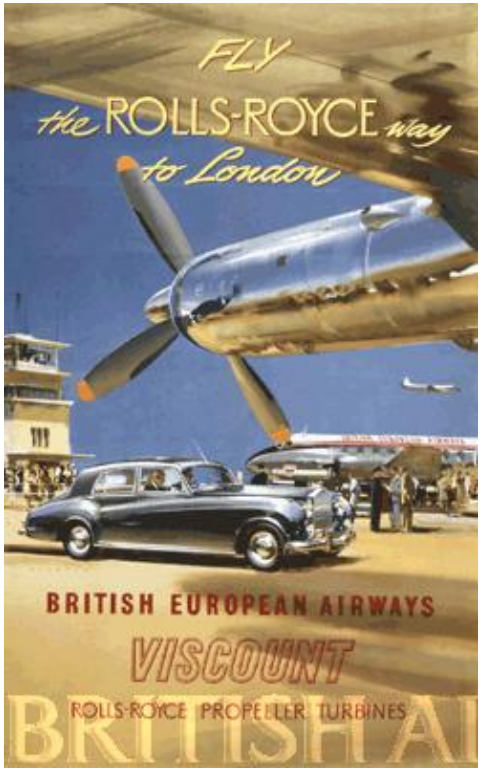
Open Rotor Engine Design and Validation

Dr Mark Taylor
Senior Project Engineer – Open Rotor
Future Programme Engineering

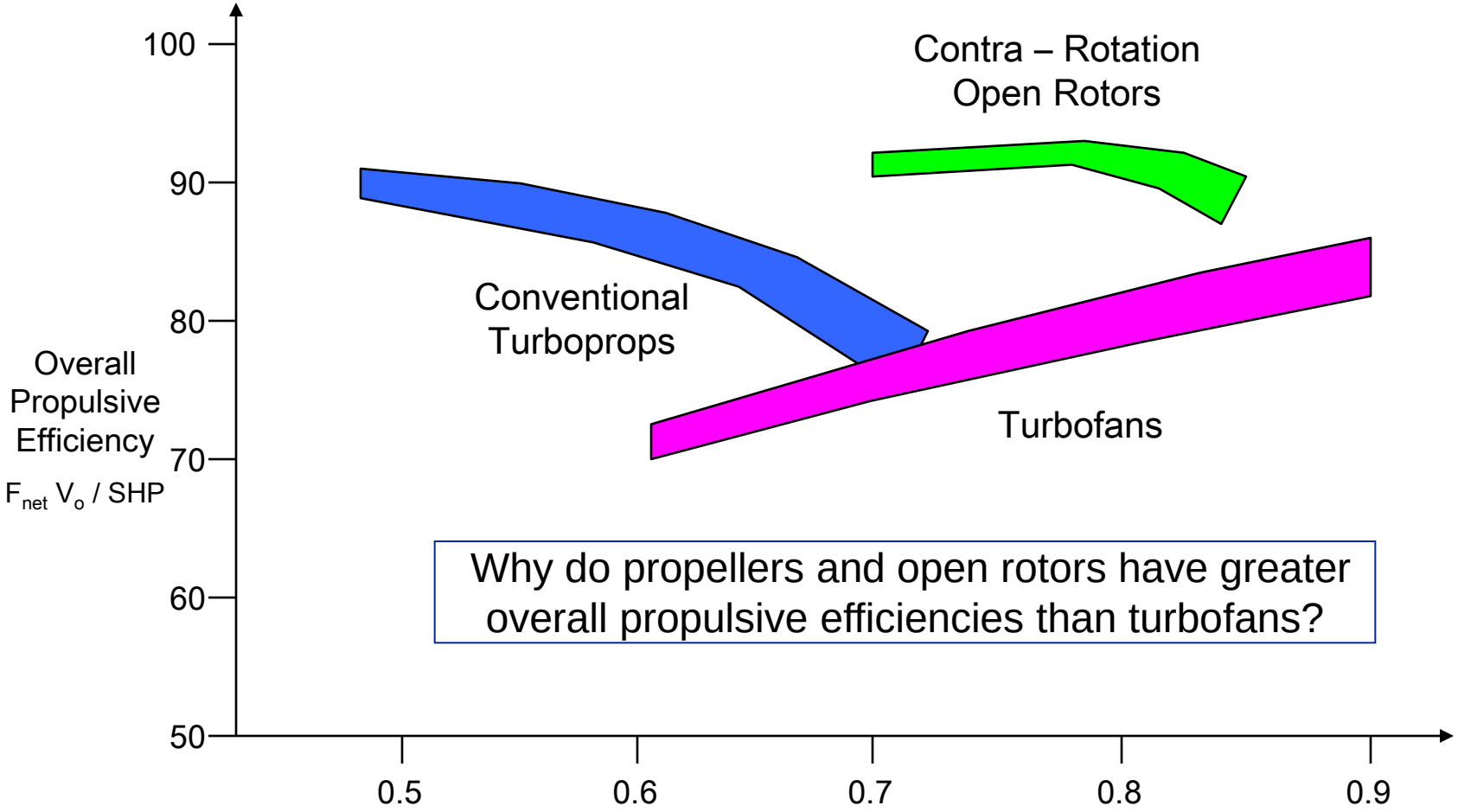
What is an Open Rotor?

