Efficiency

$$\eta = \eta_{th} \text{ x } (\eta_p \text{ x } \eta_t)$$

where

η = overall efficiency

η_{th} = thermal efficiency

η_p = propulsive efficiency

η_t = transmission efficiency

Thrust Specific Fuel Consumption

$$\text{Defined as:} \quad \frac{\text{Fuel Flow}}{\text{Thrust}}$$

Units are:

$$\left[\left(\frac{lb}{hr}\right)\frac{1}{lb}\right] \text{or, more usually} \left[\frac{lb}{lb\ hr}\right]$$

Propulsive Efficiency η_p

V = air velocity in
V_j = air velocity out
$\dot{m}_a$ = air mass flow rate

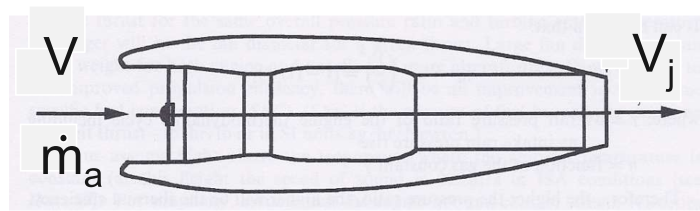
Thrust $F = \dot{m}_a \left(V_j - V \right)$

$$F = \dot{m}_a V \left(\frac{V_j}{V} - 1 \right)$$

$$\text{Propulsive efficiency} = \frac{\text{Useful power}}{\text{Power added}}$$

$$\text{Useful power} = FV = \dot{m}_a V \left(V_j - V \right)$$

$$\text{Power added} = \frac{1}{2} \dot{m}_a V_j^2 - \frac{1}{2} \dot{m}_a V^2$$



$$\eta_p = \frac{\dot{m}_a V \left(V_j - V \right)}{\frac{1}{2} \dot{m}_a \left(V_j^2 - V^2 \right)}$$

$$= \frac{2V \left(V_j - V \right)}{\left(V_j - V \right) \left(V_j + V \right)}$$

$$\eta_p = \frac{2V}{V_j + V} = \frac{2}{1 + \frac{V_j}{V}}$$

For highest η_p
$V_j = V + \Delta V$
where ΔV is as small as possible

But mass flow rate must be large

Propulsive efficiency consequences

- Highest efficiency (η_p) when $V_j = V$, but thrust (F) is zero
- For higher (thrust)/(mass flow), must accept lower propulsive efficiency

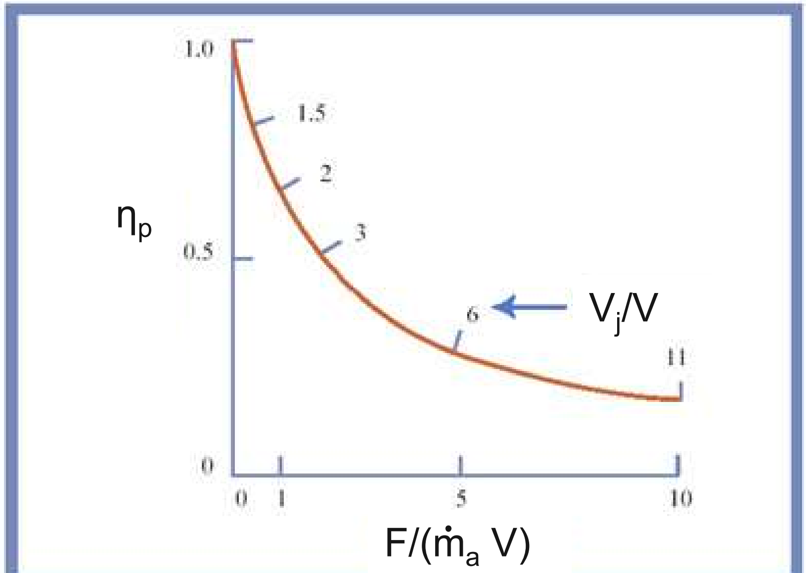
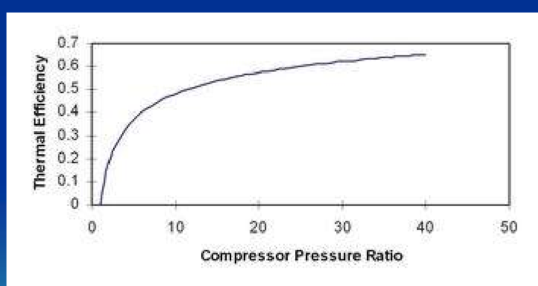


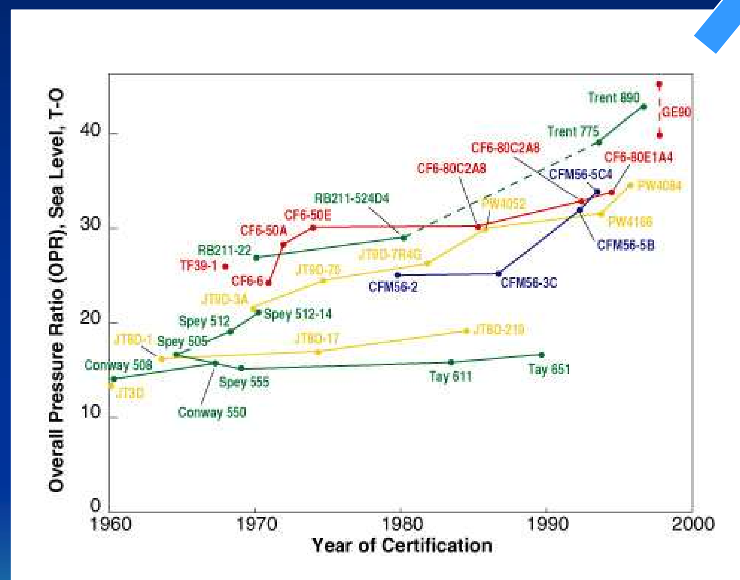
Image adapted from: Kerrebrock, J. L. *Aircraft Engines and Gas Turbines*. 1991.

Historical trends in overall pressure ratio

RB3025 OPR=62
GE9X   OPR=60

Higher thermal efficiency achieved with higher overall pressure ratio

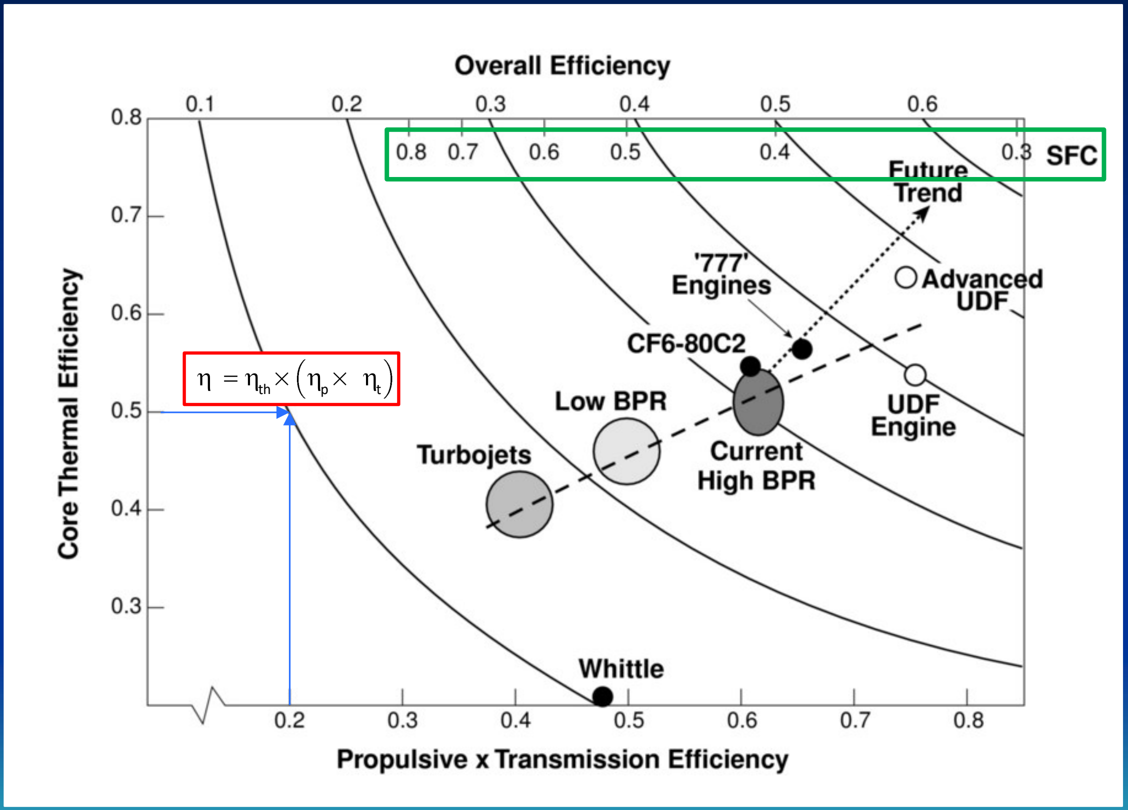




Source: web.mit.edu

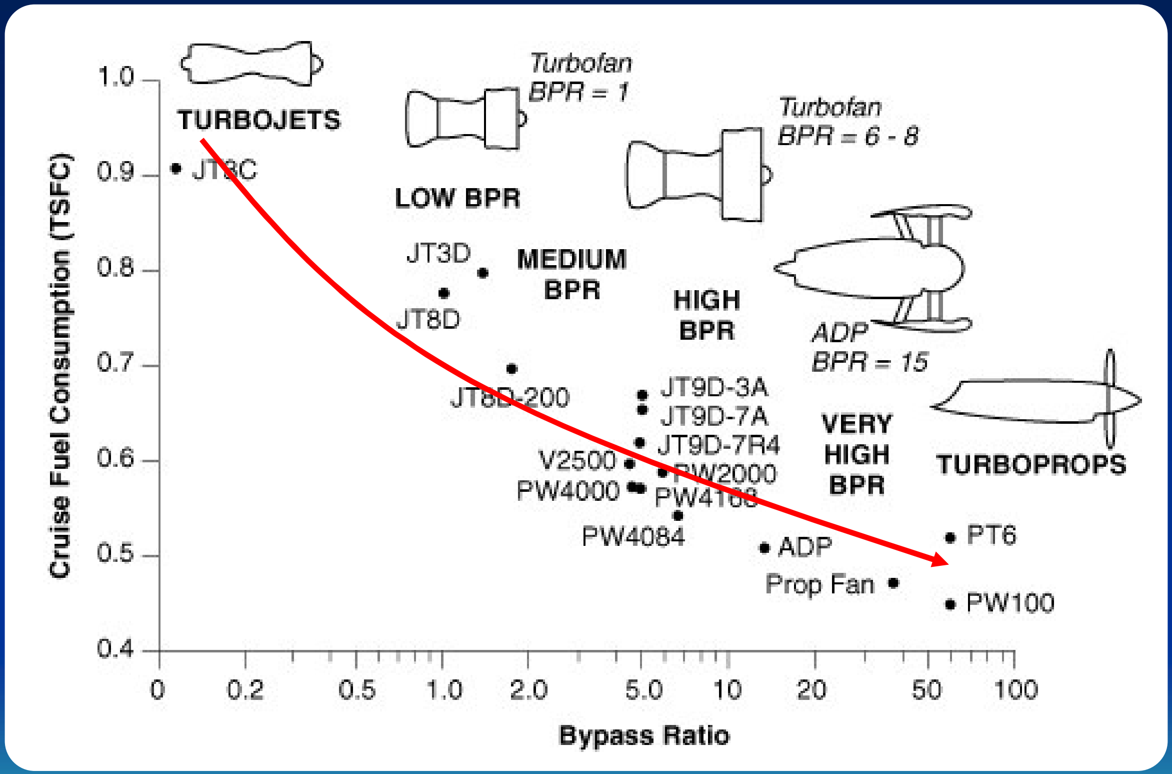
Trends in thermal and propulsive efficiences

- Improvement in propulsive efficiency comes at a cost in engine weight

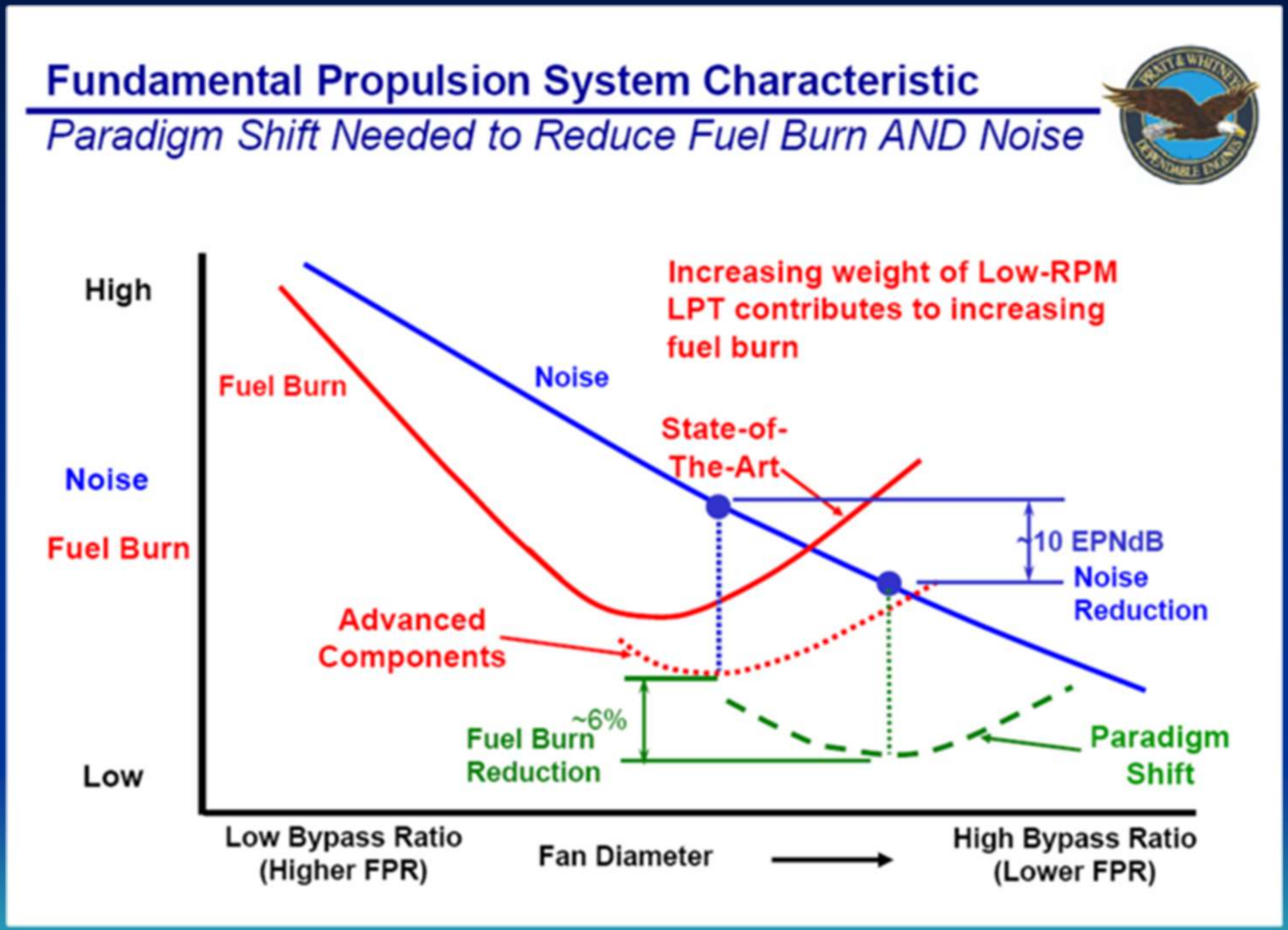


Source: MIT http://mit.edu/16.unified/www/FALL/thermodynamics/notes/node84.html

Trends in TSFC



Source: Epstein, 1998



Fundamental Propulsion System Characteristic
Paradigm Shift Needed to Reduce Fuel Burn AND Noise
High
Noise
Fuel Burn
Low
Fuel Burn
Noise
Increasing weight of Low-RPM LPT contributes to increasing fuel burn
State-of-The-Art
~10 EPNdB
Noise Reduction
Advanced Components
~6%
Fuel Burn Reduction
Paradigm Shift
Low Bypass Ratio (Higher FPR)
Fan Diameter
High Bypass Ratio (Lower FPR)

Possible paths

Current designs

Unducted fan

Higher BPR by refining fan and turbine design

Geared fan

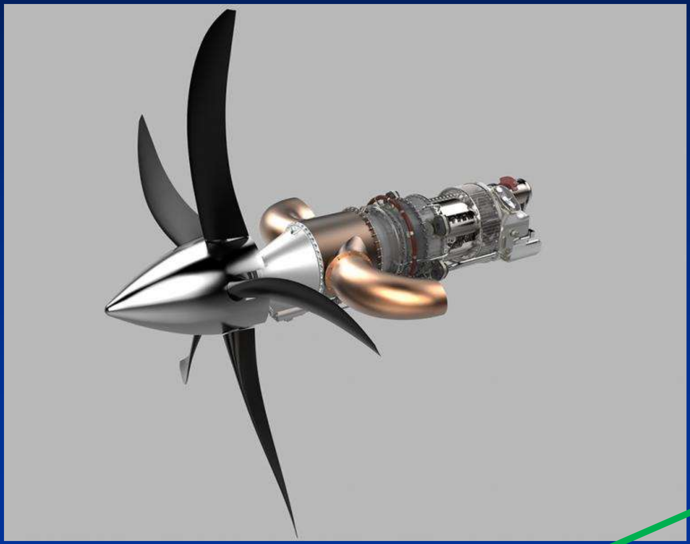
Propellers

- Propeller is most efficient propulsor
  - Increases $C_{L_{max}}$ for takeoff and landing
  - Limited by tip speed
  - Swept blades permit increase in tip speed
  - Cannot be stealthy

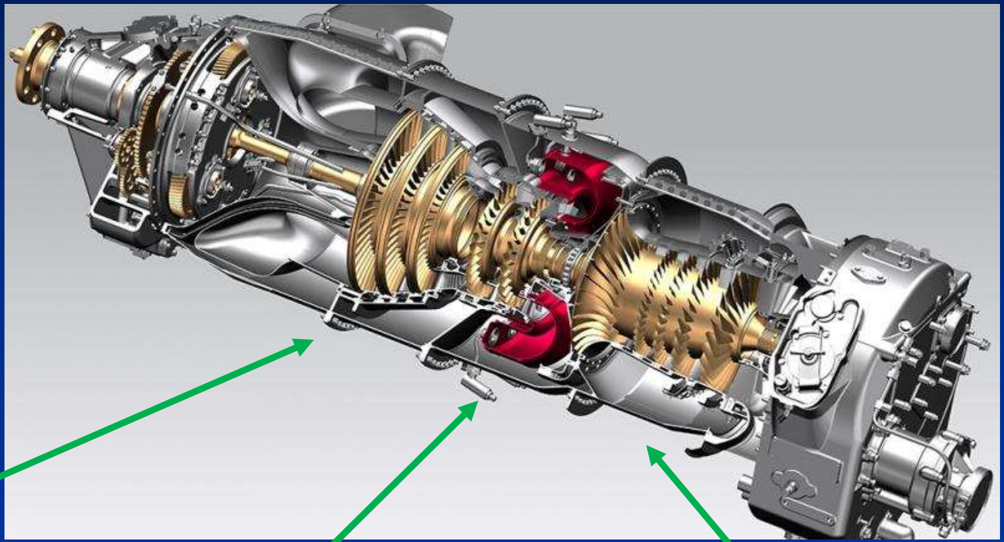
Lockheed C-130H

Lockheed Martin C-130J

GE Advanced Turboprop (ATP)



GE-93

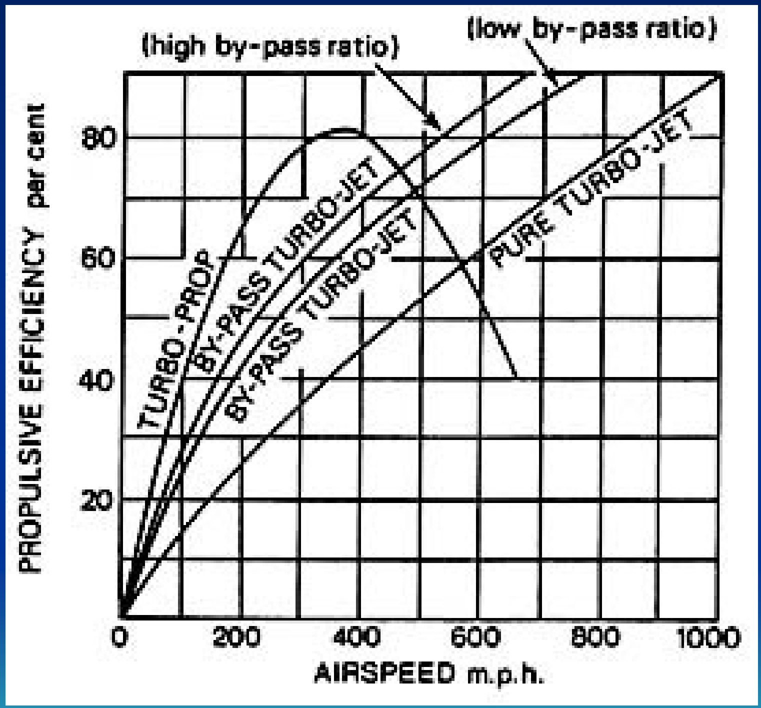


GE-93 Cutaway

- 2 stage compressor turbine
- 3 stage power turbine
- Reverse flow annular combustor
- 4 stage axial + 1 stage radial compressor

Loss of Propeller Propulsive Efficiency Limits Speed

- If blades are unswept, propulsive efficiency falls off at around 350 m.p.h. (300 kt)
- Swept blades permit speeds up to 360 kt