An open rotor is a gas turbine engine where the fan is not within the nacelle. In such designs the fan is referred to as a propeller and can be either a single rotation propeller, i.e., a turboprop, or a pair of contra-rotating propellers, i.e., an open rotor or propfan.



Why Does an Open Rotor Offer an Advantage Relative to the Turbofan?

Trends with Flight Mach Number



Why do propellers and open rotors have greater overall propulsive efficiencies than turbofans?

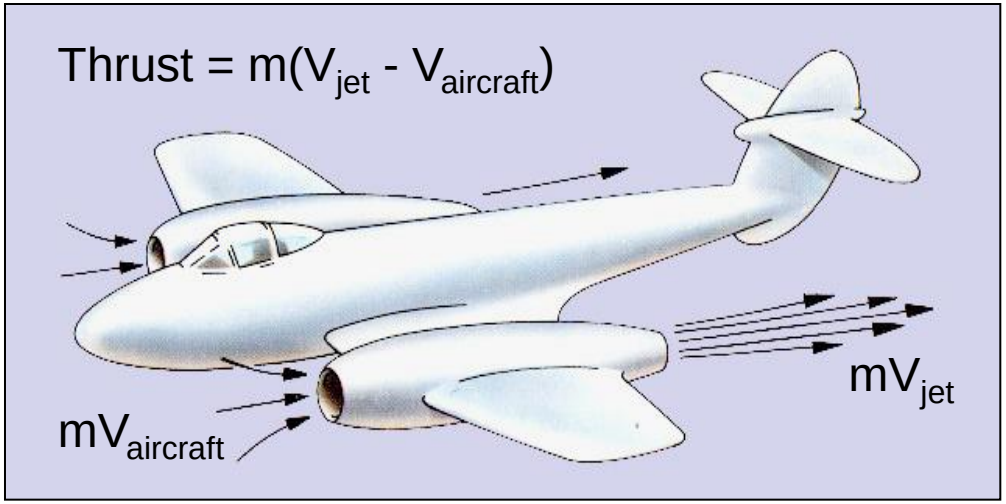
$$\eta_{\text{Overall Propulsive}} = \eta_{\text{Propulsive (Froude)}} \times \eta_{\text{propeller}}$$

Propellers (Open Rotors) vs Jet Propulsion

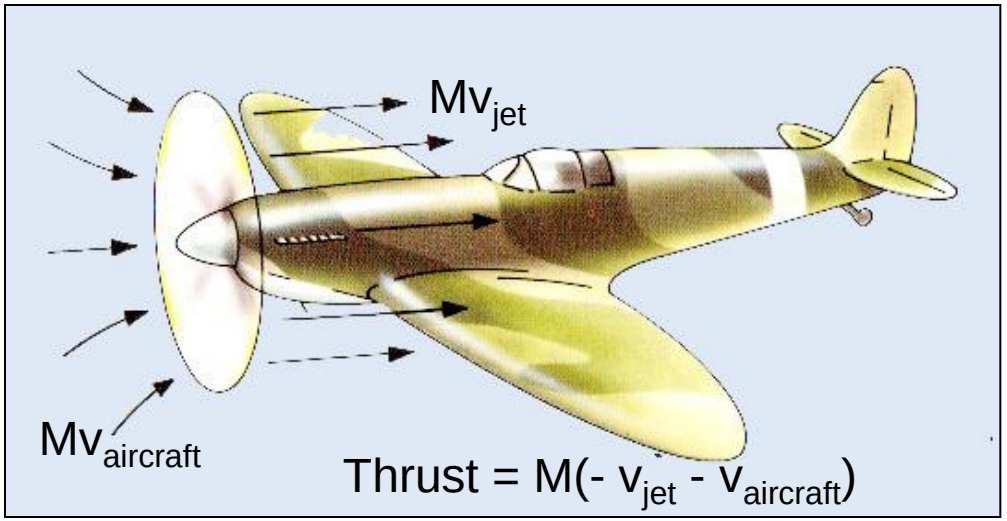
Propulsive Efficiency

Jet - moves small mass of gas at HIGH VELOCITY

$$\eta_{Propulsive} = \frac{2}{1 + \frac{V_J}{V_{aircraft}}}$$

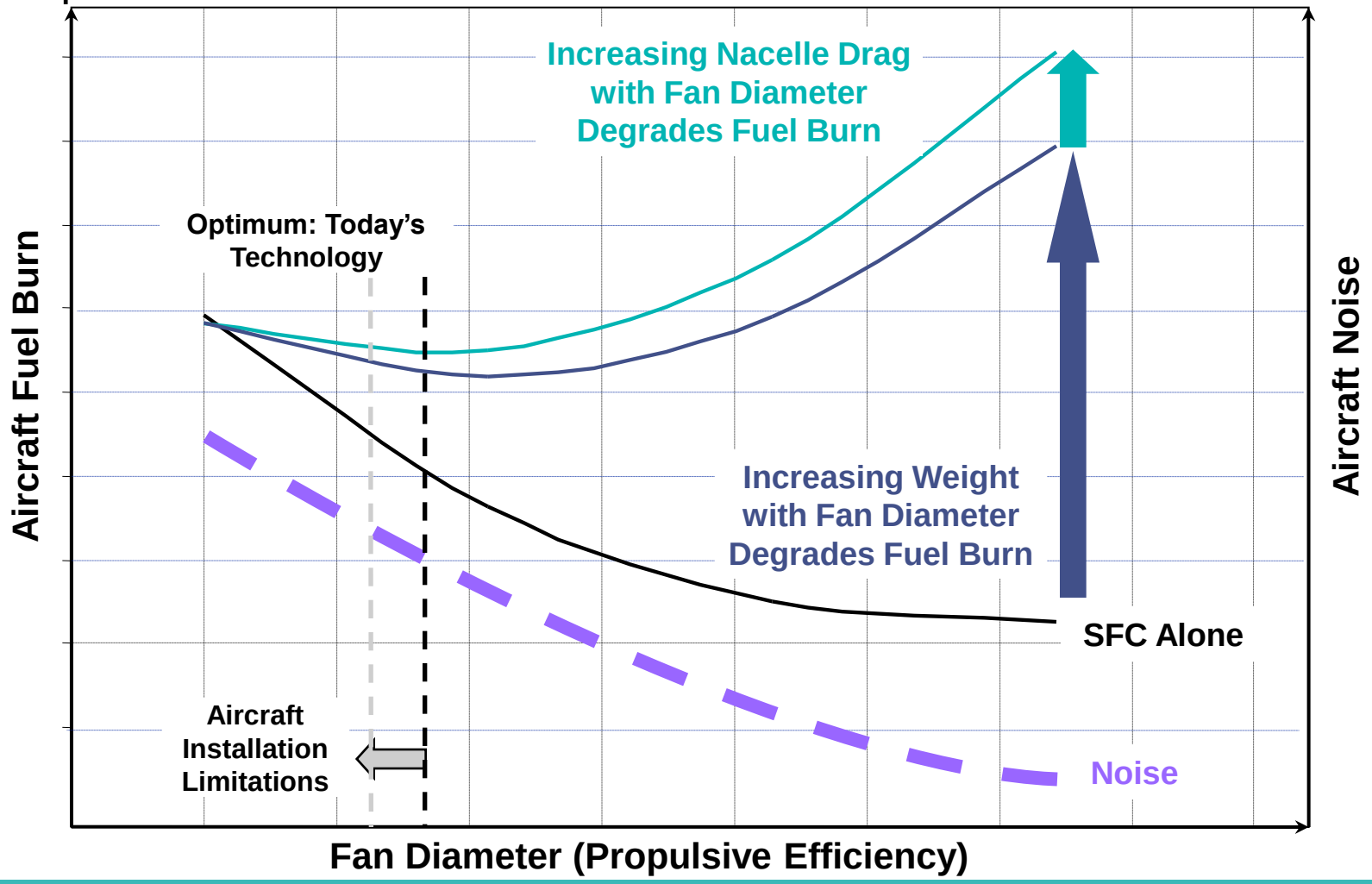


Propeller - moves LARGE MASS of air at low velocity



Why Can You Achieve Increased Propulsive Efficiency on an Open Rotor Relative to the Turbofan?