High Bypass Ratio Turbofan

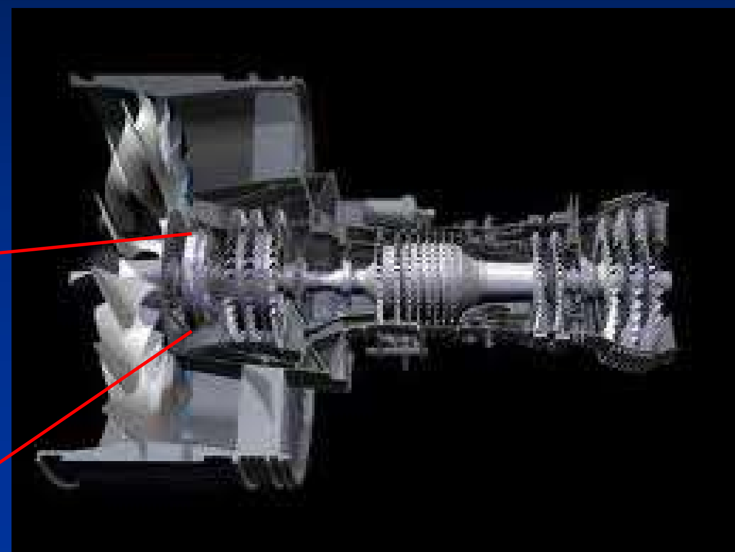
- GE90
  - Twin spool
  - Composite fan blades
  - Thrust from 74,000 lb to 115,000
  - BPR = 9, OPR = 40
  - IOC 1995
  - T/W = 5.6
  - Installed on B777

High Bypass Ratio Turbofan

- RR Trent 1000
  - Three spool
  - Composite fan blades
  - Thrust from 53,000 – 78,000 lb
  - BPR 10.8 to 11; OPR = 52
  - IOC 2007
  - Installed on B787
  - No bleed: power takeoff on IP shaft
  - Engine T/W = 6.2

Geared turbofan

- PW-1000 series
  - Planetary gearbox is compact and light (similar to 2nd stage of PT-6 reduction gearbox)



Rolls-Royce RB3025

- BPR = 12:1
- OPR = 62:1

- Unsuccessful candidate for 777X (GE offered “development contribution” in exchange for exclusive contract for GE9X)

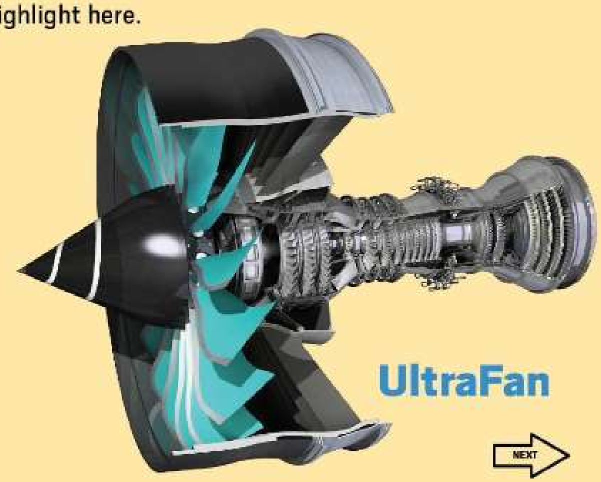
www.flightglobal.com

Advancing Propulsion

AVIATION WEEK

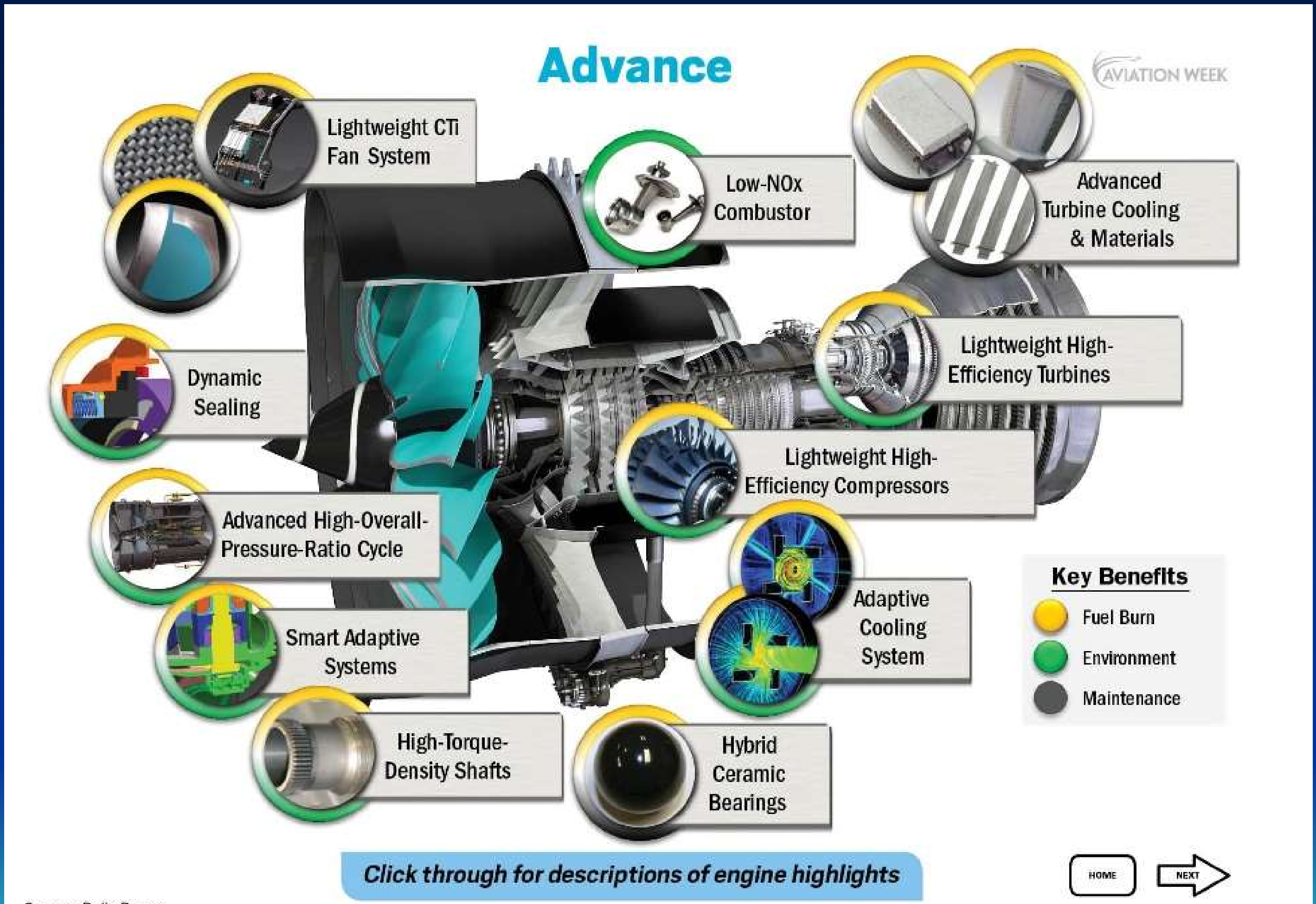
Rolls-Royce is revealing more about its engine development plan, which calls for a two-phase evolution from today's Trent XWB. The first engine, the Advance, is aimed at entry into service around 2020 and will have a bypass ratio in excess of 11:1, an overall pressure ratio of more than 60:1 and a fuel-burn level at least 20% better than the current Trent 700. The second, more ambitious follow-on engine is called the UltraFan, which Rolls first revealed in concept form in early 2012 as part of NASA's Environmentally Responsible Aviation (ERA) study with Lockheed Martin. The engine could be ready for service in 2025 and is targeted at a fuel-burn improvement of at least 25% over the Trent 700. The UltraFan will incorporate a fan-drive gear system that drives a variable pitch fan and is outlined with a 15:1 bypass ratio and overall pressure ratio of 70:1.

The two-step evolution involves not only fundamental changes in engine architecture but also the introduction of multiple new technologies that we highlight here.



NEXT

Source: Rolls-Royce



Source: Rolls-Royce

Advance

AVIATION WEEK

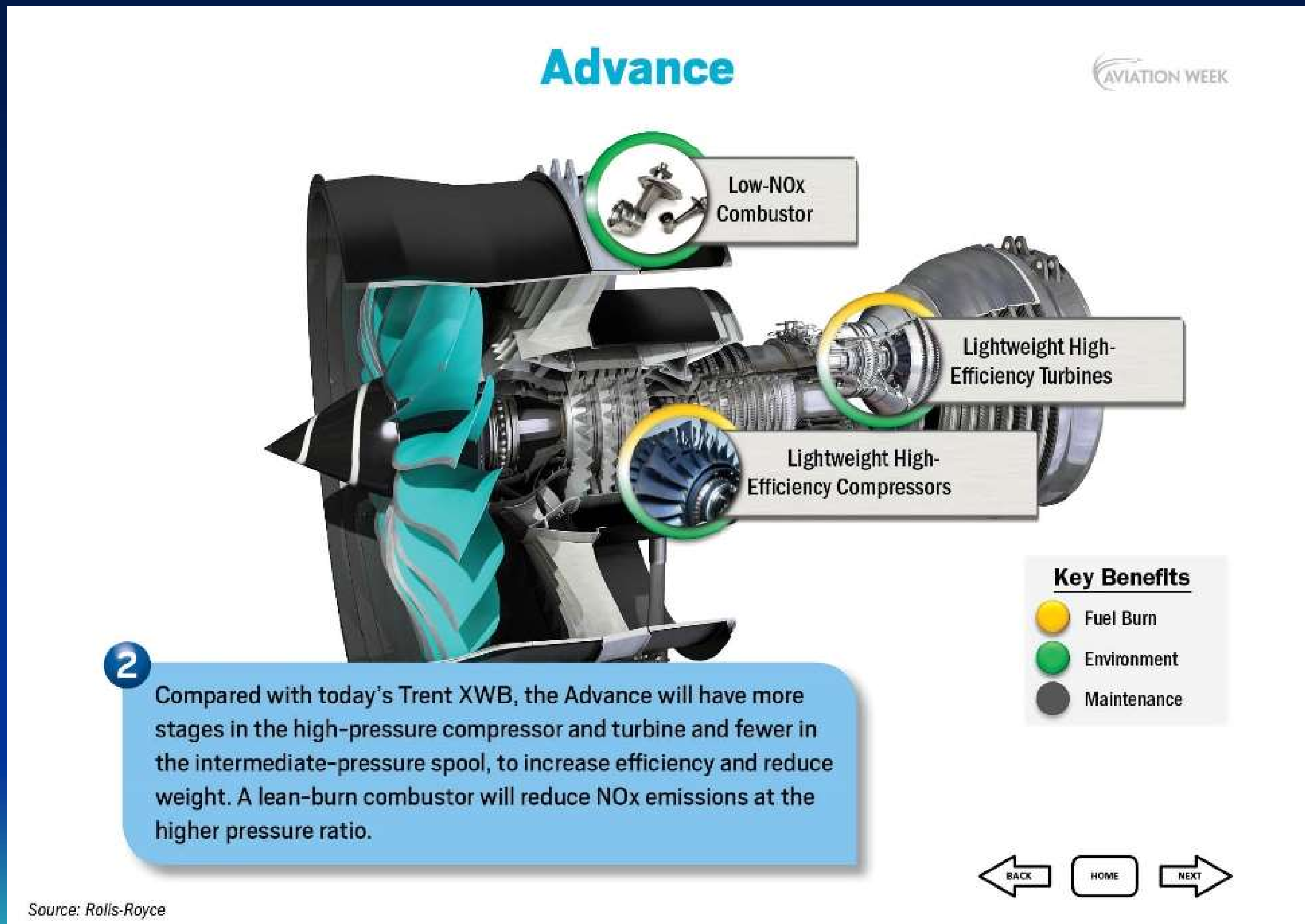
The most obvious external feature of the Advance will be the engine's lightweight CTi (composite-titanium) wide-chord fan blades. In addition, harnesses and pipes will be embedded in a composite "raft" that attaches to the composite fan casing for easier assembly.

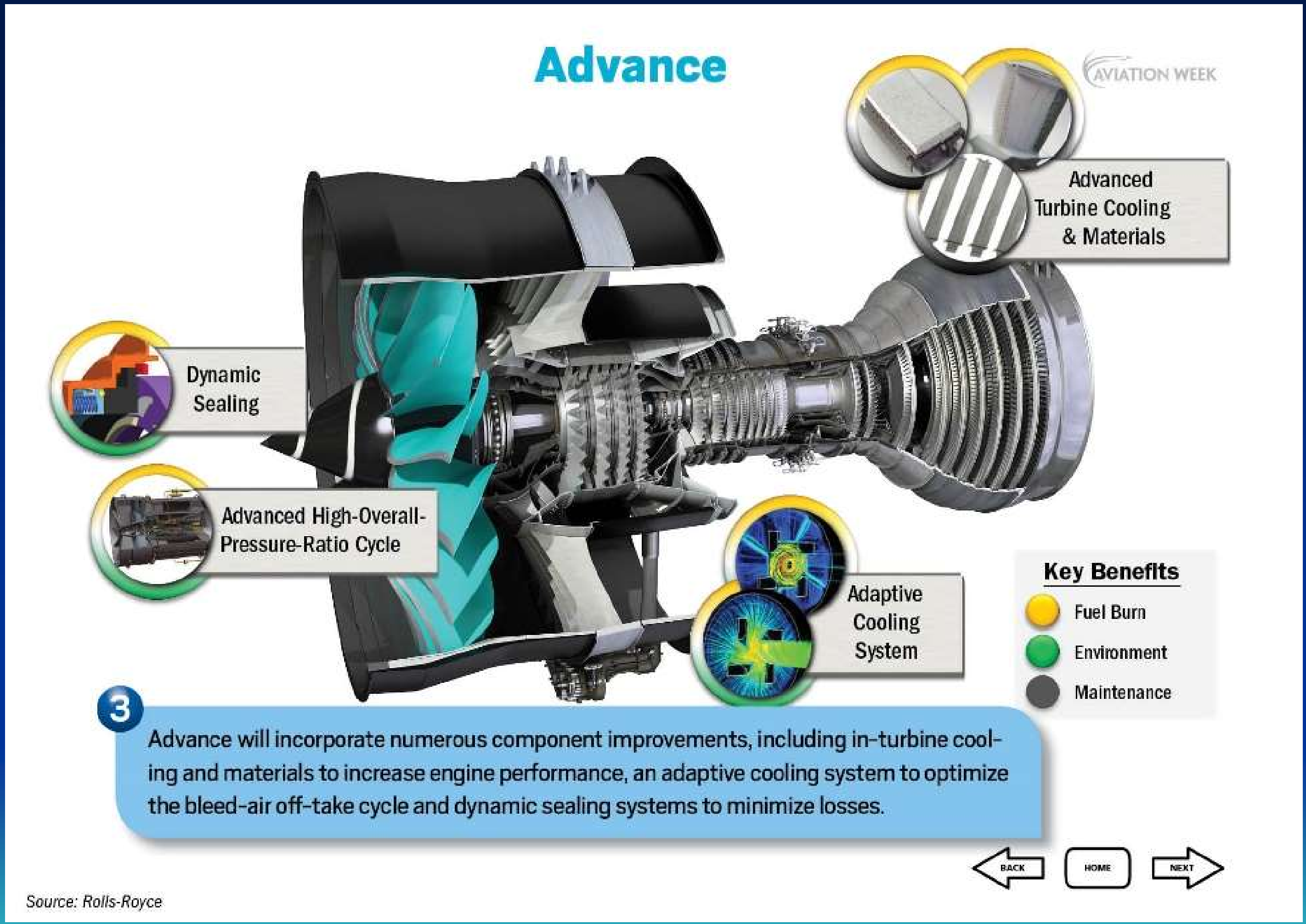
Key Benefits

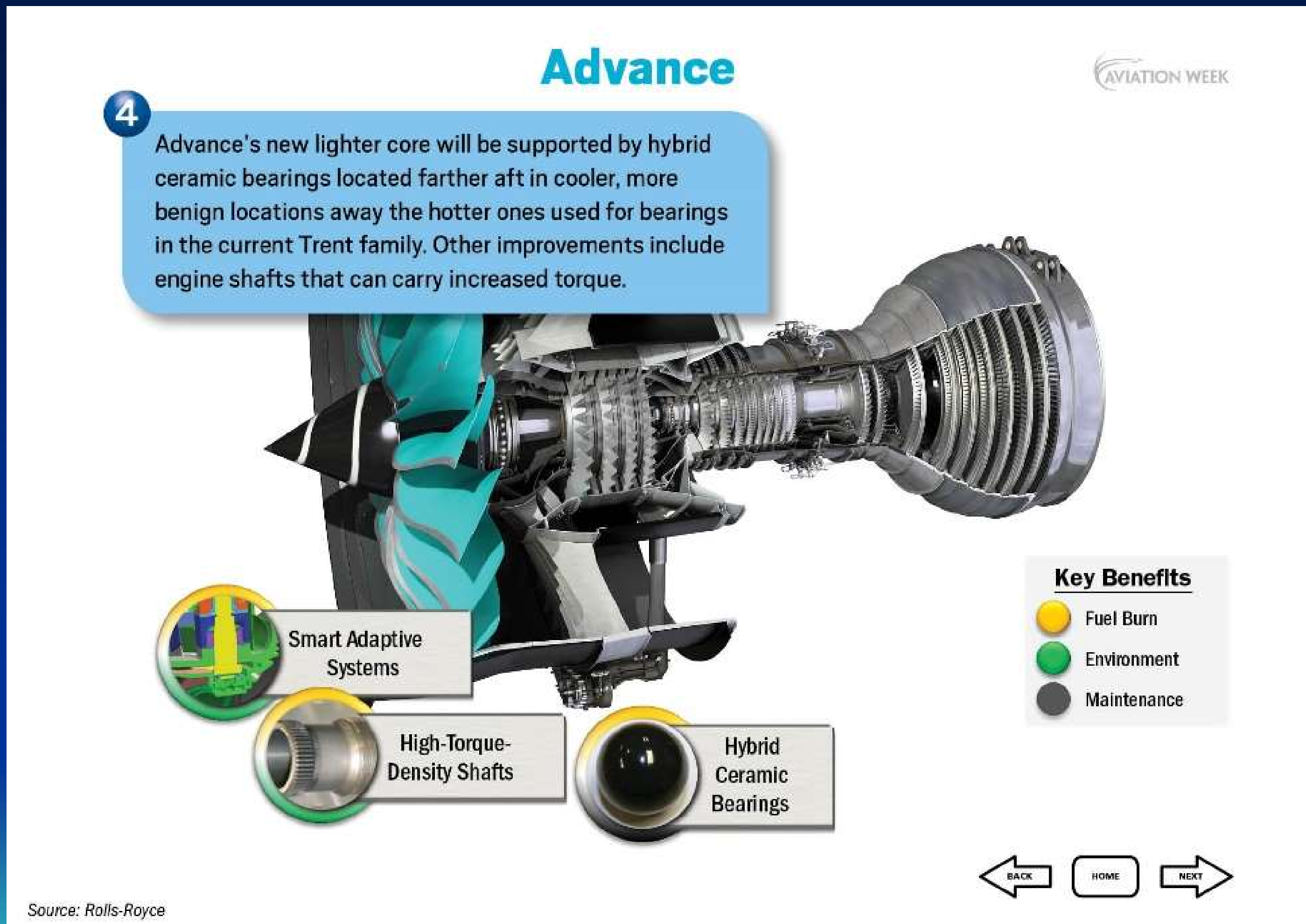
- Fuel Burn
- Environment
- Maintenance

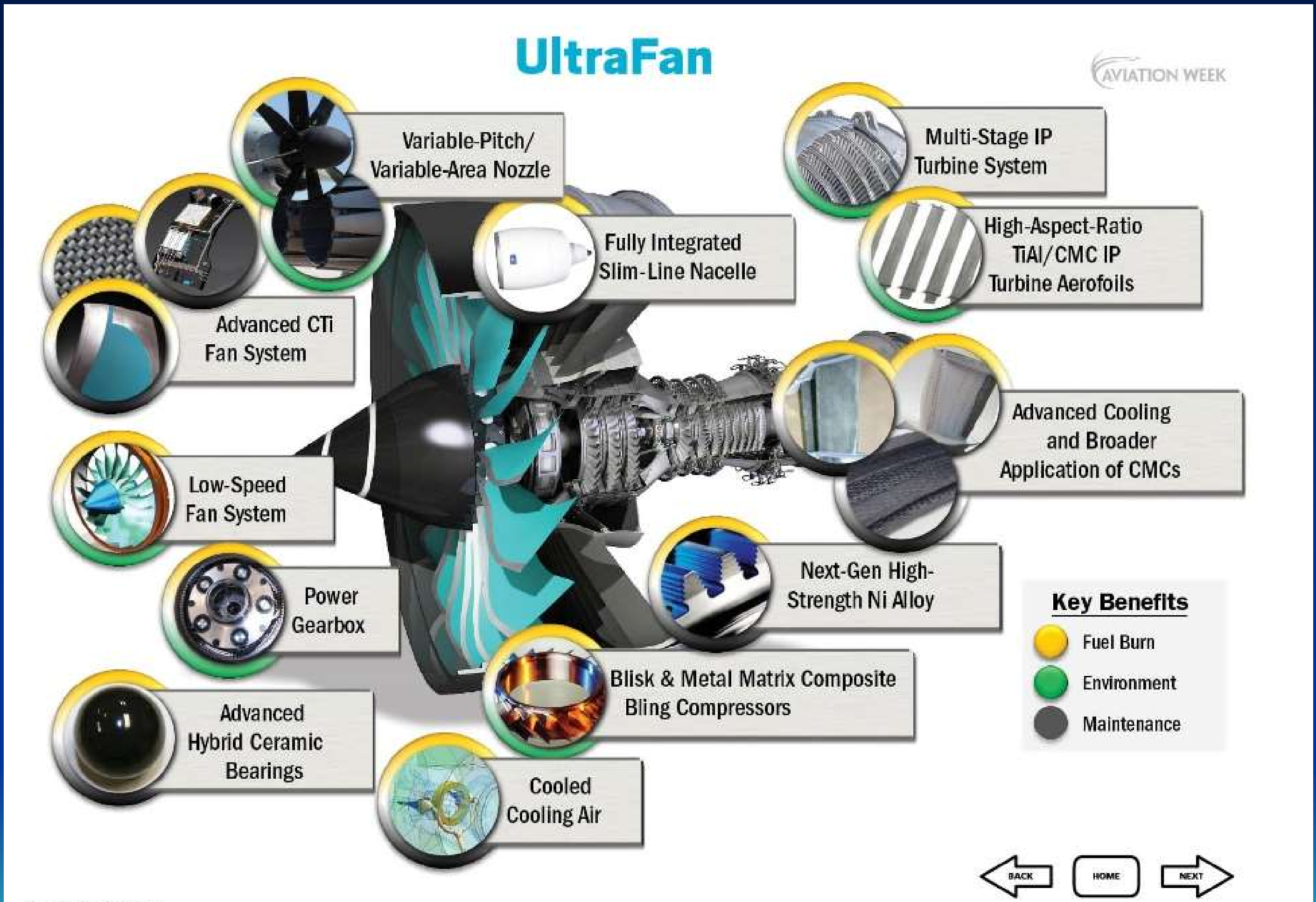
BACK HOME NEXT

Source: Rolls-Royce

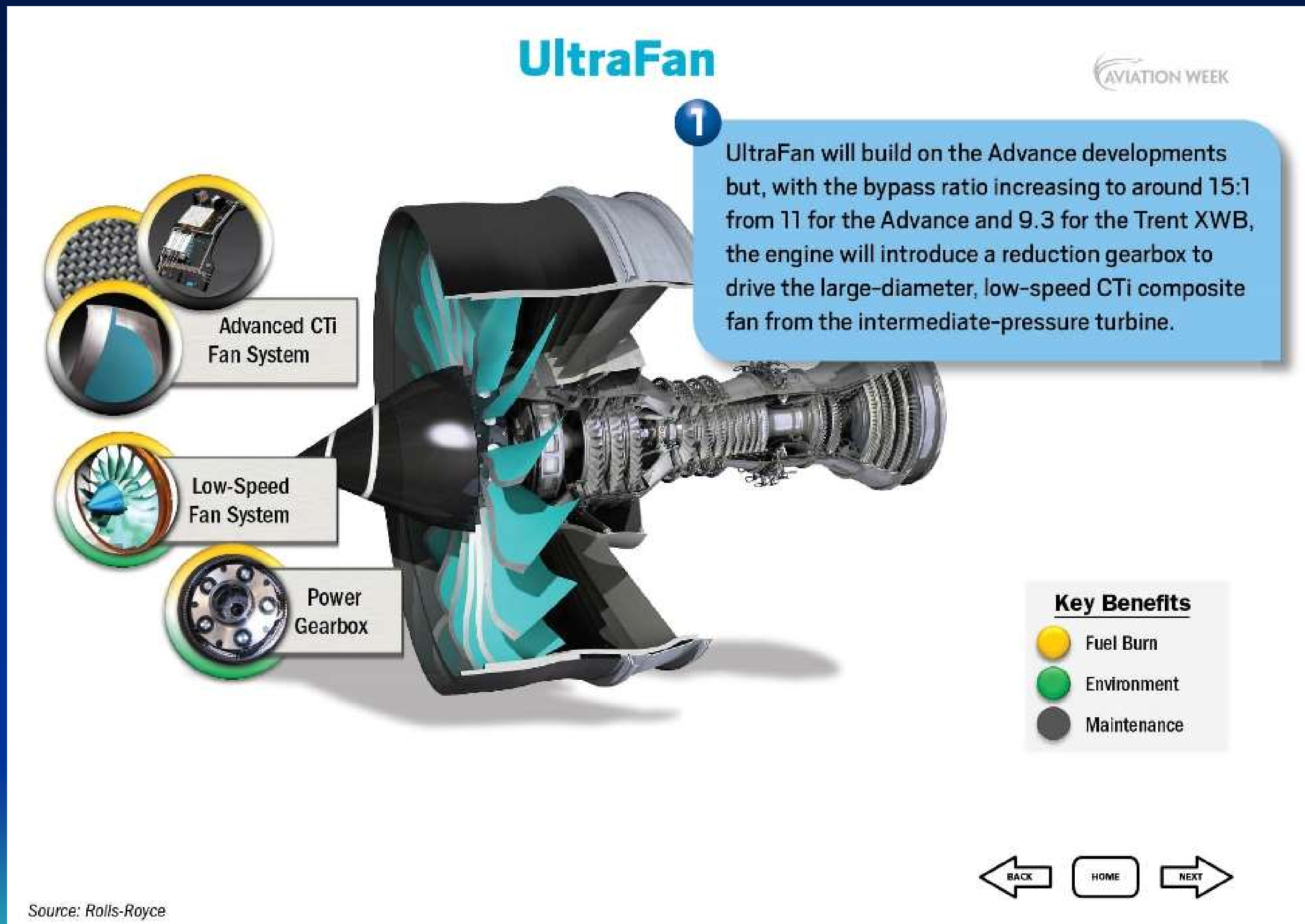

Advance
AVIATION WEEK
Low-NOx Combustor
Lightweight High-Efficiency Turbines
Lightweight High-Efficiency Compressors
Key Benefits
Fuel Burn
Environment
Maintenance
2
Compared with today's Trent XWB, the Advance will have more stages in the high-pressure compressor and turbine and fewer in the intermediate-pressure spool, to increase efficiency and reduce weight. A lean-burn combustor will reduce NOx emissions at the higher pressure ratio.
BACK
HOME
NEXT
Source: Rolls-Royce

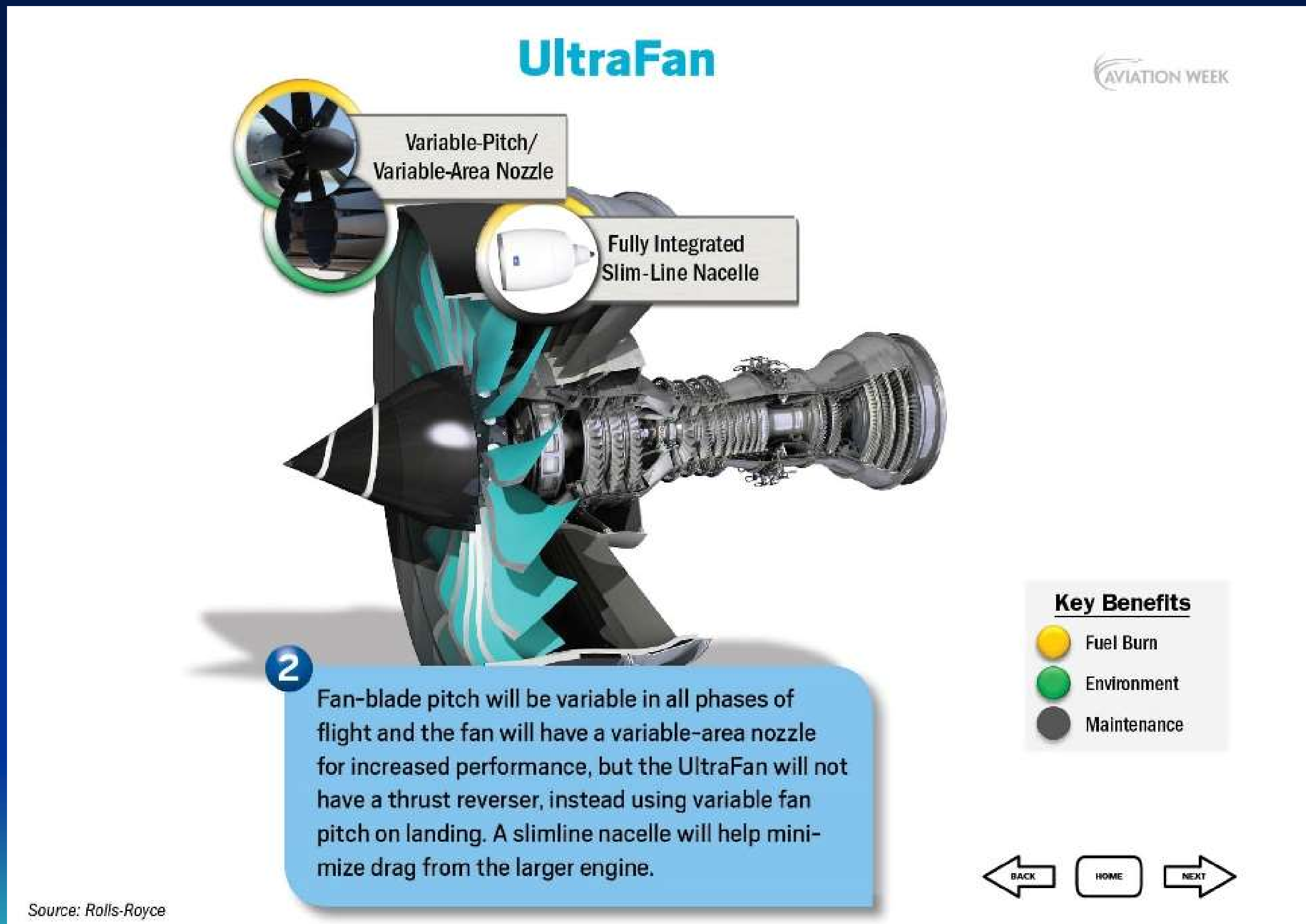

Advance
AVIATION WEEK
Advanced Turbine Cooling & Materials
Dynamic Sealing
Advanced High-Overall-Pressure-Ratio Cycle
Adaptive Cooling System
Key Benefits
Fuel Burn
Environment
Maintenance
3
Advance will incorporate numerous component improvements, including in-turbine cooling and materials to increase engine performance, an adaptive cooling system to optimize the bleed-air off-take cycle and dynamic sealing systems to minimize losses.
BACK
HOME
NEXT
Source: 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.
Smart Adaptive Systems
High-Torque-Density Shafts
Hybrid Ceramic Bearings
Key Benefits
Fuel Burn
Environment
Maintenance
BACK
HOME
NEXT
Source: Rolls-Royce



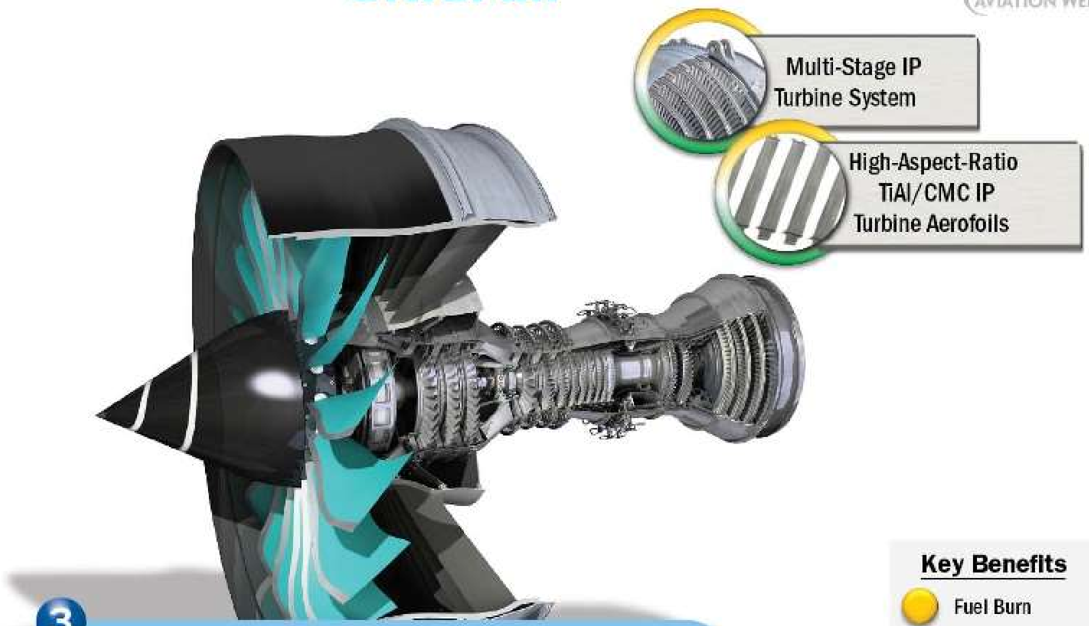
Source: Rolls-Royce


UltraFan
AVIATION WEEK
1
UltraFan will build on the Advance developments but, with the bypass ratio increasing to around 15:1 from 11 for the Advance and 9.3 for the Trent XWB, the engine will introduce a reduction gearbox to drive the large-diameter, low-speed CTi composite fan from the intermediate-pressure turbine.
Advanced CTi Fan System
Low-Speed Fan System
Power Gearbox
Key Benefits
Fuel Burn
Environment
Maintenance
BACK
HOME
NEXT
Source: Rolls-Royce


UltraFan
AVIATION WEEK
Variable-Pitch/ Variable-Area Nozzle
Fully Integrated Slim-Line Nacelle
2
Fan-blade pitch will be variable in all phases of flight and the fan will have a variable-area nozzle for increased performance, but the UltraFan will not have a thrust reverser, instead using variable fan pitch on landing. A slimline nacelle will help minimize drag from the larger engine.
Key Benefits
Fuel Burn
Environment
Maintenance
BACK
HOME
NEXT
Source: Rolls-Royce

UltraFan

AVIATION WEEK



Key Benefits

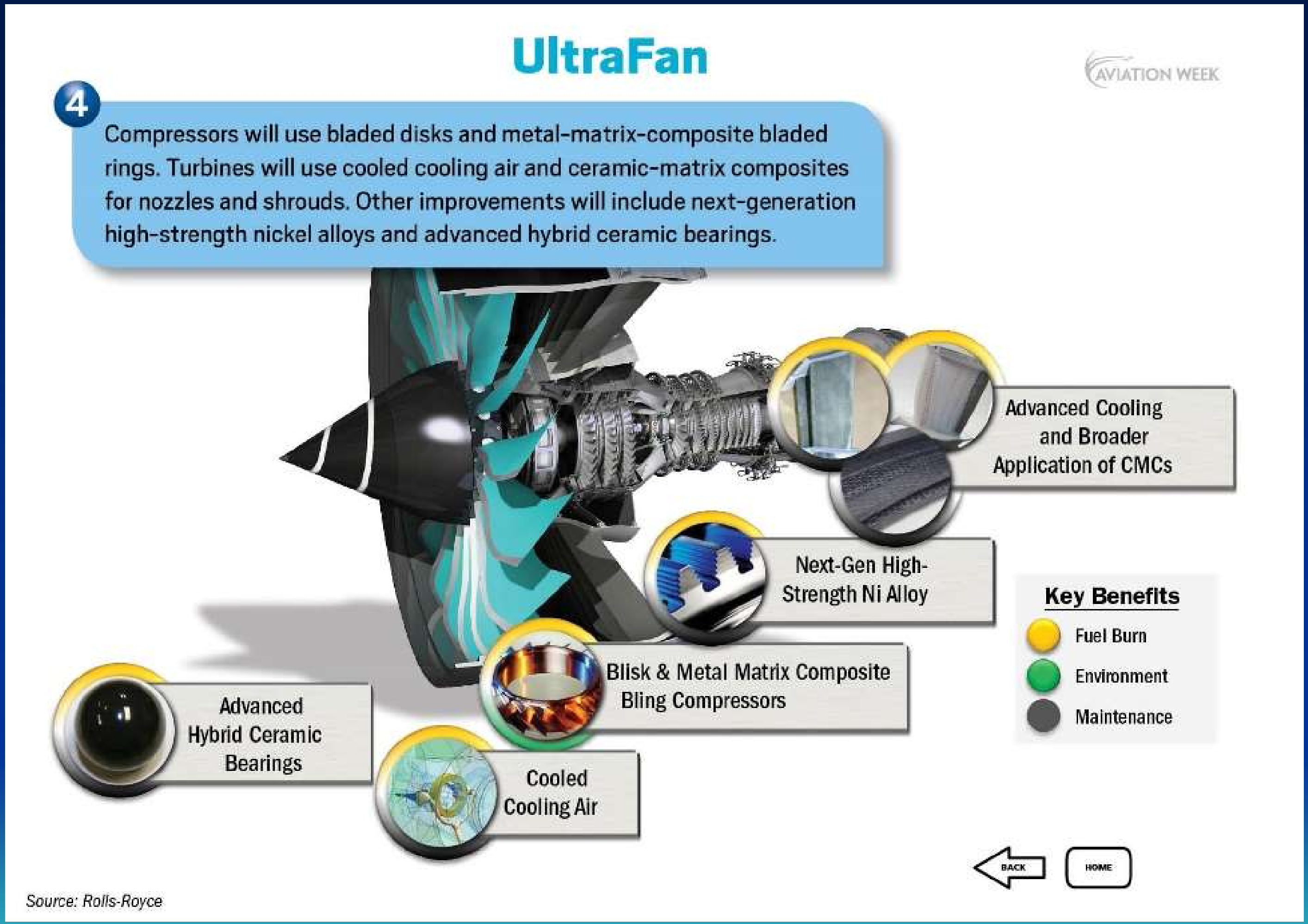
- Fuel Burn
- Environment
- Maintenance

3

UltraFan will dispense with the low-pressure turbine of the Trent and Advance engines and drive both the intermediate-pressure (IP) compressor and geared fan from the IP turbine, which will have more stages and higher-aspect-ratio titanium-aluminide blades and ceramic-matrix composite nozzles.

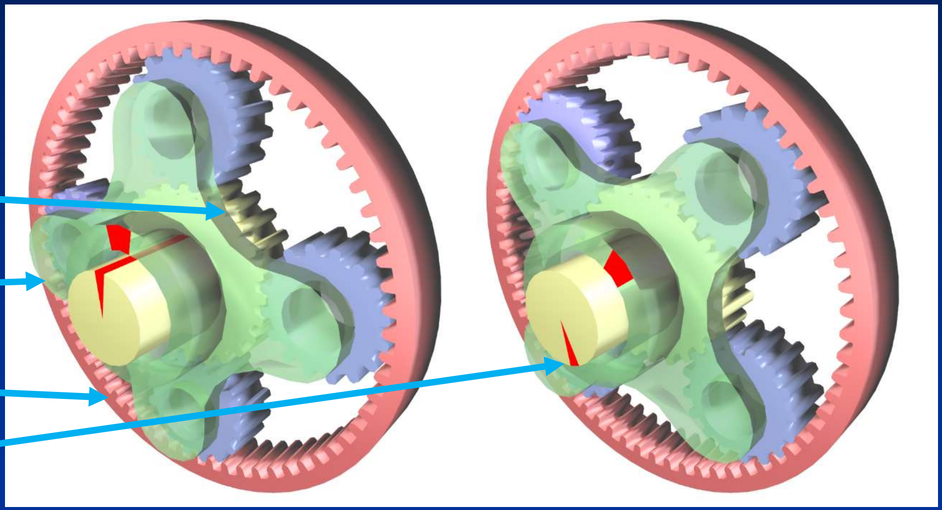
BACK HOME NEXT

Source: Rolls-Royce


UltraFan
AVIATION WEEK
4
Compressors will use bladed disks and metal-matrix-composite bladed rings. Turbines will use cooled cooling air and ceramic-matrix composites for nozzles and shrouds. Other improvements will include next-generation high-strength nickel alloys and advanced hybrid ceramic bearings.
Advanced Cooling and Broader Application of CMCs
Next-Gen High-Strength Ni Alloy
Key Benefits
Fuel Burn
Environment
Maintenance
Blisk & Metal Matrix Composite Bling Compressors
Advanced Hybrid Ceramic Bearings
Cooled Cooling Air
BACK
HOME
Source: Rolls-Royce

Ultrafan Gearbox

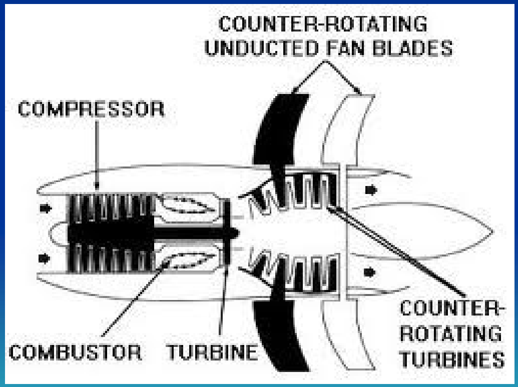
- Gear reduction
  - Turbine shaft power input at sun gear (yellow)
  - Fan attached to the planetary carrier (green)
  - Ring gear fixed (pink)
  - Gear ratio with equal diameter gears is 4:1



Unducted fan

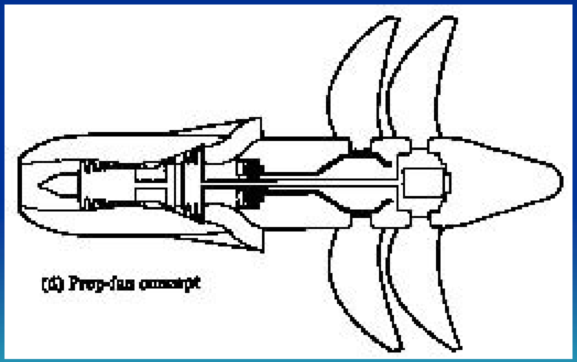
- GE36 UDF
  - Used F404 core
  - Contra-rotating props attached to LP "stators" and rotors
  - No gearbox
  - Killed by drop in oil prices in 1986