Optimised Fan Diameter – Advanced Turbofan & Geared Turbofan



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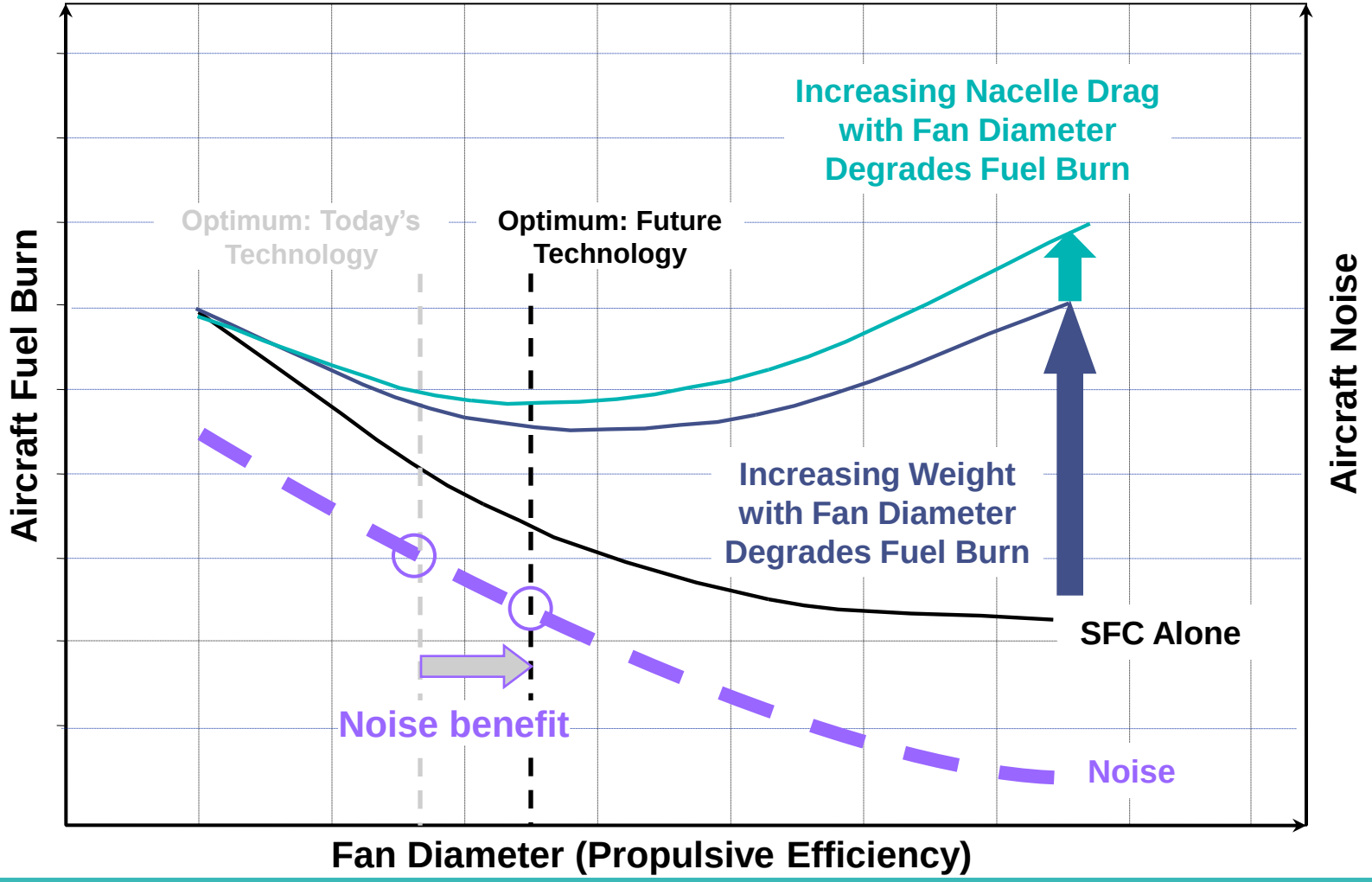

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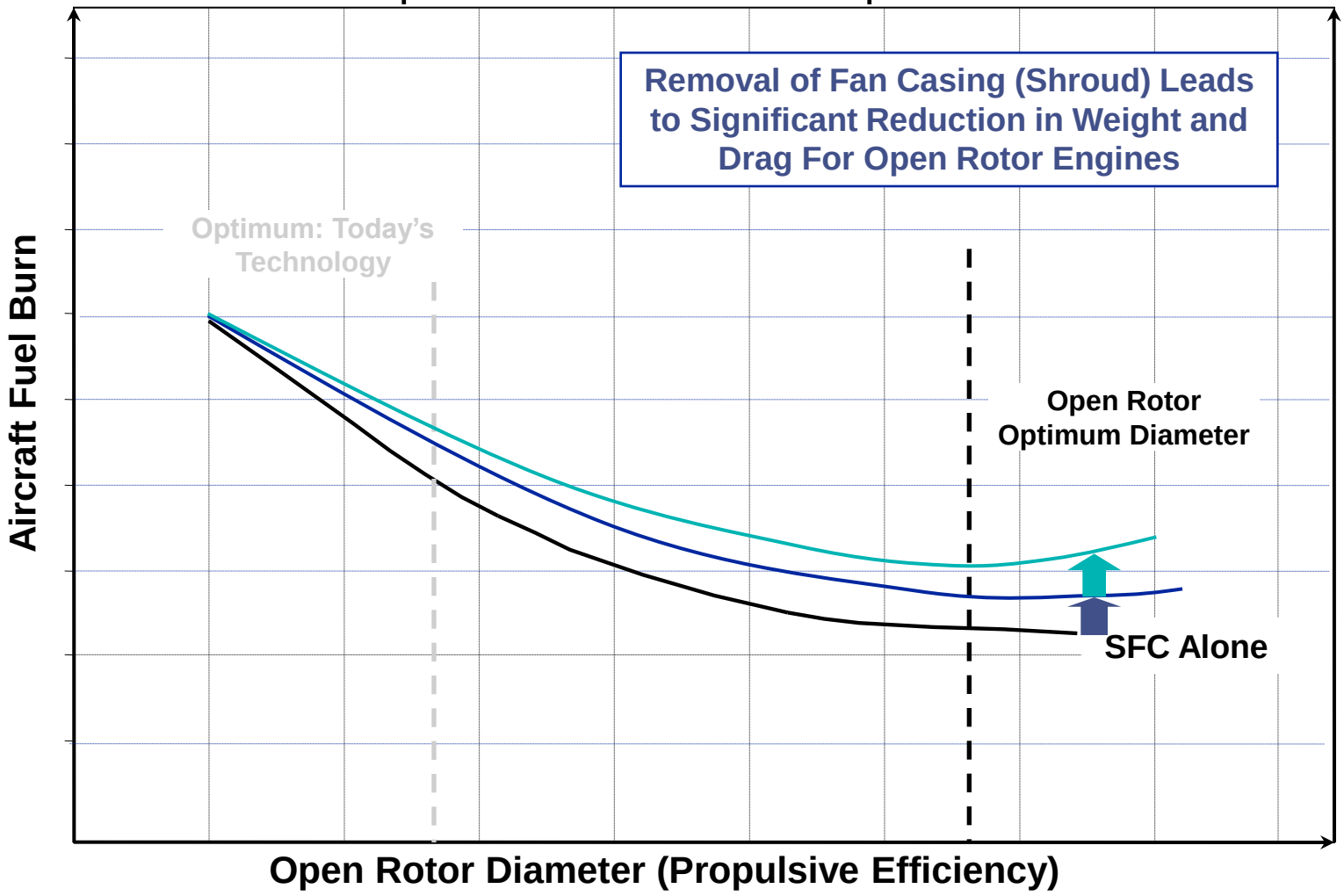
Optimised Diameter – Open Rotor