McDonnell Douglas MD-81 with GE36



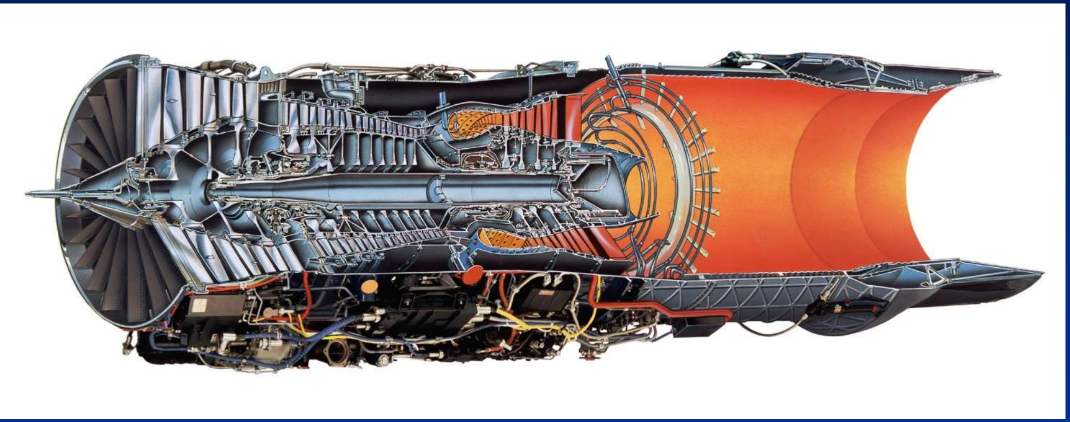
Geared Prop-fan

- Rolls-Royce prop-fan has geared counter-rotating fans
- Possible application to future Airbus concept



Copyright: Rolls-Royce

F100-PW-100 Turbofan Engine



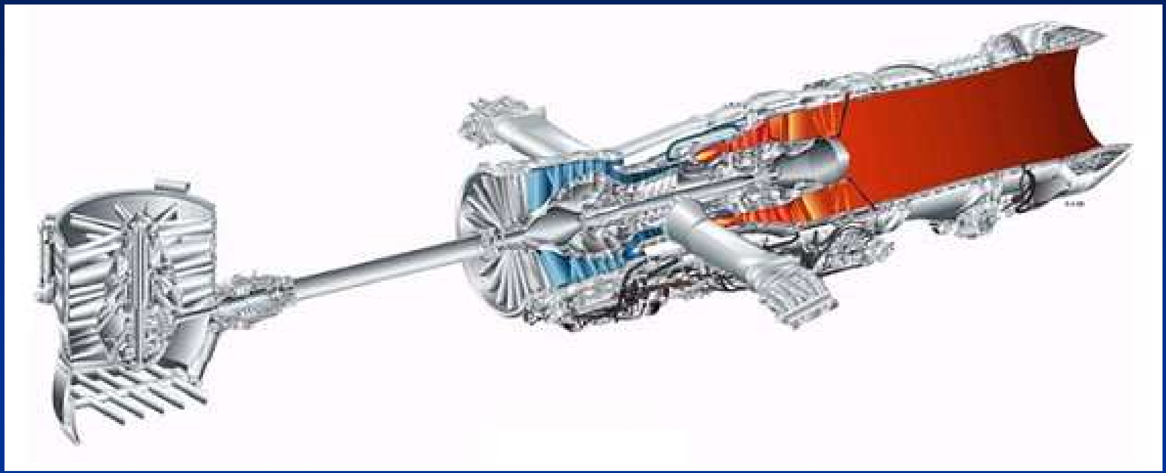
Source: UTC

- Powers F-15 & F-16
- F_n SLS (uninst.) = 23,000 lb
- BPR = 0.36
- OPR = 32
- Length = 190 in
- Diameter = 44 in
- Bare weight = 2737 lb
- Over 7000 produced

Low Bypass Ratio Turbofan

- F119-PW-100 on F-22
- 35,000 lb thrust class
- Thrust vectoring
- 2-spool (counter-rotating)
- 3-stage fan, 6-stage HP compressor

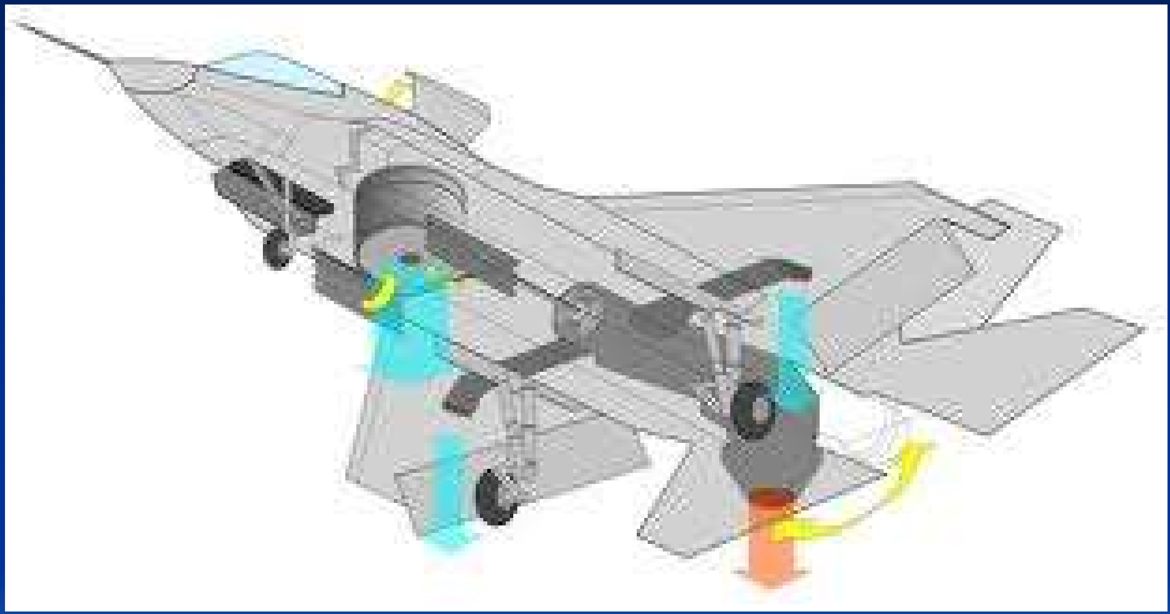
Low BPR Adapted for V/STOL



- F135-PW-100 on F-35A (USAF)
- F135-PW-400 on F-35C (USN)
- F135-PW-600 on F-35B (USMC) (shown here)

- 50,000 lb thrust
- 1-stage HP turbine, 2-stage LP turbine
- 110^0 thrust vectoring on main nozzle

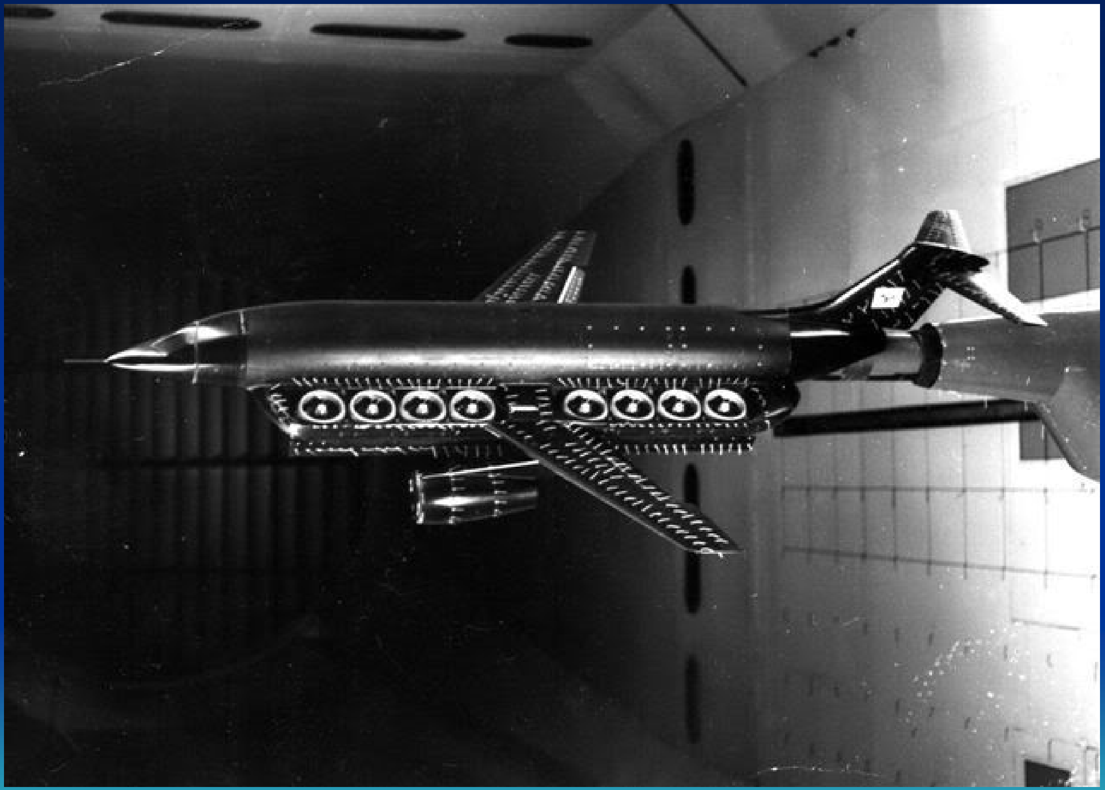
F-35B Engine Installation



F-35B Initial Sea Trial

Infinitely Strange VTOL Possibilities

- HS.141 VTOL airliner
  - 16 x RB.202 lift fans
  - 2 x RR Speys for propulsion



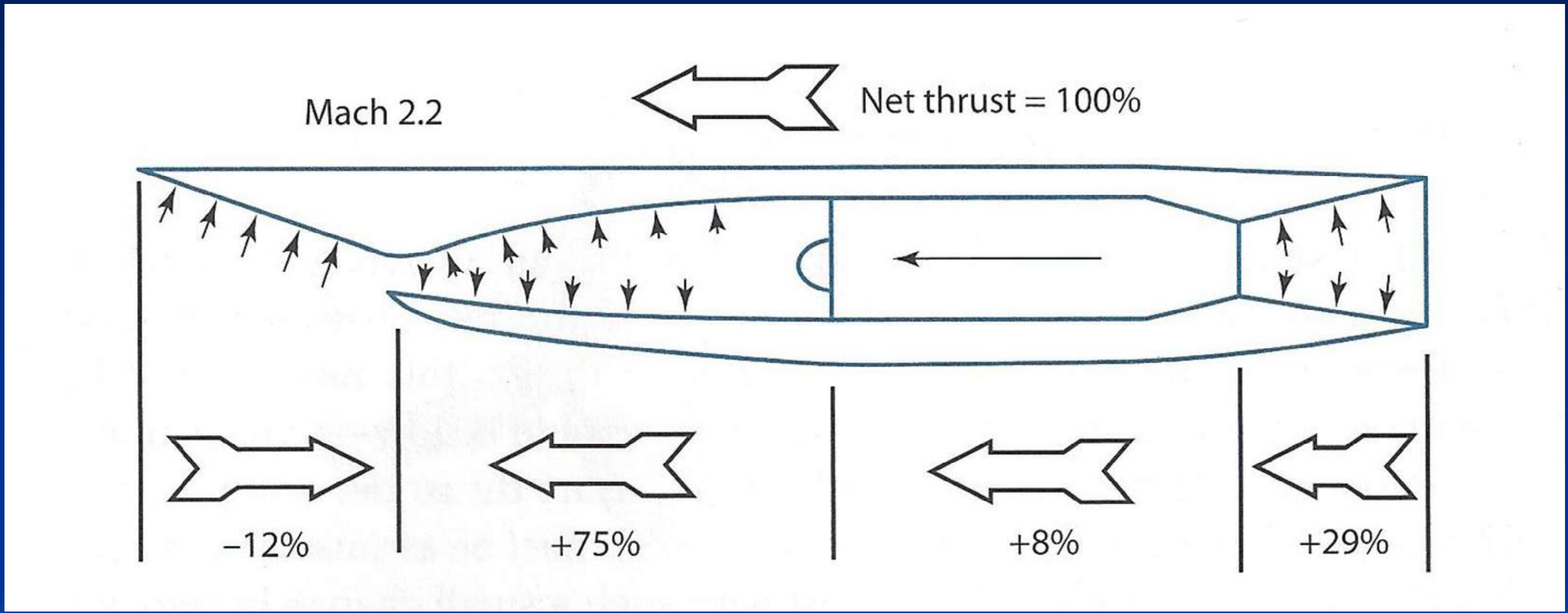
SR-71

- Max speed: M3.3+ @ 80,000 ft
- Range: 2,900 n.mi.
- Rate of climb: 11,810 ft/min
- W/S: 84 lb/ft^2
- T/W: 0.44
- Last flight: 9 Oct 1999

J58 Turboramjet

- Variable cycle turbojet/turboramjet
- Thrust: 34,000 lb
- Sfc: dry - 0.9 lb/lb/hr
  a/b - 1.9 lb/lb/hr

Nacelle Thrust – Drag Accounting



Source: Raymer

North American A-5 with GE J79 turbojets

Electric Propulsion

Airbus E-Fan

- 2 ducted variable-pitch fans
- Total power 60 kW
- Composite structure
- Flew across English Channel in July 2015

Solar Impulse 2

- Solar cells on aerodynamic surfaces
- Batteries to maintain altitude at night
- Attempting round-the-world flight
- Loaded weight: 5,100 lb
- Span: 236 ft
- 4 motors: 13 kW (17.4 HP) each
- Photovoltaic cells: 17,248 rated at 66 kW peak
- Li-ion batteries: 4 x 41 kWh

Electric Propulsion: NASA X-plane Demonstrator

- 3-year $15M project for Distributed Electric Propulsion (DEP) X-plane
- Cape Air working with NASA on requirements for 9-seat thin-haul commuter

Source: AW&ST

NASA X-plane Demonstrator

- Tecnam P2600T light piston twin with modified electric propulsion wing
- Fixed-pitch props
- Demonstrator will use 200 Wh/kg
- Economically feasible at 400-500 Wh/kg
- W/S = 50 lb/ft^2 (baseline Tecnam P2600T has 17 lb/ft^2)

Source: AW&ST

NASA X-plane Demonstrator

- Truck testbed reaches 75 mph at Edwards AFB

Source: AW&ST

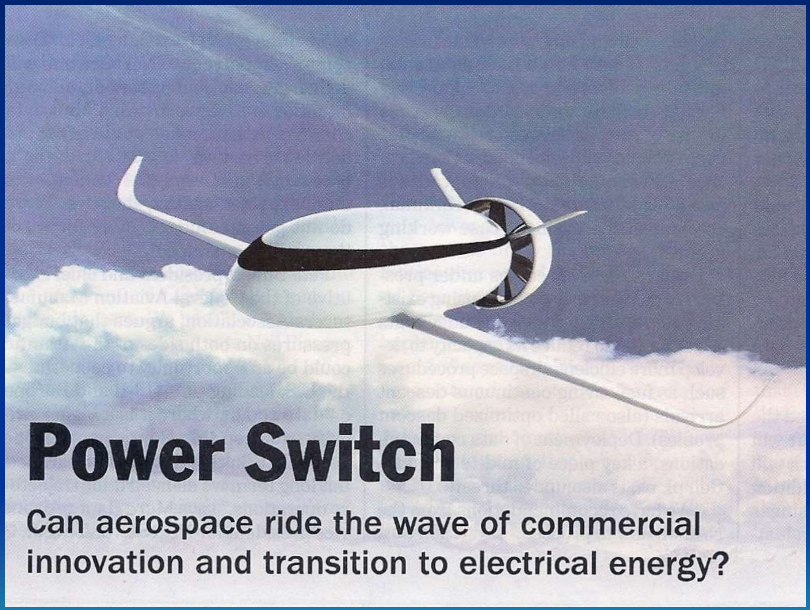
Boeing SUGAR Volt

- Hybrid turbine-electric
- Battery packs in wing pods
- High AR strut-braced wing
- Emissions 30% of existing airliners

Source:Boeing

Airbus VoltAir

- Announced in 2011
- Counter-rotating props on rear fuselage
- All-electric propulsion
- Removable Li-Ion batteries in lower fuselage



Airbus eThrust Airliner

- Hybrid propulsion
- Turboshaft drives generator
- Power stored in batteries
- Superconducting cables distribute power to embedded fans
- E-fan has Li-Poly energy density of 180 Wh/kg (will upgrade to 250)
- eThrust needs 800 Wh/kg

Where to locate engines?

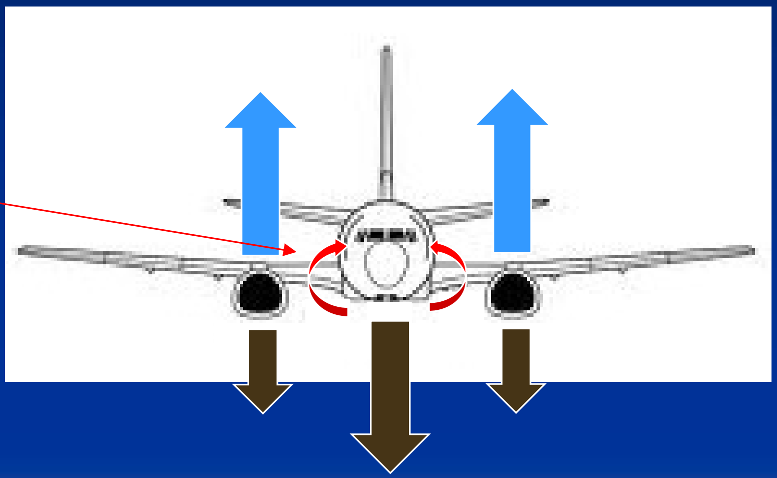
First Jet Bomber

- You could mount them on the forward fuselage (but not a good idea)

Junkers Ju 287
First flight 1944/08/16
Max speed 272 m/s (529 kt)

Wing Root Bending Relief

- Engines mounted on wing reduce wing root bending



ADAC Aircraft Design & Consulting

Nacelle On Underside of Wing

- Good choice of location, but a stub pylon is now preferred

Messerschmitt Me 262
First flight (with jet engines) 1942/07/18

Centered On Wing

- Front wing spar passes in front of engine
- Rear spar passes around jet pipe

Gloster Meteor
First flight 1943/03/05

Gloster Meteor

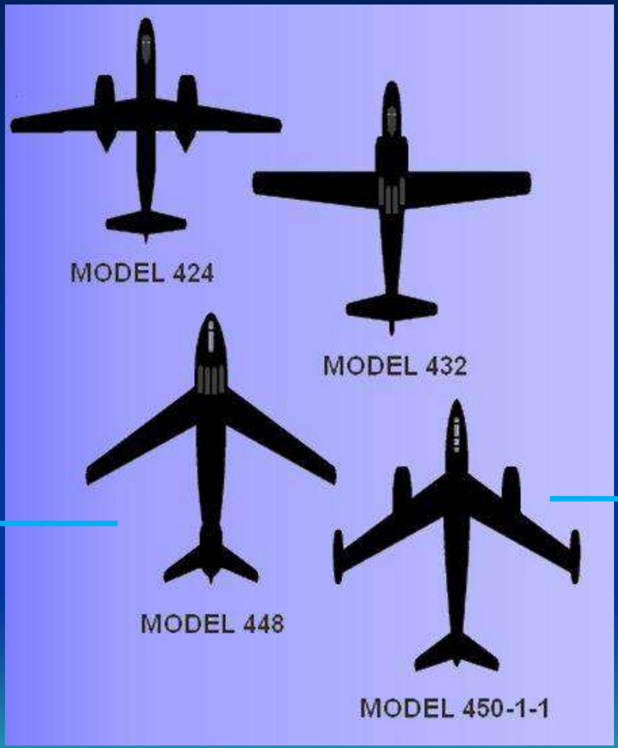
2 or 4 Engines on Pylons under Wing

- First used on Boeing B-47
- Configuration for nearly all subsonic transport aircraft

B-47 Configuration Development

- Configuration development looked at many different engine locations

http://www.sporistics.com/?p=asset:500877866397

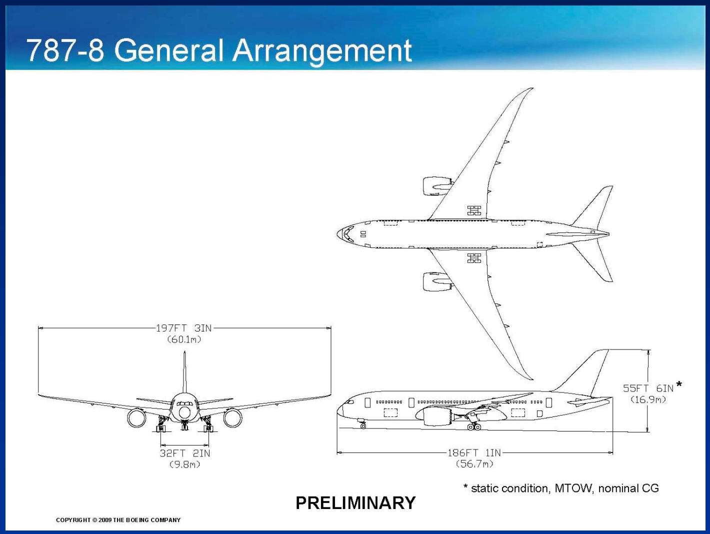


www.wingweb.co.uk

https://www.agefotostock.com/age/en/Stock-Images/Rights-Managed/MEV-10844173

2 or 4 Engines on Wing (cont'd)

- Advantages
  - Wing root bending relief
  - Easy to change engine type
  - Lower probability of collateral damage from catastrophic engine failure
  - Engines easily accessible



Source: Boeing

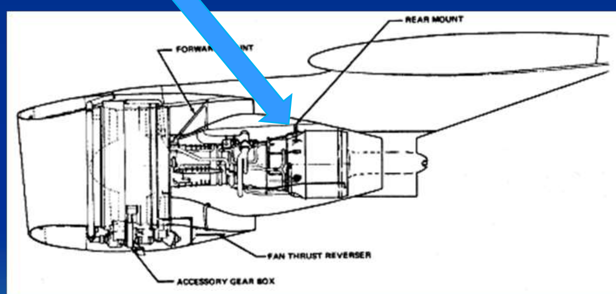
Source: ChromeAlloy ad

Uncontained Engine Failure

- DL275 DTW-NRT 2011/10/23
- Boeing 747-400
- Failure occurred soon after takeoff
- “duct segment(s) that either partially or fully disengaged from the rear turbine case”
- All stage 3 low pressure turbine blades fractured
- Most parts passed downward and outward
- Pylon also overstressed