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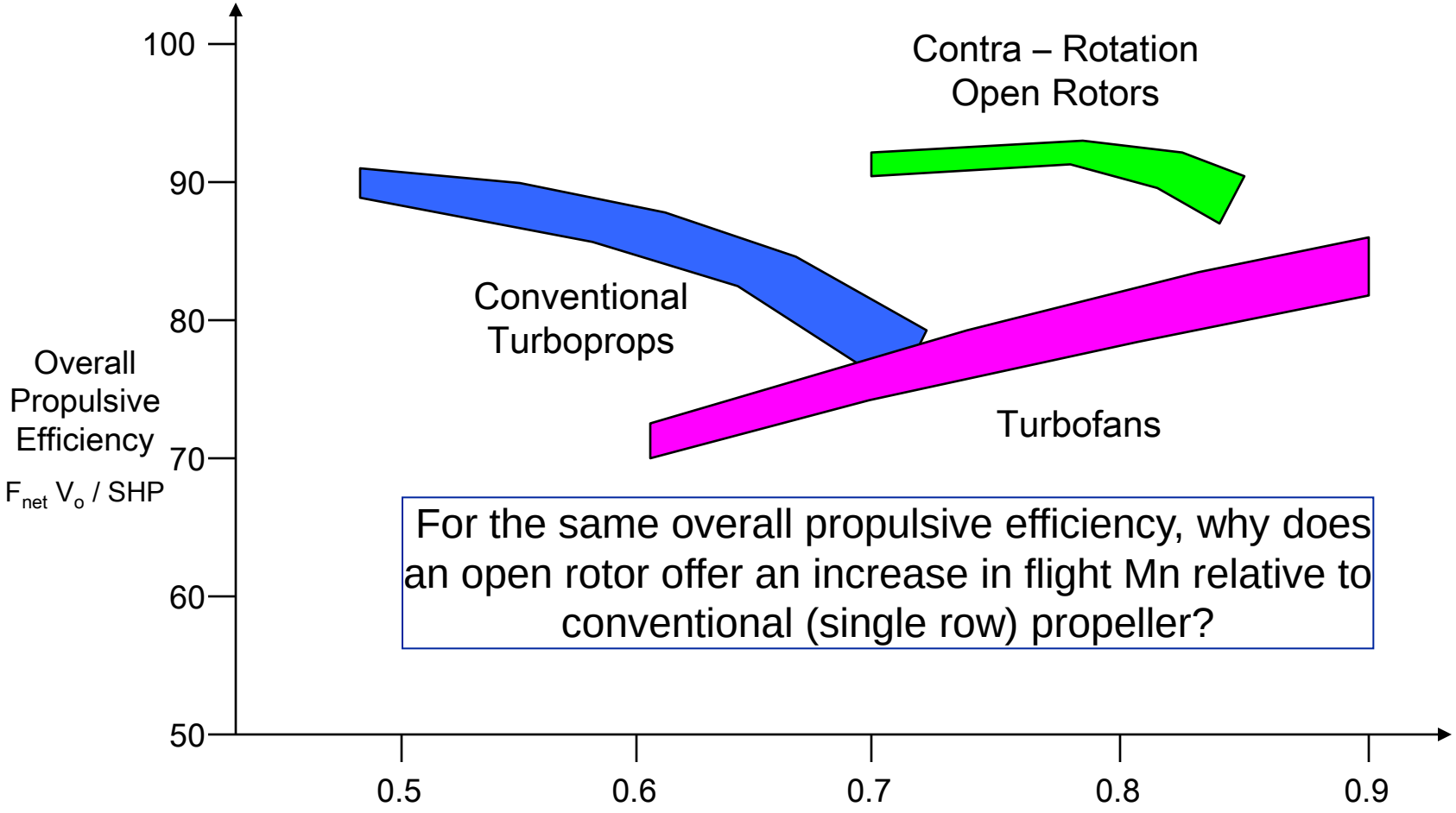
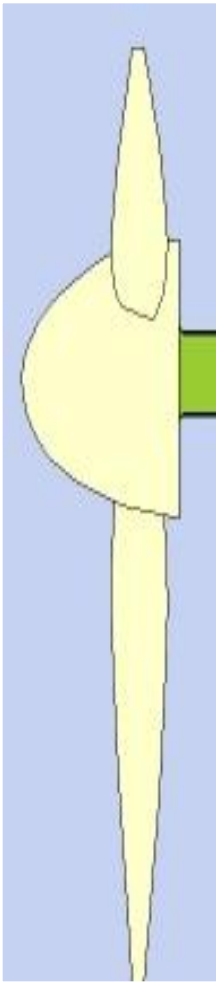
Trends with Flight Mach Number



For the same overall propulsive efficiency, why does an open rotor offer an increase in flight Mn relative to conventional (single row) propeller?

$$\eta_{\text{Overall Propulsive}} = \eta_{\text{Propulsive (Froude)}} \times \eta_{\text{propeller}}$$

Why Does an Open Rotor Offer an Increase in Flight Mn Relative to Conventional Propeller?



There are three types of propeller performance loss

Rotational - The torque input into the propeller has to be reacted by the air, resulting in rotational flow or swirl in the propeller wake, which is lost energy.

Axial – Equivalent to propulsive (Froude) efficiency. To reduce axial losses – increase propeller diameter

Profile - This is effectively the 2D drag on the aerofoil, including skin friction and compressibility losses. To reduce profile loss - maintain surface finish & aerofoil profile and Operate below drag rise Mach number (aerofoil design & sweep)

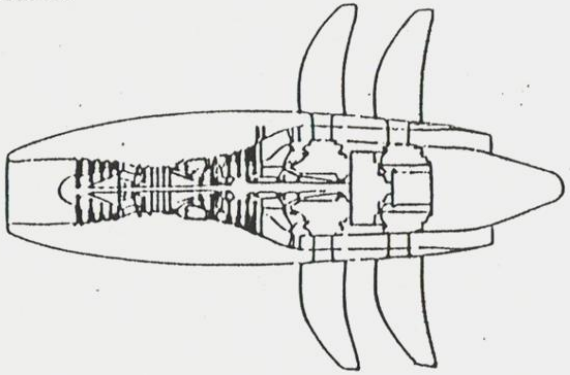
In order to keep the tips of the blades subsonic at cruise (reduced shock loss and cabin noise), the rotational speed of the rotor has to be reduced, which leads to rotational flow or swirl in the propeller wake.

The use of a second propeller to capture this swirl flow allows the overall efficiency to be significantly improved whilst maintaining a propeller diameter that can be integrated with the airframe.

Slide content courtesy - Dowty Propellers

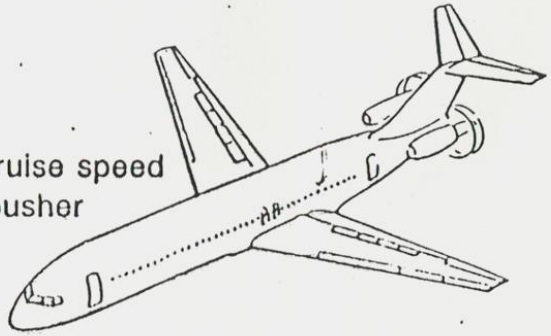
Historical Perspective

Propfan – Advanced study engine



Commercial transport

- Medium range
- 0.7 – 0.8Mn aircraft cruise speed
- Twin, rear mounted pusher
- 100 to 180 seats