Uncontained Engine Failure (con’td)

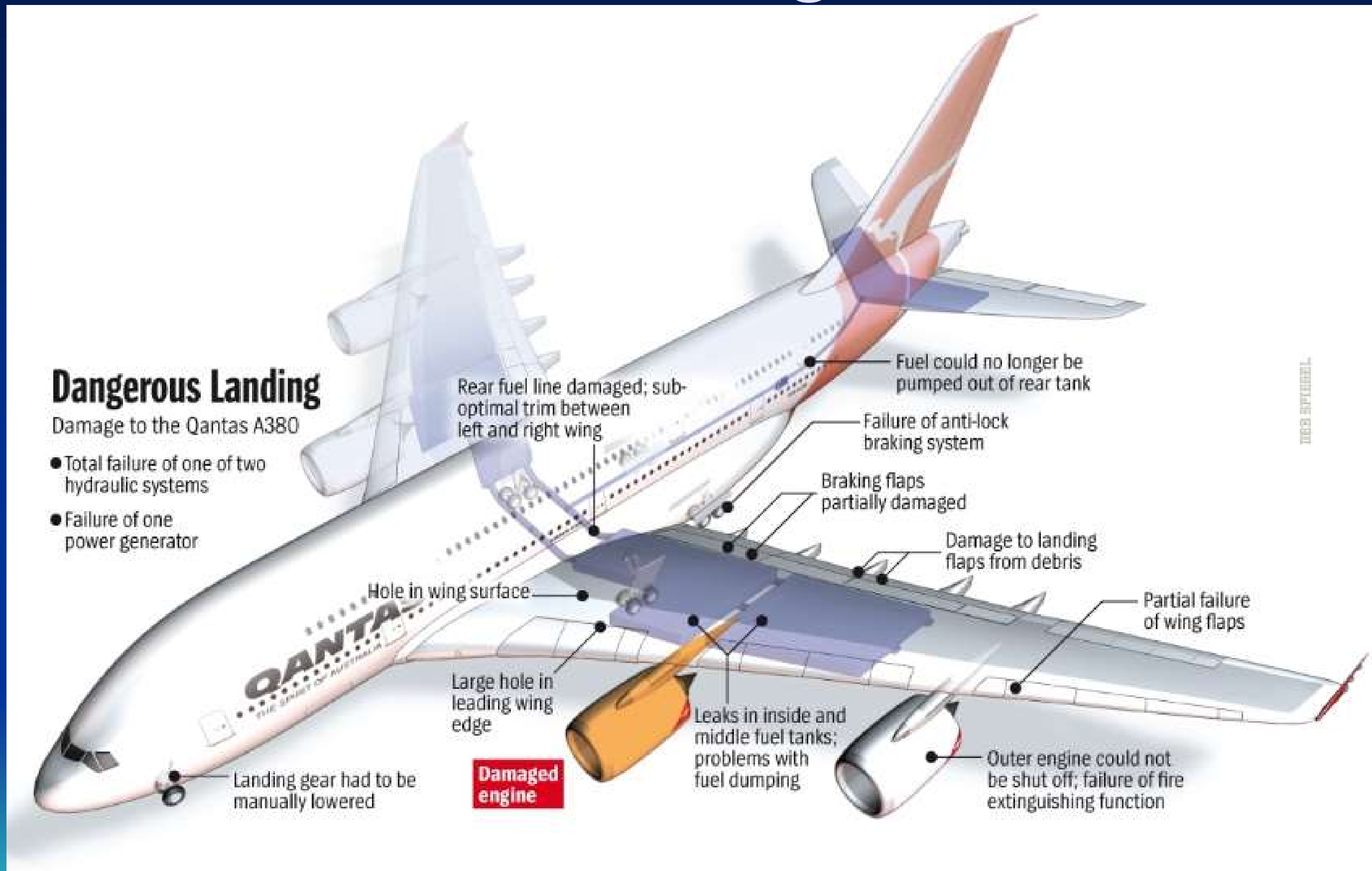
- A few parts damaged inboard aileron and underside of wing
- Would like to locate core ahead of front spar



Source: www.adg.stanford.edu

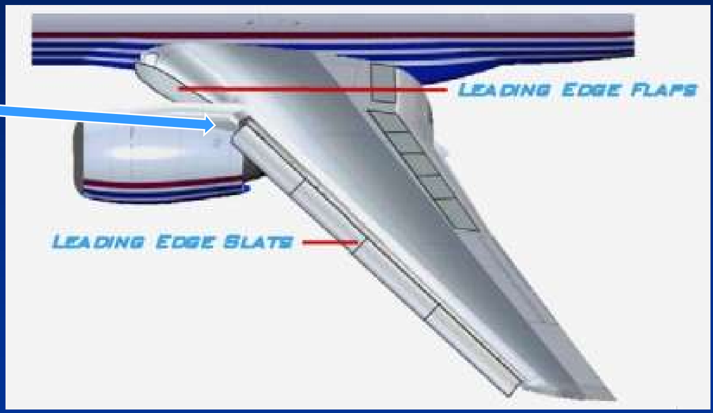
Uncontained Engine Failure

Uncontained Engine Failure



2 or 4 Engines on Wing

- Disadvantages
  - Need break in leading/trailing edge slats/flaps for pylon/jet exhaust
  - Controllability with one engine inoperative (OEI)
  - Noisy cabin (especially at rear)

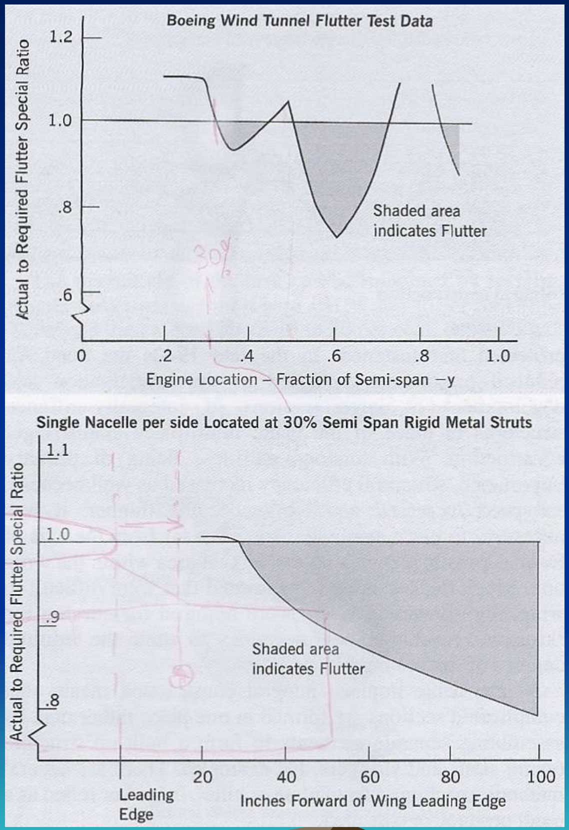


Boeing 737

  - Increased probability of FOD pickup

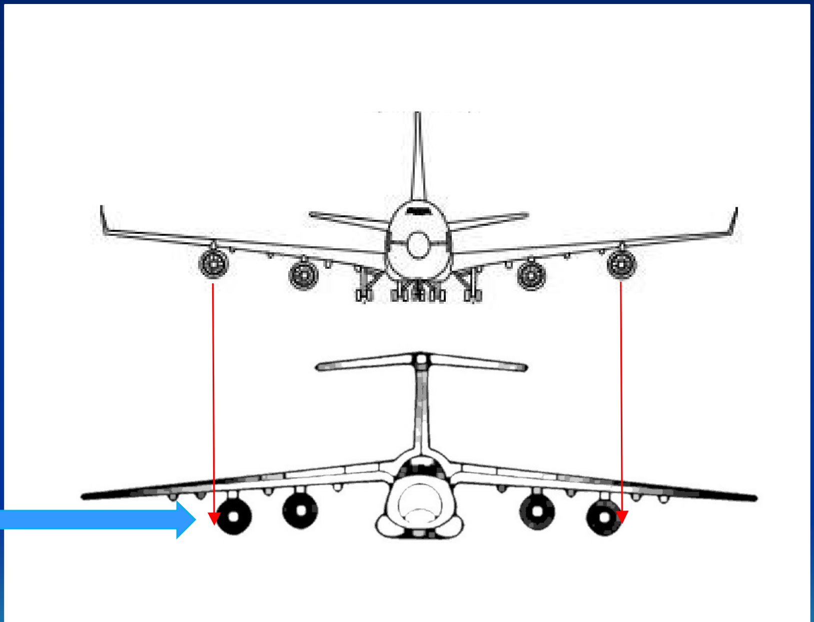
Nacelle Location Impact on Flutter

- Both spanwise and fore-and-aft location of the nacelles are critical in reducing wing flutter
- Limit on forward location is contrary to conventional understanding of wing flutter



Effect of TOFL on Spanwise Nacelle Location

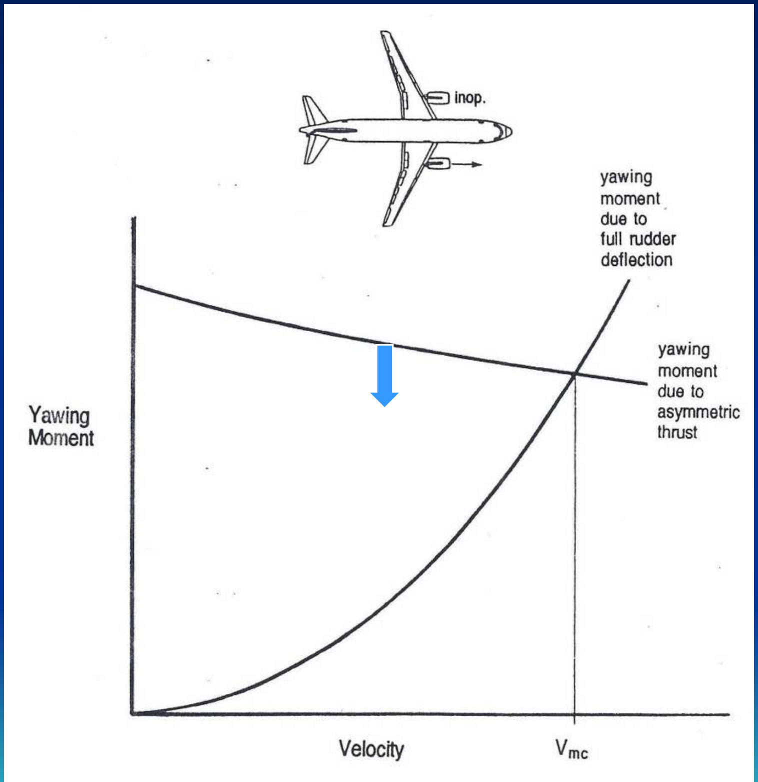
- C-5 can take off from short field length (i.e. lift off at lower speed than 747)
- For engines #1 and #4, nacelles are moved inboard to reduce V_{MC}



Effect of TOFL on Spanwise Nacelle Location

- Effect of reduced moment arm on V_{MC}
- Ensure that

  $V_{MC} < V_2$



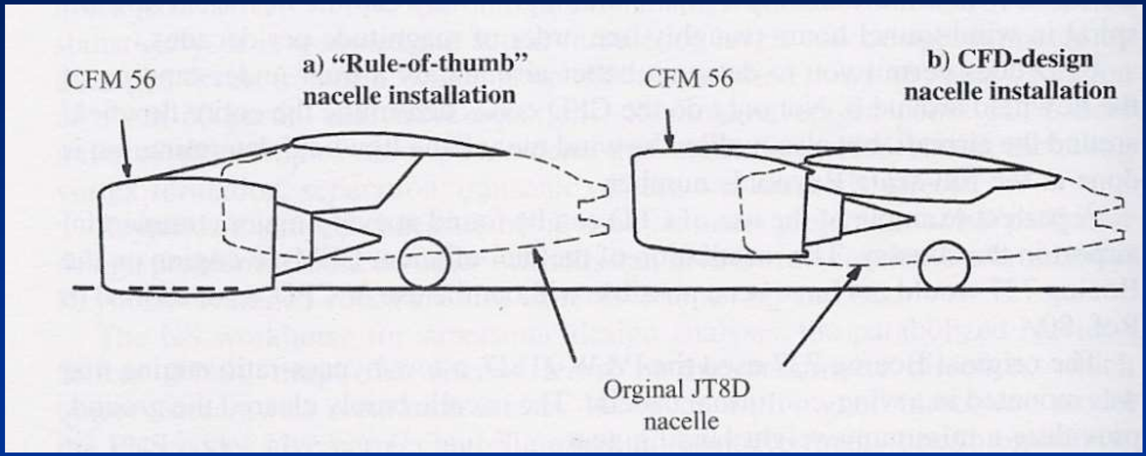
Source: Schaufele

Dangers of FOD Pickup

- Large negative pressure at inlet induces tornado-like vortex
- Can suck up gravel and other debris
- Solution is to use bleed air sheet under inlet

http://farm4.static.flickr.com

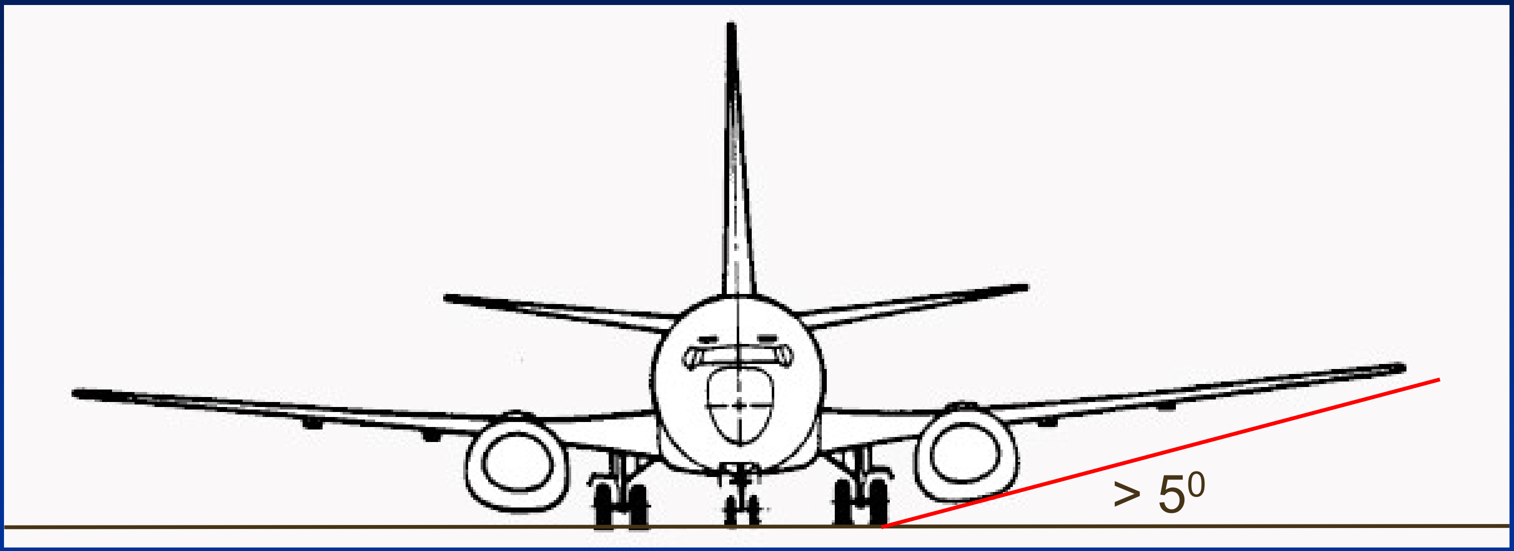
Consider Engine Growth



Source: Raymer – Aircraft Design

- Boeing failed to consider increase in bypass ratio
- Lengthening MLG strut would require wing redesign

Lateral Ground Clearance



Source: flightlineaviationmedia.com

Potential Ground Strike

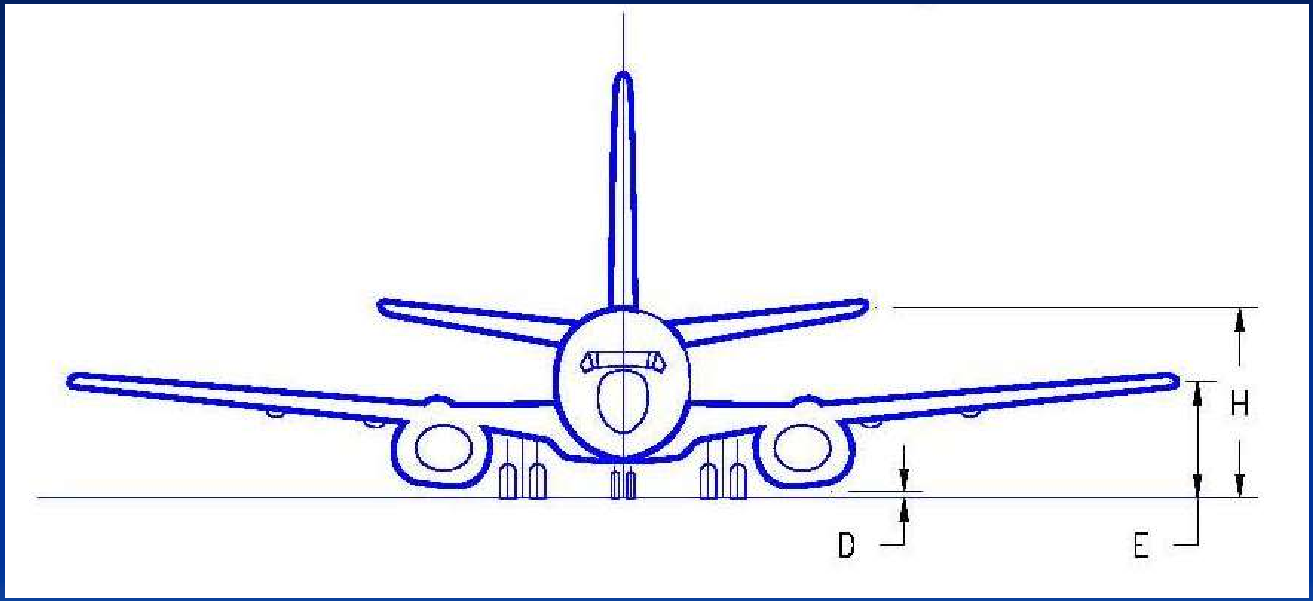
- Sufficient dihedral and MLG strut length to minimize probability of outboard engine ground strike

KE A380 at NRT

B.737 Nacelle Ground Clearance

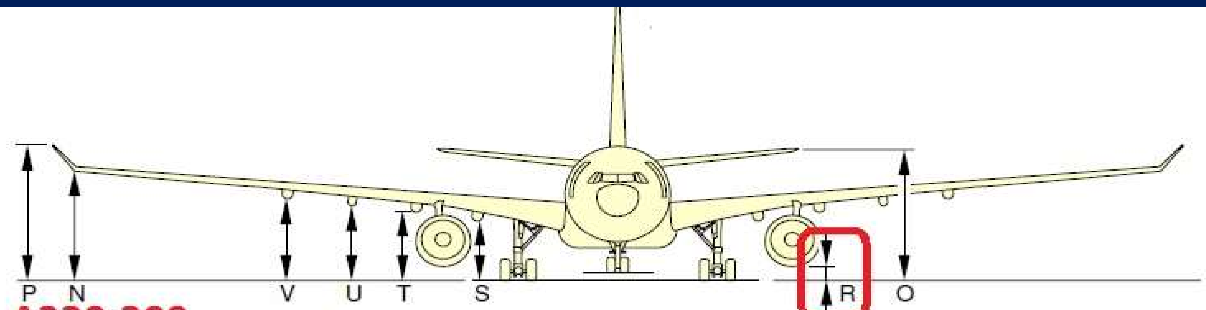
Model	D_{max} [ft-in]	D_{min} [ft-in]
-600	2-0	1-6
-700	2-0	1-6
-800	2-1	1-7
-900	2-1	1-7

D_{max} @ OEW
D_{min} @ MTW



Source: boeing.com

A330 Nacelle Ground Clearance



A330-300

MRW 212 900 kg 469 360 lb	119 000 kg CG 26.8%		MAXIMUM RAMP WEIGHT CG 15%		MAXIMUM RAMP WEIGHT CG 36.5%	
	m	ft	m	ft	m	ft
GE = R	0.94	3.08	0.76	2.49	0.79	2.59
PW = R	0.90	2.95	0.72	2.36	0.75	2.46
RR = R	0.87	2.85	0.69	2.26	0.72	2.36

0.67 for 330-200

A330-200F

PW R	1.13	3.71	0.89	2.92	0.95	3.12
RR R	1.06	3.48	0.82	2.69	0.87	2.85

Increased nacelle clearance with A330-200F nose gear 0.82-0.67=0.15m or 6"

Source: airliners.com

Engines Mounted on Top of Wing

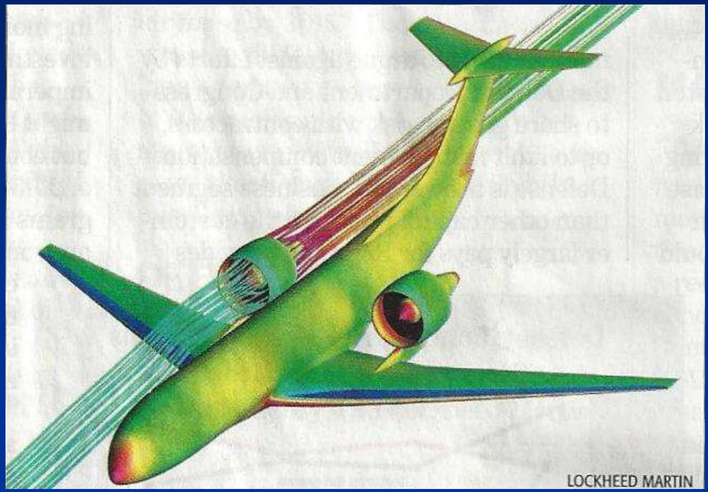
- Advantages
  - Wing root bending relief
  - Short landing gear and airstairs
  - Protection from FOD
  - Fan noise reduction on ground
- Disadvantages
  - Reduced length of t.e. for flaps
  - Inlet in high-speed flow

VFW-Fokker 614

HondaJet

Engines Mounted on Top of Wing

- Lockheed Martin studies for AFRL
  - Mcruise = 0.82
  - 5% increase in ML/D compared with underwing



Hybrid Wing Body

- 4%-scale model in National Transonic Facility at NASA Langley

Hybrid Wing Body

- Lockheed Martin studies started in 2009
- Carries outsized cargo lifted by C-5
- Burns 70% less fuel than C-17
- Over-wing nacelles permit very-high-BPR engines

Hybrid Wing Body

- Multi-role tanker/transport
- 15% more efficient than Boeing KC-46A

Special Purpose Applications

- Beriev Be-200
- Martin Seamaster
  - Keeps excessive spray from entering inlet


MARTIN YP6M-1 SEAMASTER *

Supersonic Trijet

Advantages

- More space for MLG
- Wing spar can project into fuselage

Disadvantages

- At high subsonic speeds (for transcon ops), inlet is close to upper surface shock
- Inlet is in high velocity (low-pressure) area


BUSINESS AVIATION

Full Speed Ahead

Airbus engineering expertise will help accelerate supersonic business jet design toward production

Now with three engines, the 160-ft.-long, Mach 1.6 Aerion AS2 has reached the advanced design stage.