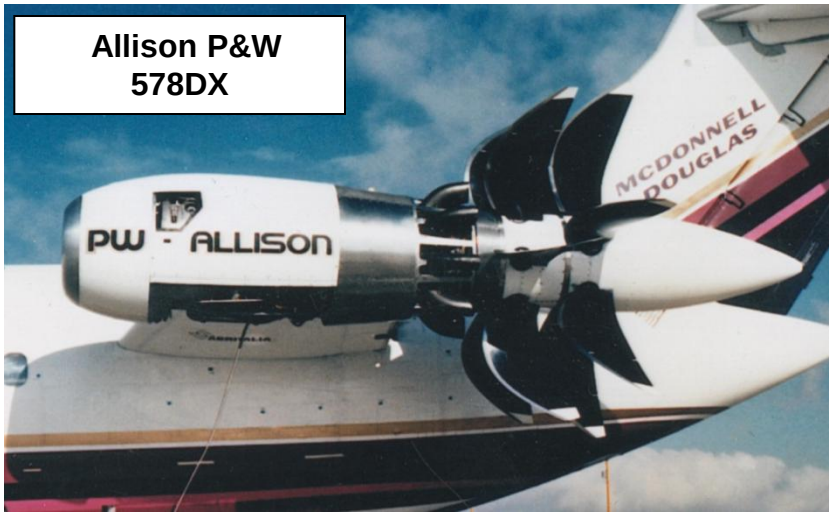


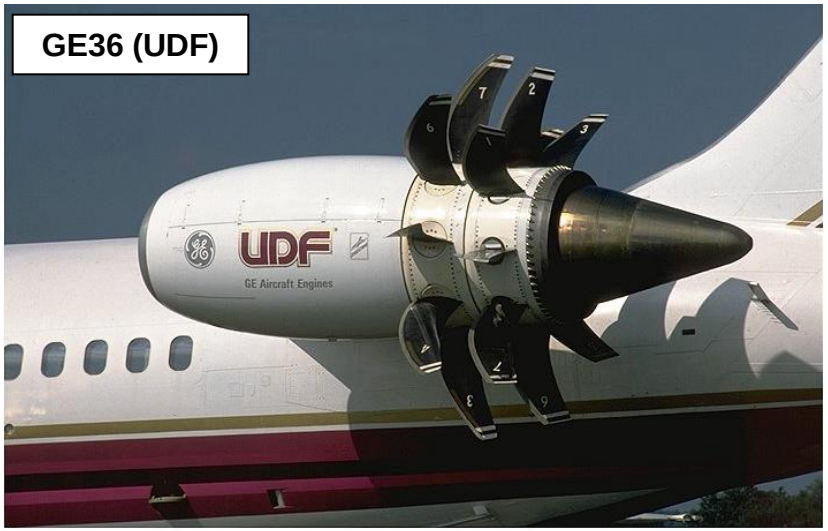
- Up to 35% improved fuel consumption relative to current engines
- Optimum matching of turbine and propeller speeds
- Duct and thrust reverser not required

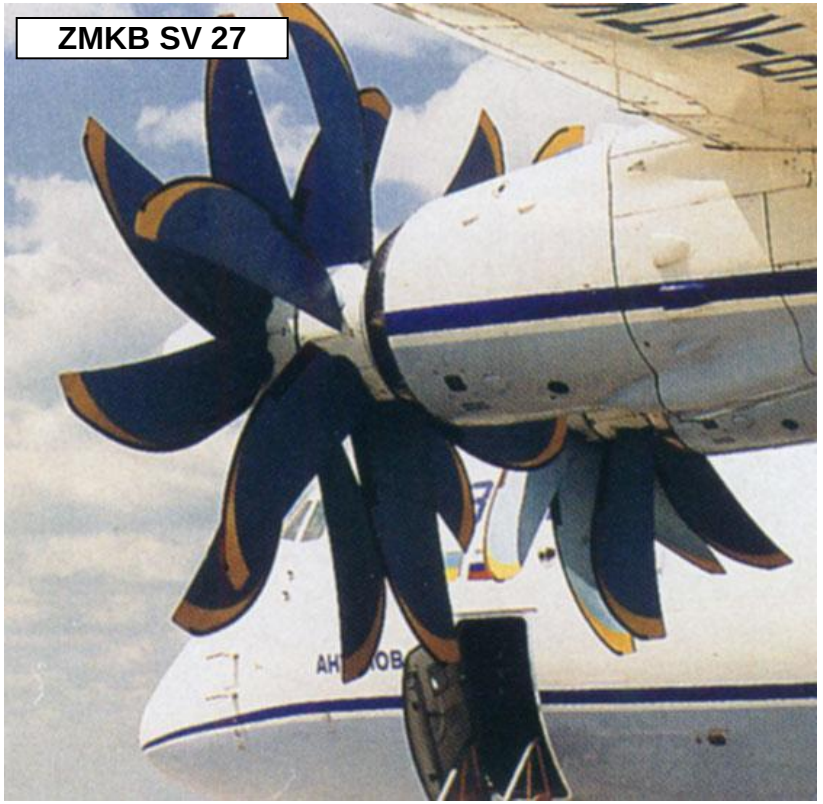
Military transport

- Four engines
- Wing mounted tractor
  - Better low speed flying characteristics
  - Avoids structural problems round rear freight door