Source: Aviation Week 2014/09/29

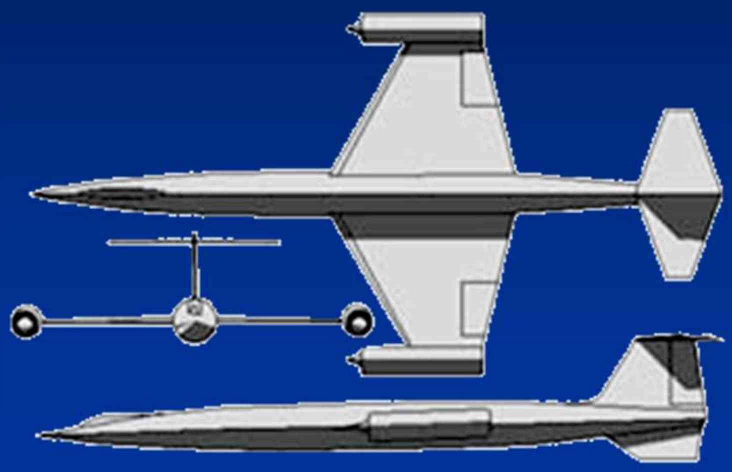
Engines Mounted on Top and Bottom of Wing

- Advantages
  - Reduced yawing moments after engine unstart
  - Noise shielding of upper jet by lower jet
  - Engines mounted on single structural rail
- Disadvantages
  - Different design for upper and lower inlets
  - Higher inlet losses on upper inlet
  - More difficult access to upper engine nacelle

Lockheed Supersonic Cruise Vehicle (SCV) circa 1976

Nacelles On Wingtips

- Design for hydrogen-powered reconnaissance
- Loss of control if OEI at low speed



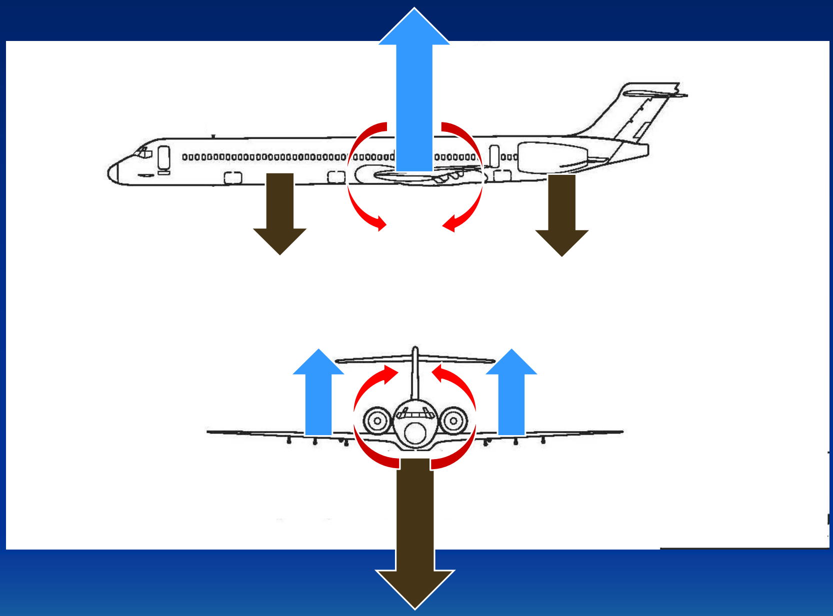
Lockheed CL400

Engines tucked under wing

- D-nacelle inlet located in region of high pressure
- Wing must be made stronger to prevent flutter
- Takes up valuable trailing edge space

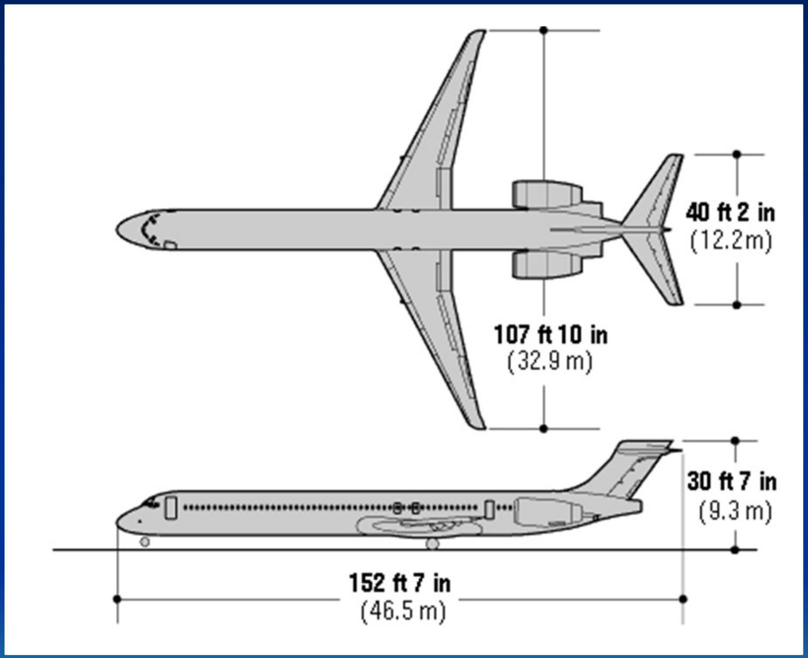
Fuselage And Wing Root Bending

- Engines mounted on rear fuselage induce additional wing and fuselage bending
- Made worse by
  - Stretched fuselage
  - Heavier engines



2 or 4 Engines on Rear Fuselage

- Advantages
  - Clean wing
  - Short landing gear
  - Easily accessible cabin
  - Quieter cabin (except at extreme rear)
  - Easier OEI handling



Source: Boeing

McDonnell Douglas MD-90

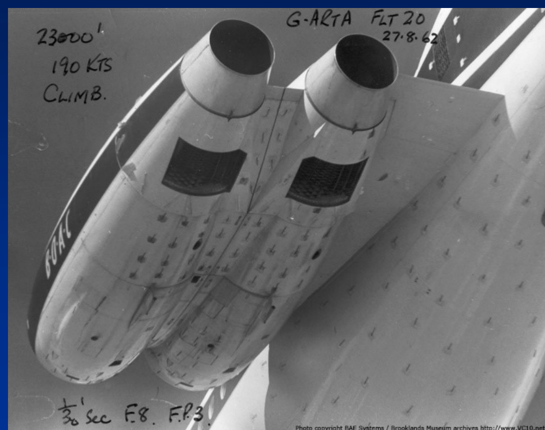
2 or 4 Engines on Rear Fuselage

- Disadvantages
  - No wing root bending relief
  - Increased fuselage bending
  - Higher c.g. travel (more trim drag when cabin is full)
  - Higher pylon weight
  - More difficult engine accessibility
  - Shorter moment arm for tail volume
  - Requires T-tail
  - Increased probability of structural damage from catastrophic engine failure

Vickers VC10 as RAF tanker

VC10 Nacelle and Pylon Mods.

Before



After

- Extended fairing between engine nacelles
- Extended pylon trailing edge
- Moved nacelles outboard
- Eliminated inboard thrust reversers

Single Engine VLJs

- PiperJet Altaire
  - Williams FJ44 turbofan
  - 6-7 pax
  - 2 crew
  - Cancelled in 2011
- Eclipse VLJ
  - Developed by Swift Engineering in 28 weeks
  - Eclipse declared bankruptcy

Source: www.lightjets.ch

Source: www.gizmag.com

Jet-powered Biplane

- Mielec PZL M-15
  - Built in Poland for USSR
  - Cropduster
  - V_{max} = 108 kt

Source: www.airplane-pictures.net

Fighter engine location

- Reduced skin friction drag
- Permits LO inlet and nozzle
- Less accessible
- Higher probability of collateral damage

Lockheed Martin F35

Lockheed Martin F22

Chin inlet for single-engine fighter

- Uniform flow at high α
- Good separation from gun gases
- Line of sight to compressor face
- More difficult to integrate nose landing gear

Source: Richard Seaman

Very LO (VLO) Fighter

- Good IR and radar protection for inlet and nozzle
- Large penalties in inlet performance
- Not good for high-g operation

Lockheed F117

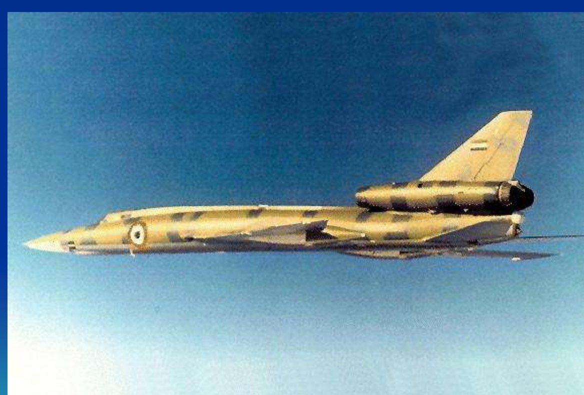
2 Engines Stacked Vertically

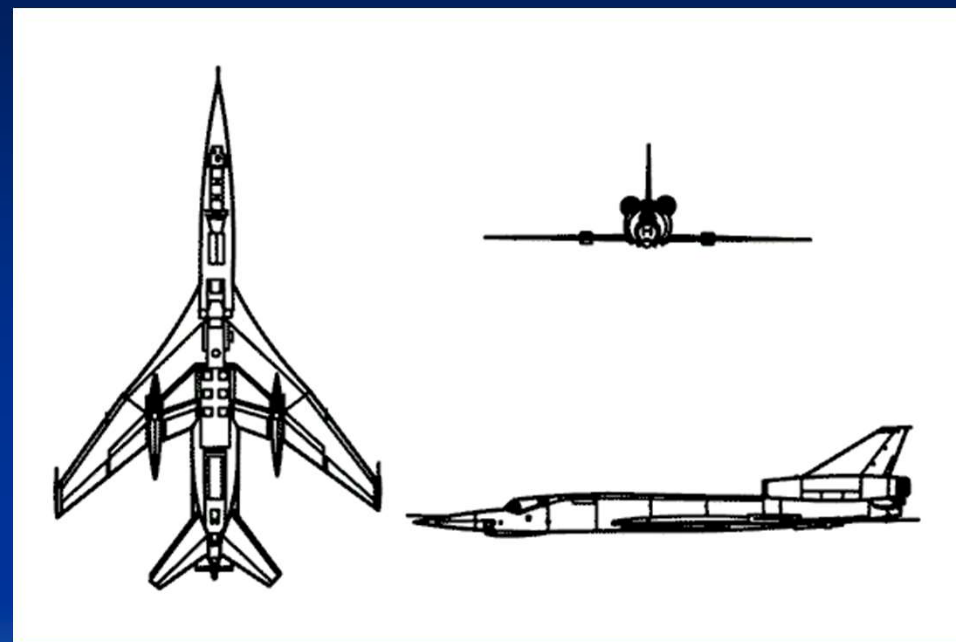
- English Electric Lightning
  - 2 R-R Avon a/b turbojets
  - Supercruise capability

Source: www.sas1946.com

2 Engines on Vertical Tail

- Tupolev Tu-22
  - First flight 1958
  - 2 X RD-7M-2 turbojets
  - 3 crew
  - Supersonic dash





Source: www.fas.org

Ground attack

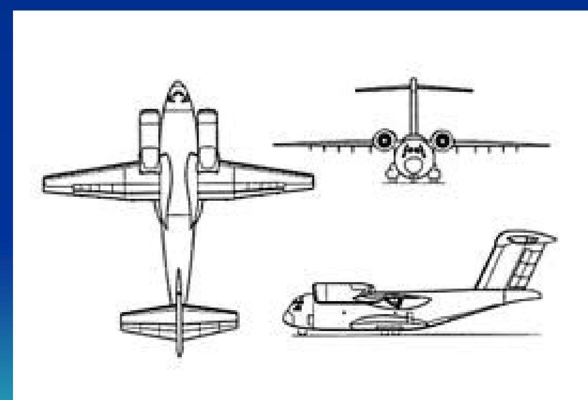
- Noise shielding at ground
- Wing offers protection to inlet from small-arms fire
- Horizontal and vertical tails offer protection from IR missiles
- Reduced probability of collateral damage from catastrophic engine failure

Fairchild A10 Thunderbolt 2

Upper Surface Blowing

- Boeing YC-14 STOL transport
- Upper Surface Blowing for higher $C_{L_{max}}$ on takeoff and landing

www.globalsecurity.com



www.globalsecurity.com

3-engine Configuration

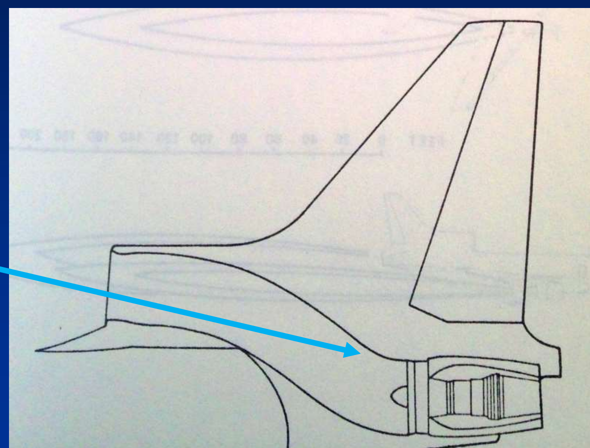
- Advantages
  - Nowhere else to put third engine
  - Easier OEI handling
- Disadvantages
  - For L1011 #2 engine, non-uniform flow at fan face
  - For L1011, noisy at rear of cabin
  - For #2 engine, more difficult accessibility

3-engine Configuration

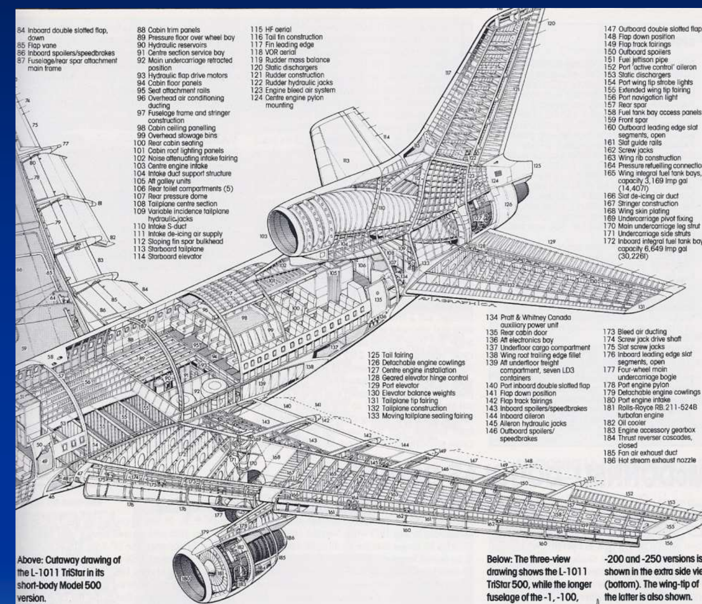
- Disadvantages
  - Heavier tail structure (need ring frames around engine)
  - Greater probability of collateral damage if engine fails catastrophically (as occurred on both DC10 and L1011)
  - Can’t easily change engine type (e.g. to an engine with increased mass flow)

S-Duct on L1011

- Long S-duct results in total pressure losses
- Separated flow occurs on curved section
  - Non-uniform flow at fan face
  - Thrust loss
  - Increased interior noise
    - Fortunately toilets were at the rear of the cabin



https://blog.tristar500.net/2016/07/number-two-engine-and-s-duct.html



Supersonic Transport

- Surmise – keep engines close to centerline to reduce engine-out yawing moments
- Engine/V-tail interference drag is probably high

Source: Aviation Week

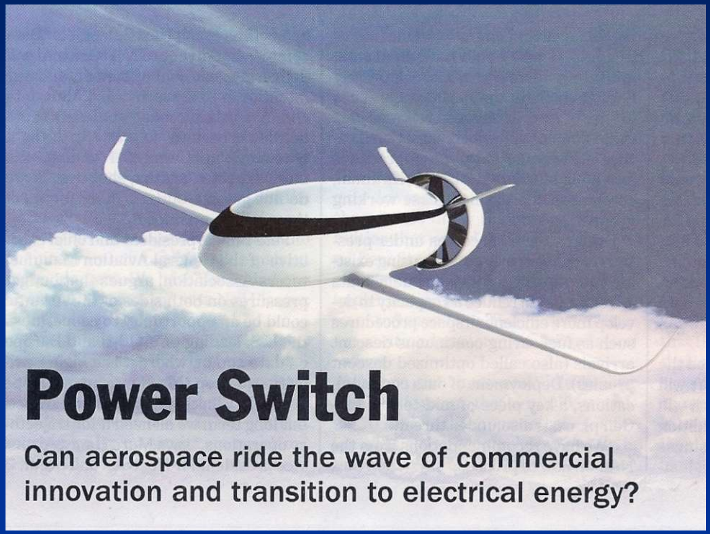
Lockheed Martin 81 pax 4,000 nmi range Mach1.6 low sonic boom SST

3 ½ Engined Aircraft

- DH.121 Trident Mk 3B
- 3 X R-R Speys
- + RB.162
- Flush inlet door
- Operated only at takeoff
- Fuselage stretch 16 ft

Boundary Layer Ingestion

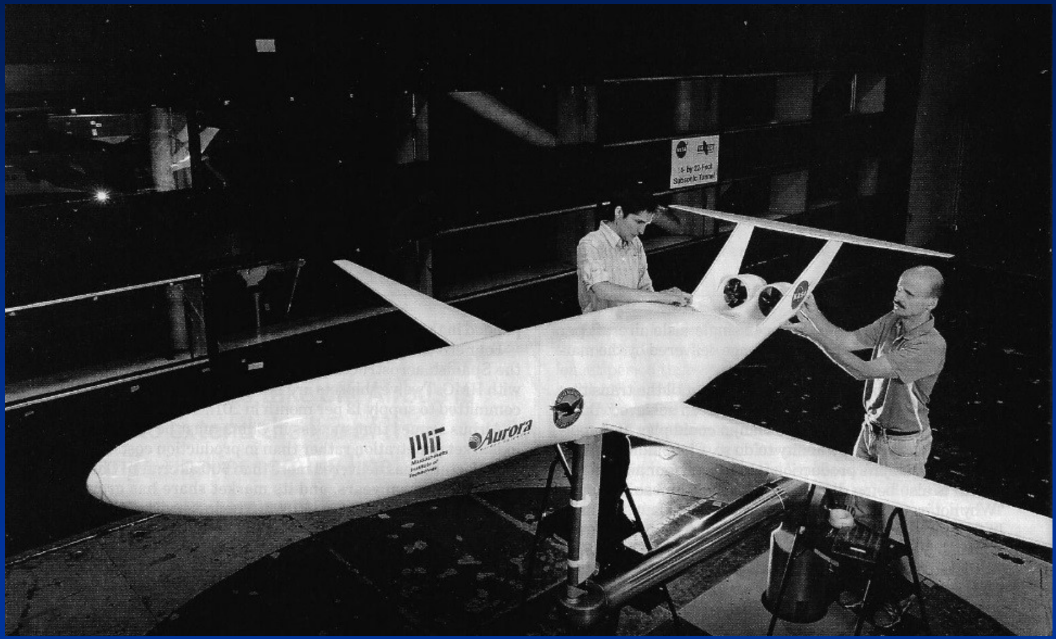
- Parasitic drag reduced by re-energizing boundary layer
- Blades must operate at lower efficiency because of non-uniform inflow



Source: Aviation Week

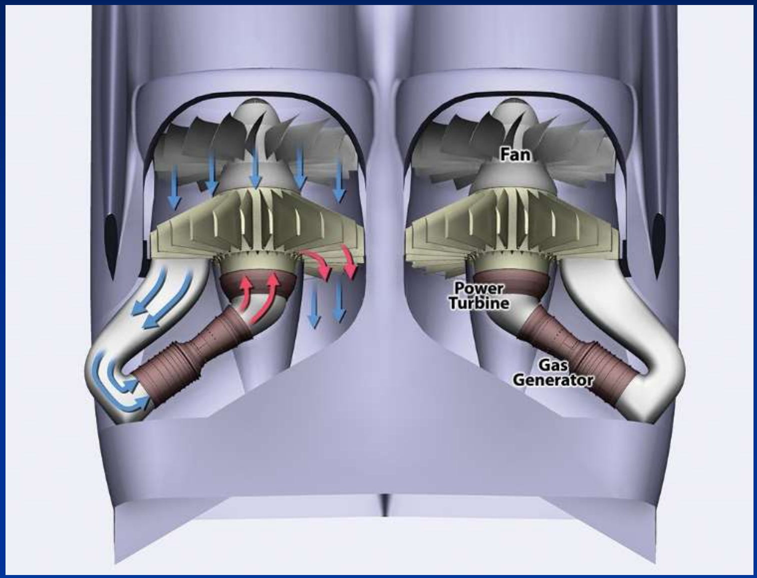
EADS Voltair electric-propulsion concept

NASA/MIT D8 Double-bubble Fuselage and NFL Wing



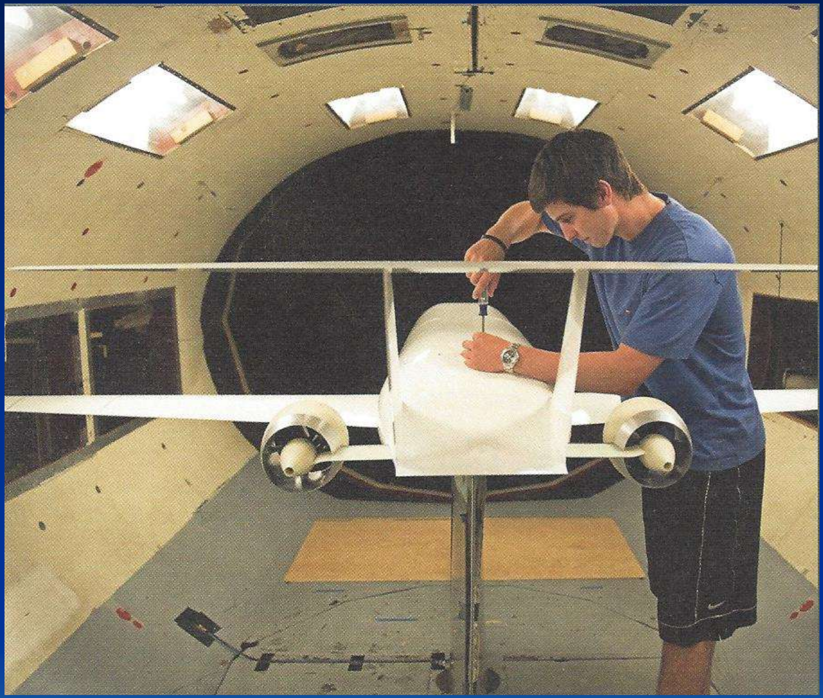
Source: Aviation Week

NASA/MIT D8 Double-bubble Fuselage and NFL Wing



Gas generator reversed (similar to P&W PT6)

Aft Fuselage Mounted Engines



Source: MIT Aero Astro 2012-13

MIT Double-bubble laminar-flow wing concept

Engines Embedded in Wing Root

- 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

Engines Embedded in Wing Root

- Advantages
  - Low wetted surface area
  - Low one-engine-inoperative (OEI) yawing moments
  - Shorter duct lengths for environmental control system (ECS)

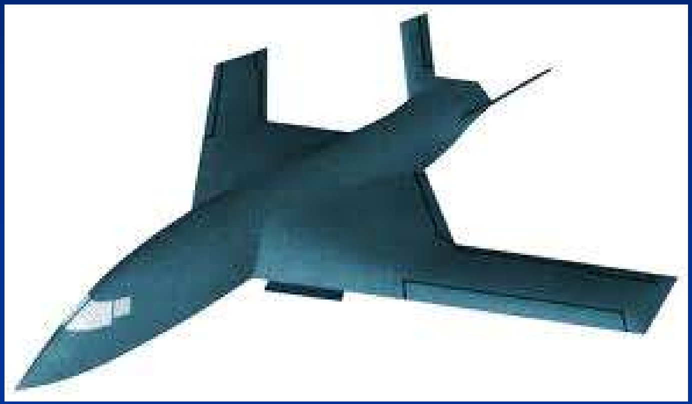
Engines Embedded in Wing Root

- Disadvantages
  - No wing root bending relief
  - Difficult to access
  - Danger of collateral damage from catastrophic engine failure
  - Difficult to change engine type
  - Tendency of jet exhaust to impinge on fuselage unless jet exhaust is angles outward

BAe Nimrod

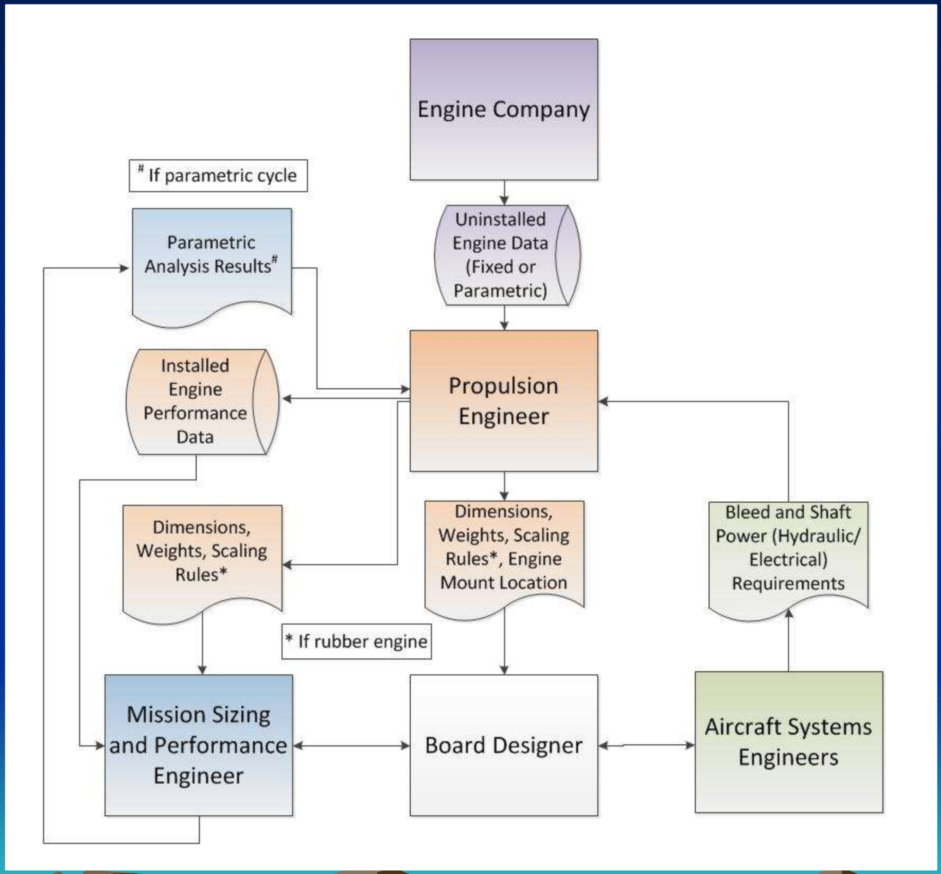
LO tactical transport

- Nacelles either below or above wing
- If above
  - Offers inlet and nozzle shielding (as for F117)
  - Degrades aerodynamic and propulsion performance



Old Dominion University project

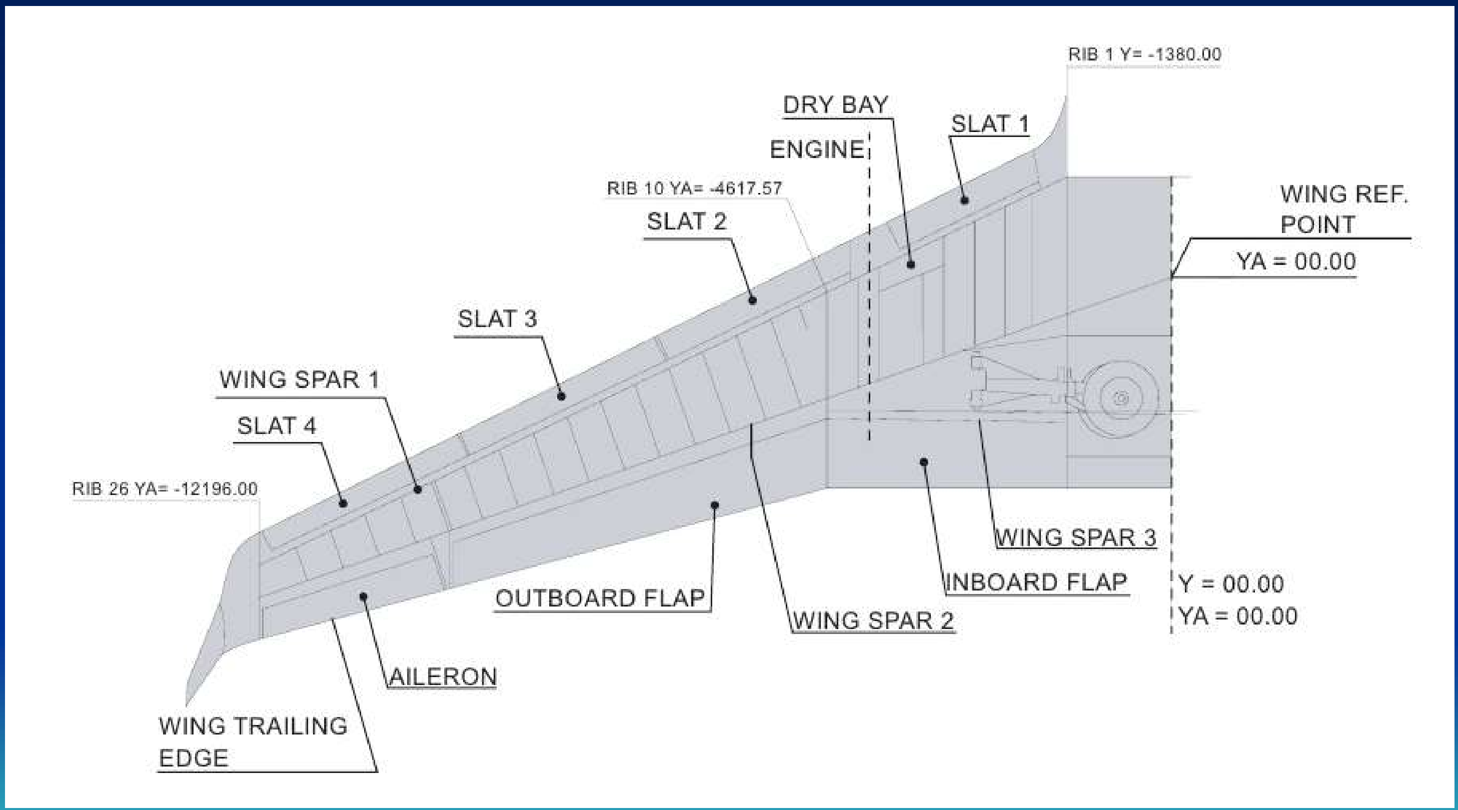
Preliminary Design Coordination



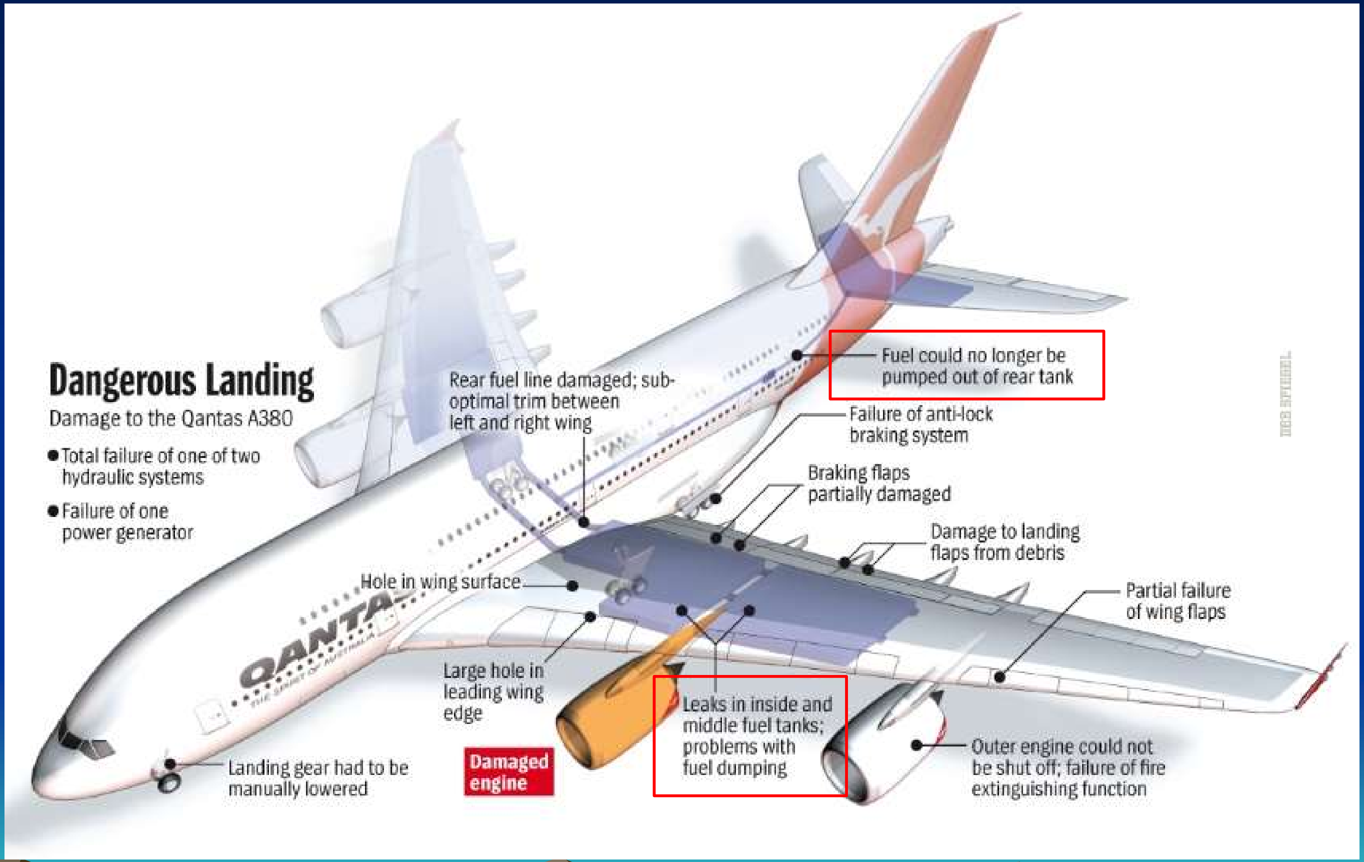
16.3

Fuel Systems

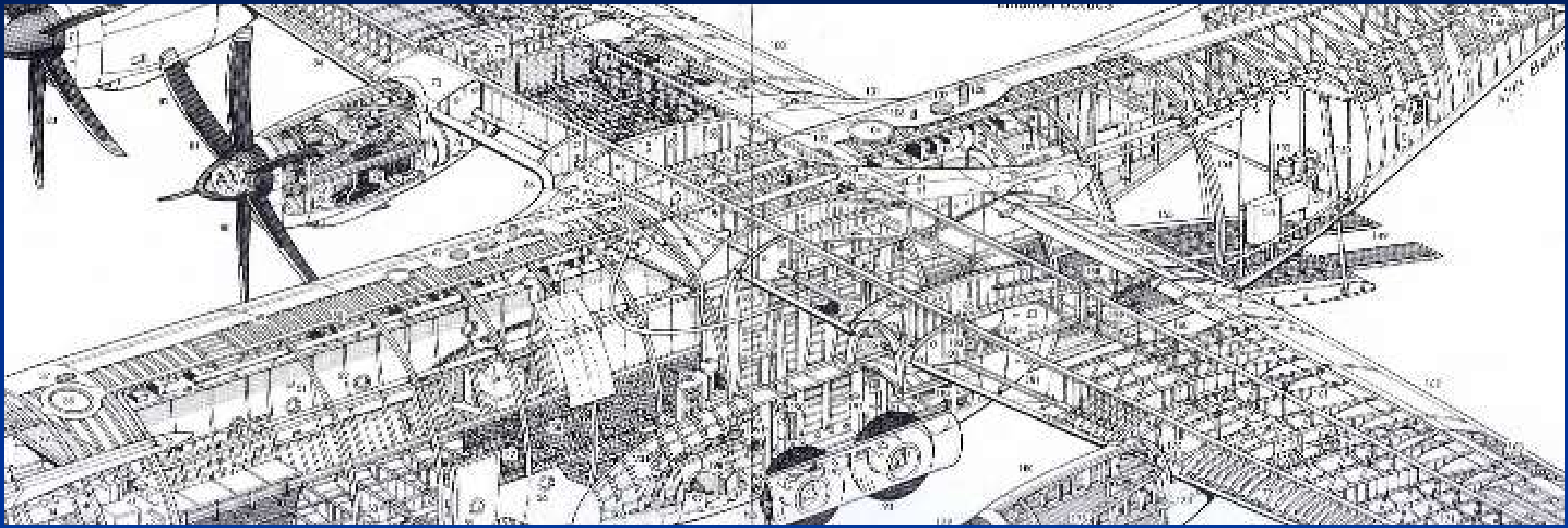
Embraer 170 Wing



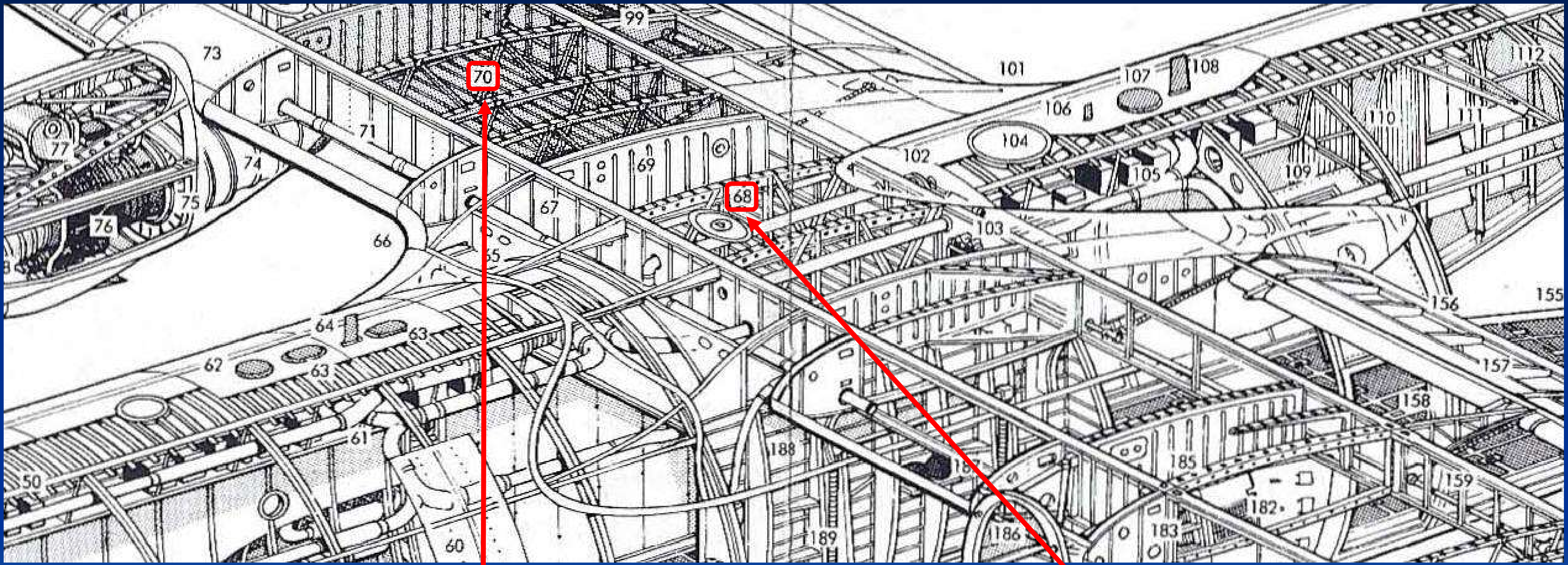
A380 Fuel Tanks



C-130 Wing



C-130 Wing – Location of Bladder Tanks

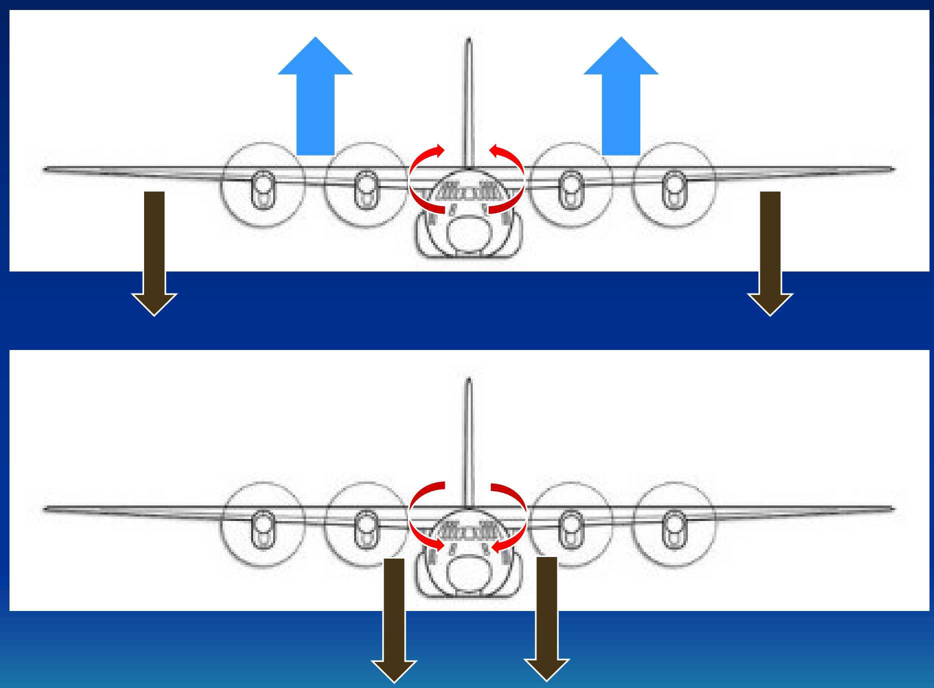


Integral fuel tank

Location of bladder fuel tanks (not shown)

C-130 – Fuel Management

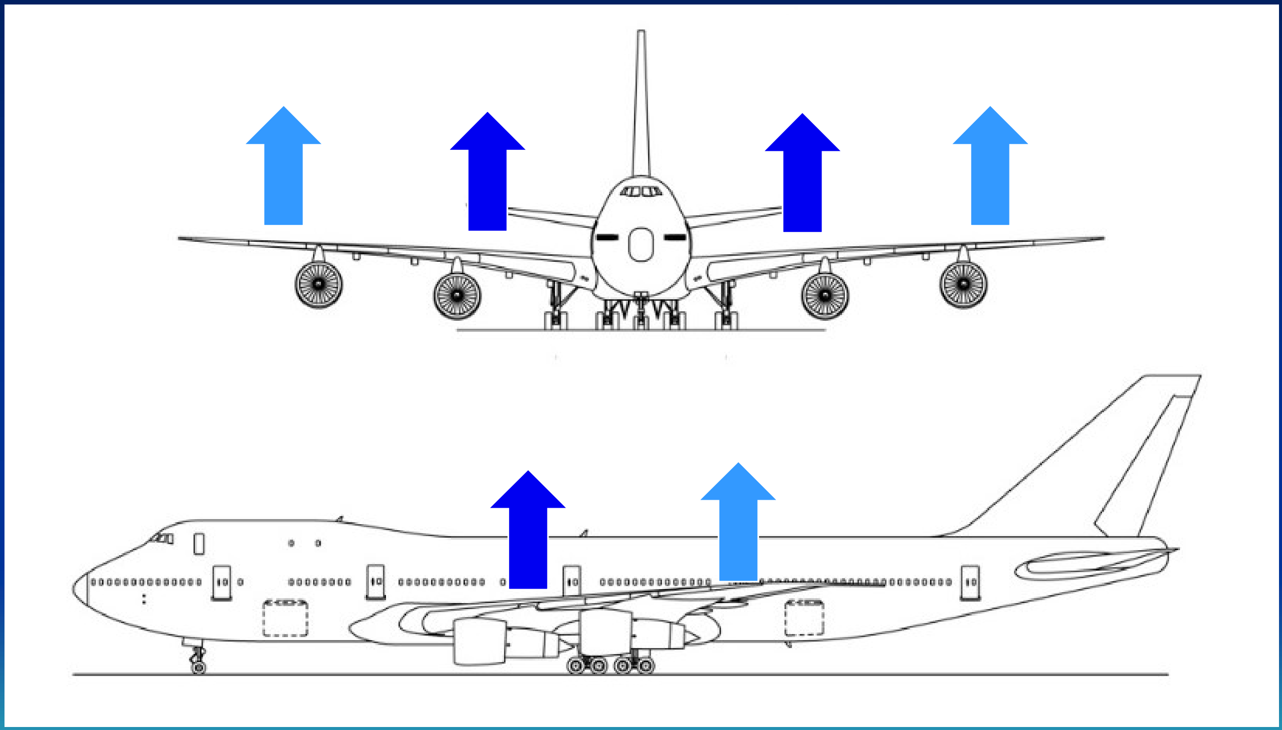
- Assault Mission
  - Fuel in outboard tanks for high-g aerial maneuvers
- Landing
  - Fuel in inboard tanks for landing inertia loads



C.g. Management

Keep fuel outboard for wing load relief

Move fuel inboard to move c.g. forward



Analytic Estimation of Wing Tank Volume and Fuel Weight

Wing Tank Volume

$$V_t = 0.54\,\frac{S^2}{b}\left(\frac{t}{c}\right)_{root}\frac{1+\lambda\sqrt{\tau}+\lambda^2\tau}{1+\lambda^2}$$

where

S = gross wing area b = wing span

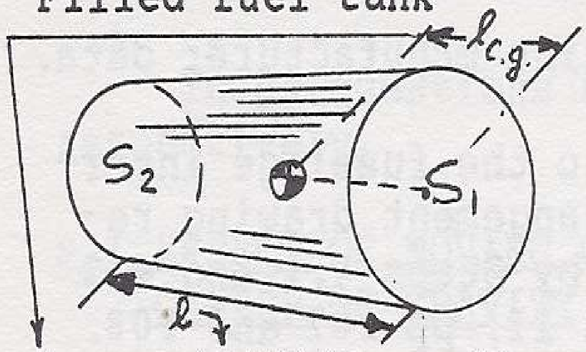
λ = taper ratio $\tau = \dfrac{\left(\frac{t}{c}\right)_{tip}}{\left(\frac{t}{c}\right)_{root}}$

JP-4 Density

Temp (deg F)	Density (lb/gal)
0	6.7
59	6.5
100	6.4

Location of Wing Tank C.G.

Filled fuel tank



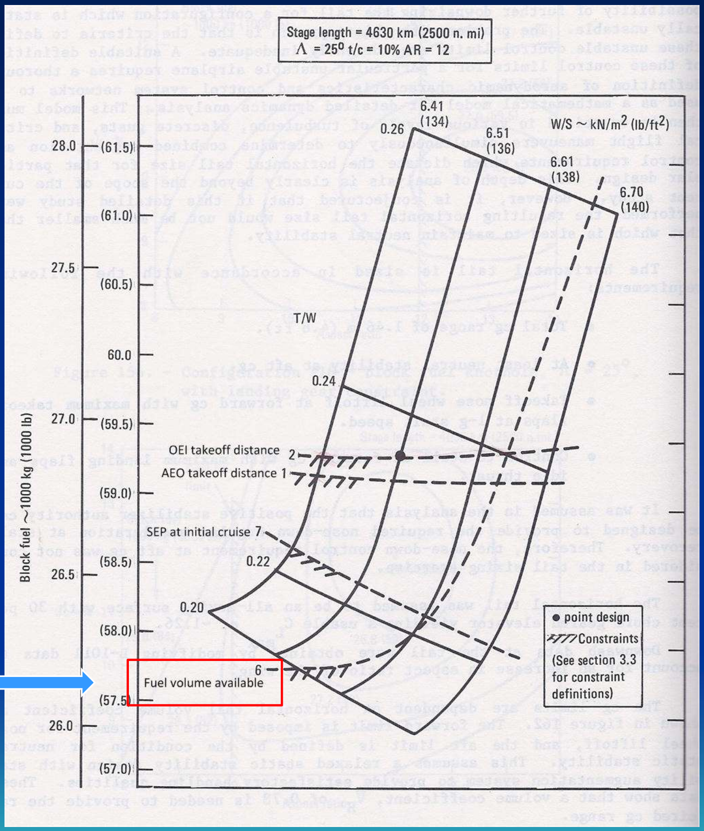
Assuming a prismoidal shape (See figure left), the c.g. is located relative to plane S_1 at:

$$l_{cg} = (1/4)\{S_1 + 3S_2 + 2(S_1S_2)^{1/2}\}/\{S_1 + S_2 + (S_1S_2)^{1/2}\}$$

L1011 Derivative Study

Tank capacity is built into aircraft sizing and performance program

- Wing fuel tank volume constraint

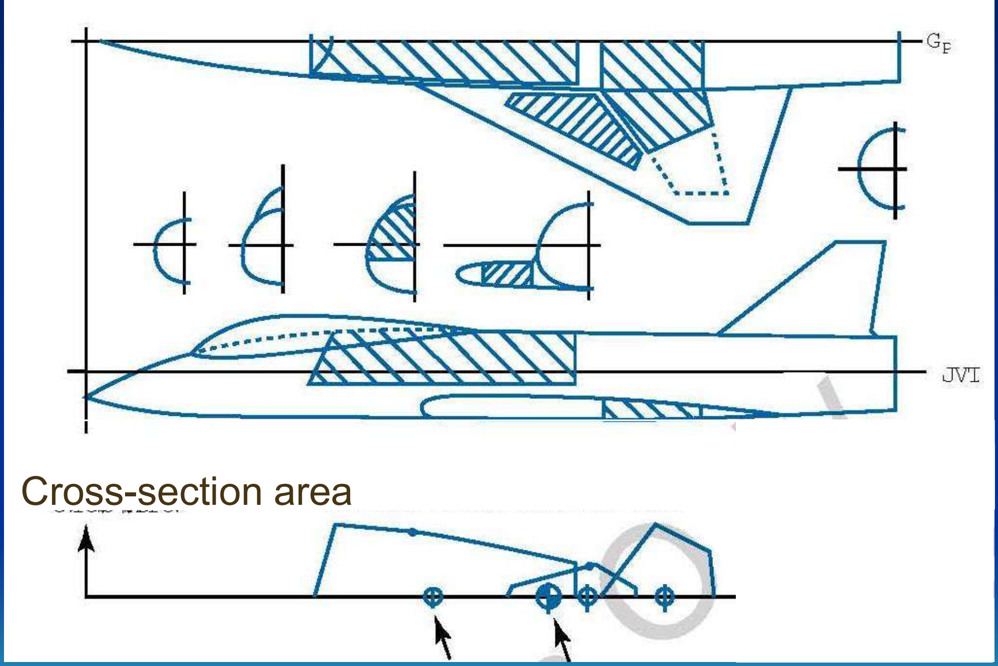


Gear Up Landing

Fuel tanks must not leak during gear up landing or structural failure, such as engine pylon

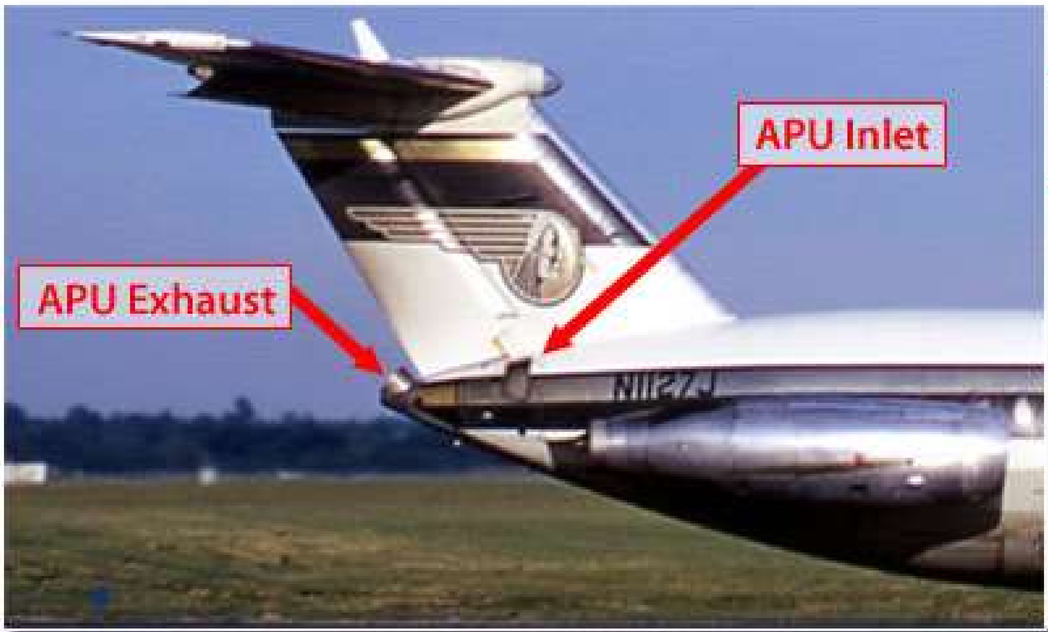
Multiple Tanks in Fuselage

- Plot tank cross-section area along x-direction
- Determine centroid of each area
- Ensure fuel c.g. is close to aircraft c.g.

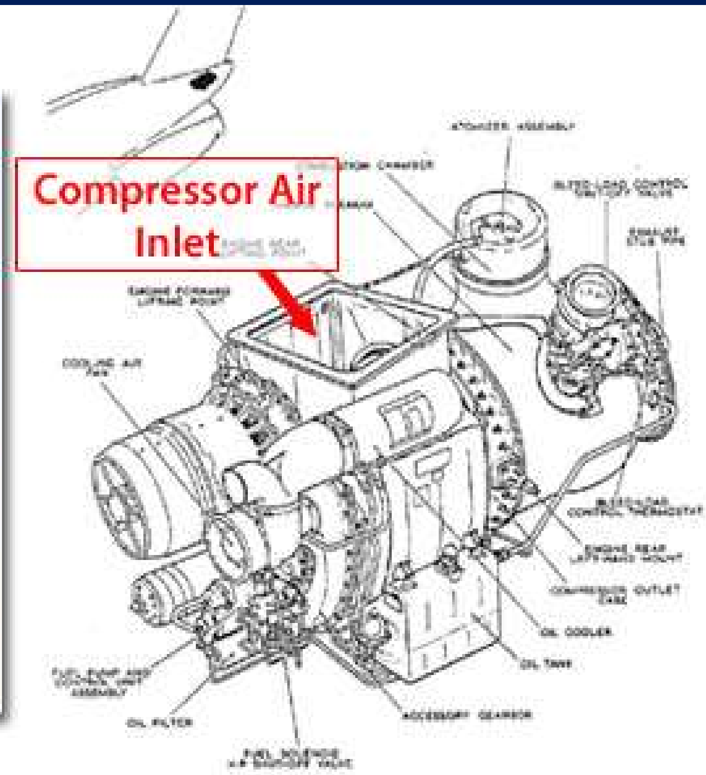


Chapters 10 and 13
Propulsion and Fuel Systems Integration
Secondary Power

Auxiliary Power Unit (APU)



BAC 1-11



https://lessonslearned.faa.gov/ll_main.cfm?TabID=1&LLID=44&LLTypeID=2

Auxiliary Power Unit (APU)

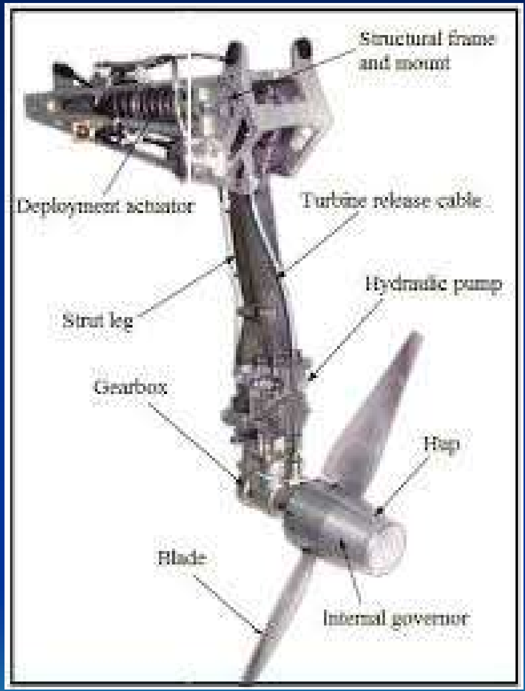
787 uses P&W AP
S5000 APU

Source: Simon Chandler

APU inlet

https://aviationweek.com/awin/boeing-tackles-787-apu-overheating-issue

Ram Air Turbine (RAT)



A-380 RAT

- Deploys automatically if all engines fail
- Provides emergency electrical power and hydraulic pressure

RAT on F-105 fighter-bomber

https://lessonslearned.faa.gov/ll_main.cfm?TabID=1&LLID=44&LLTypeID=2

Ram Air Turbine (RAT)

RAT retraction

https://aip.scitation.org/doi/abs/10.1063/1.4981189?journalCode=apc

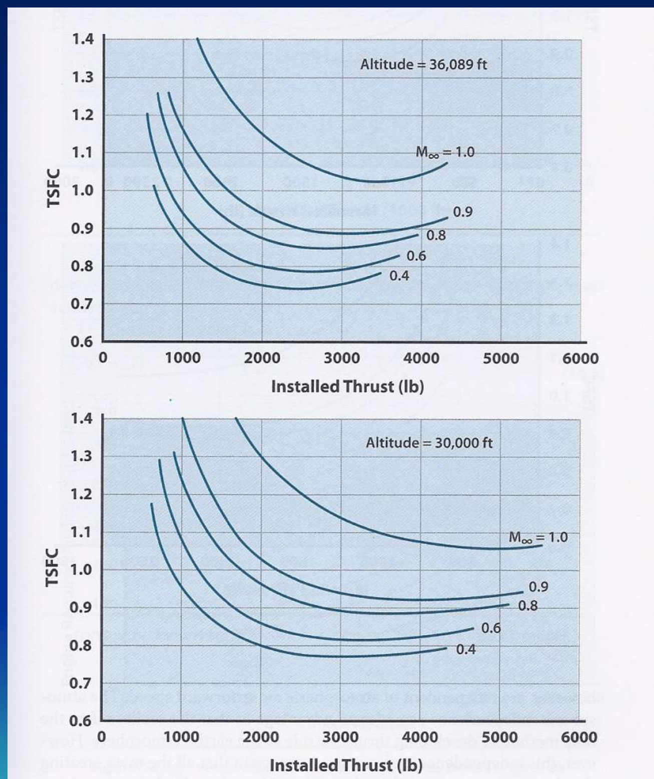
Deployed RAT on 787

https://lessonslearned.faa.gov/ll_main.cfm?TabID=1&LLID=44&LLTypeID=2

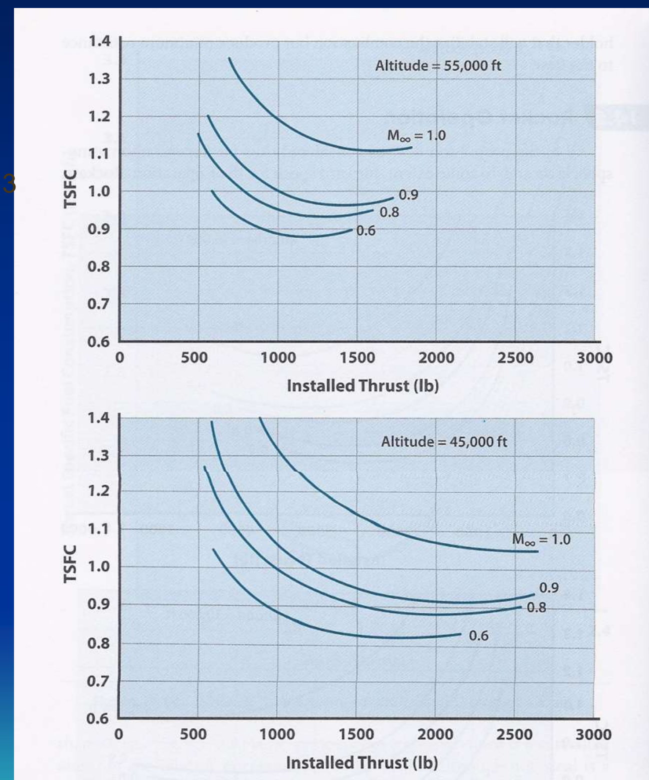
16.3

Propulsion Data Formats

F-100 Partial Power Data



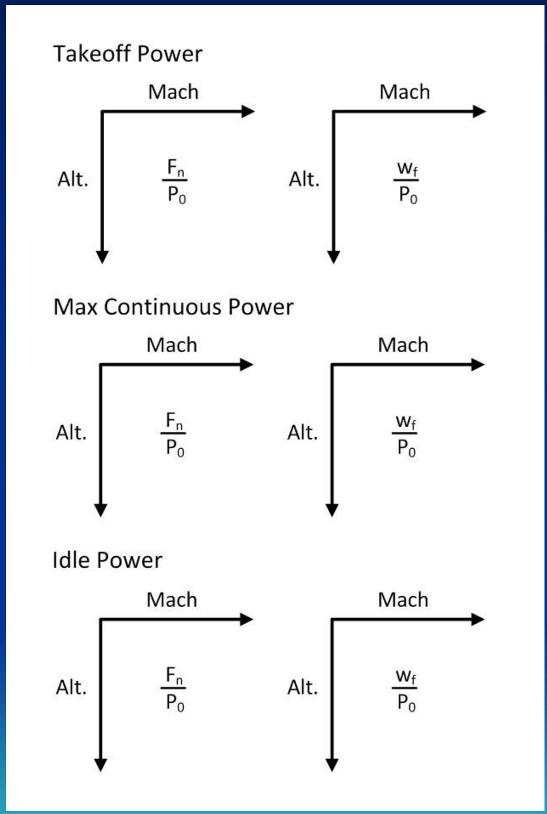
16.3



Source: Nicolai/Carichner

Typical Engine Deck Format

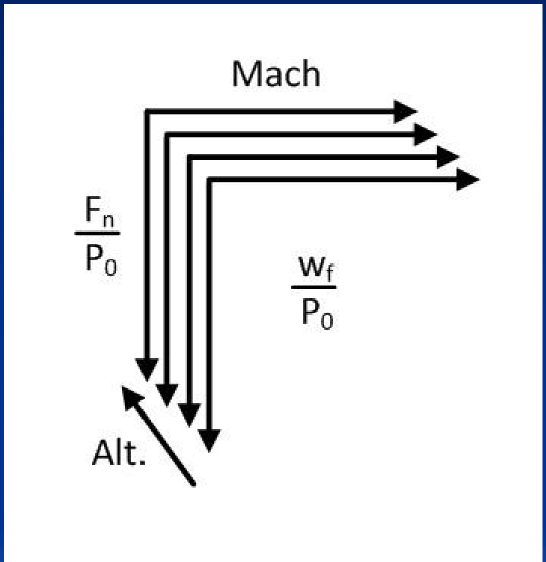
- Defined power tables
- Takeoff power is limited by duration (e.g., 1 minute)
- Other sets of tables may be offered (e.g., 15 minute duration)



Typical Engine Deck Format

- Part power tables
- Used at cruise

16.3



Propulsion and Fuel Systems Integration

The End