Historical Perspective

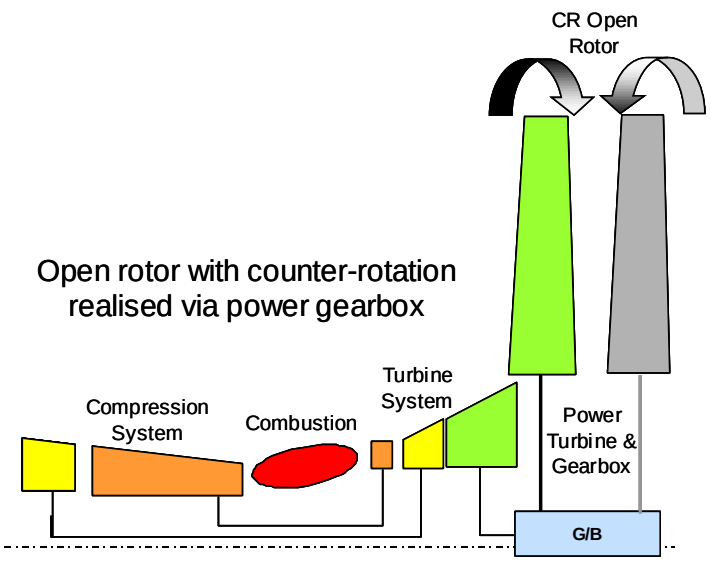




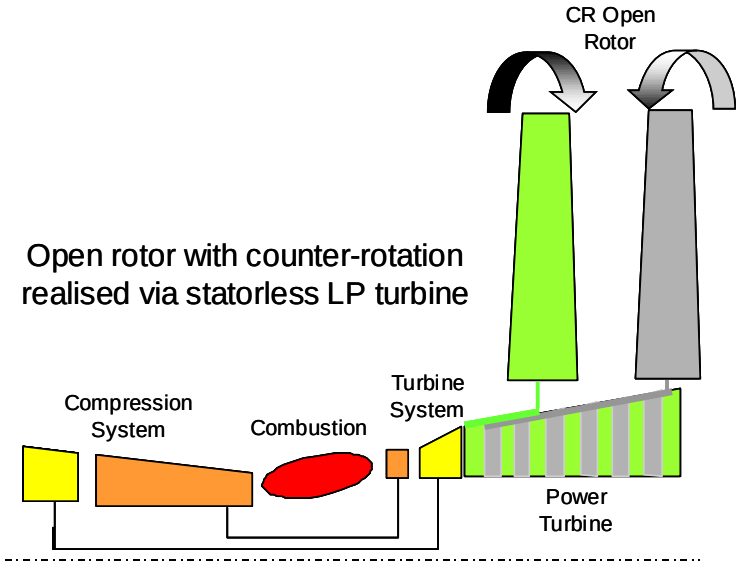


Historical Perspective

There are two principle ways of driving large slow tip speed propellers, either via a reduction gearbox driven by a high speed, low stage count, low pressure turbine (Allison P&W 578DX), or directly from a contra-rotating statorless multi-stage low pressure turbine (GE36).



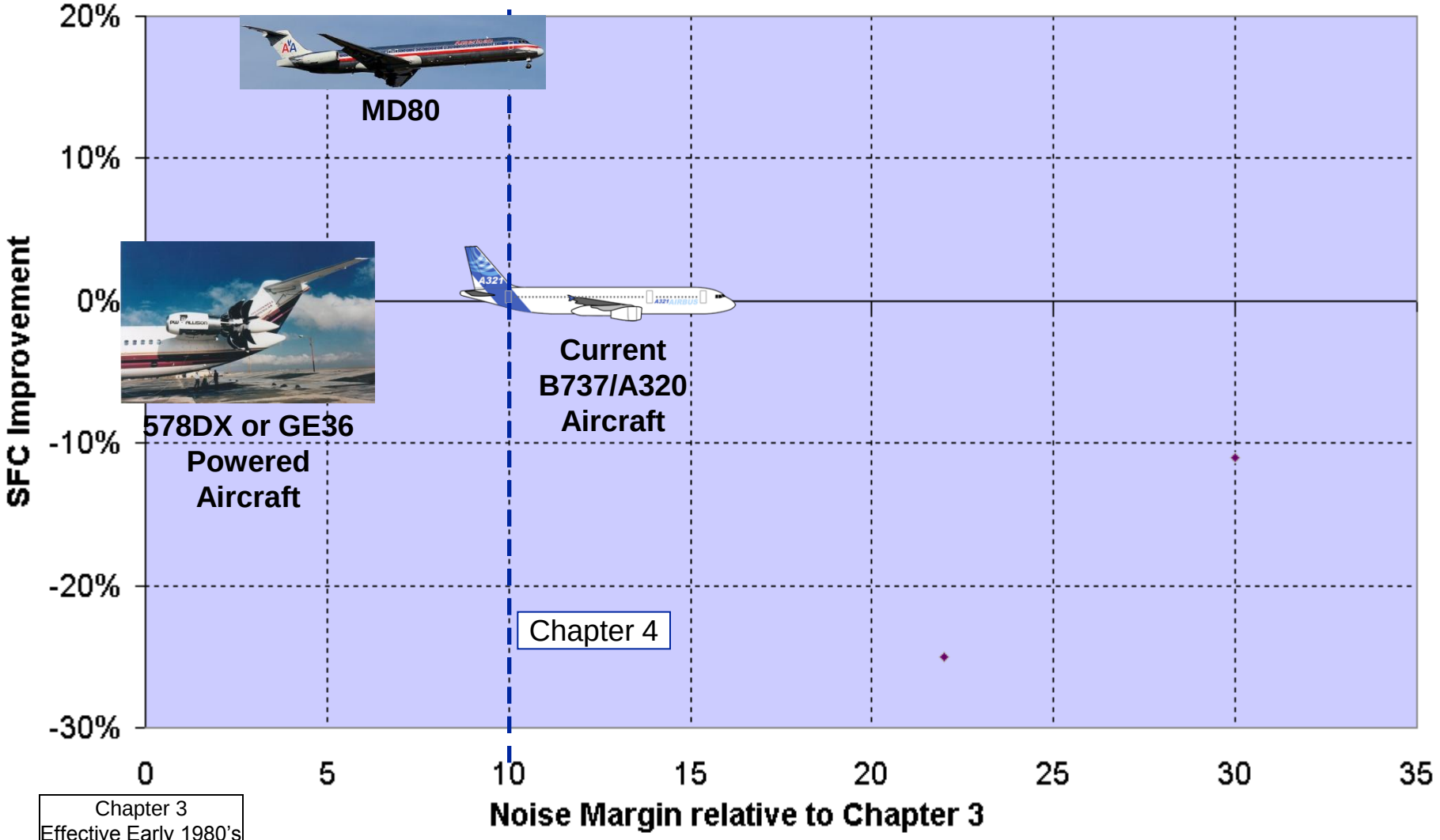
Geared Design



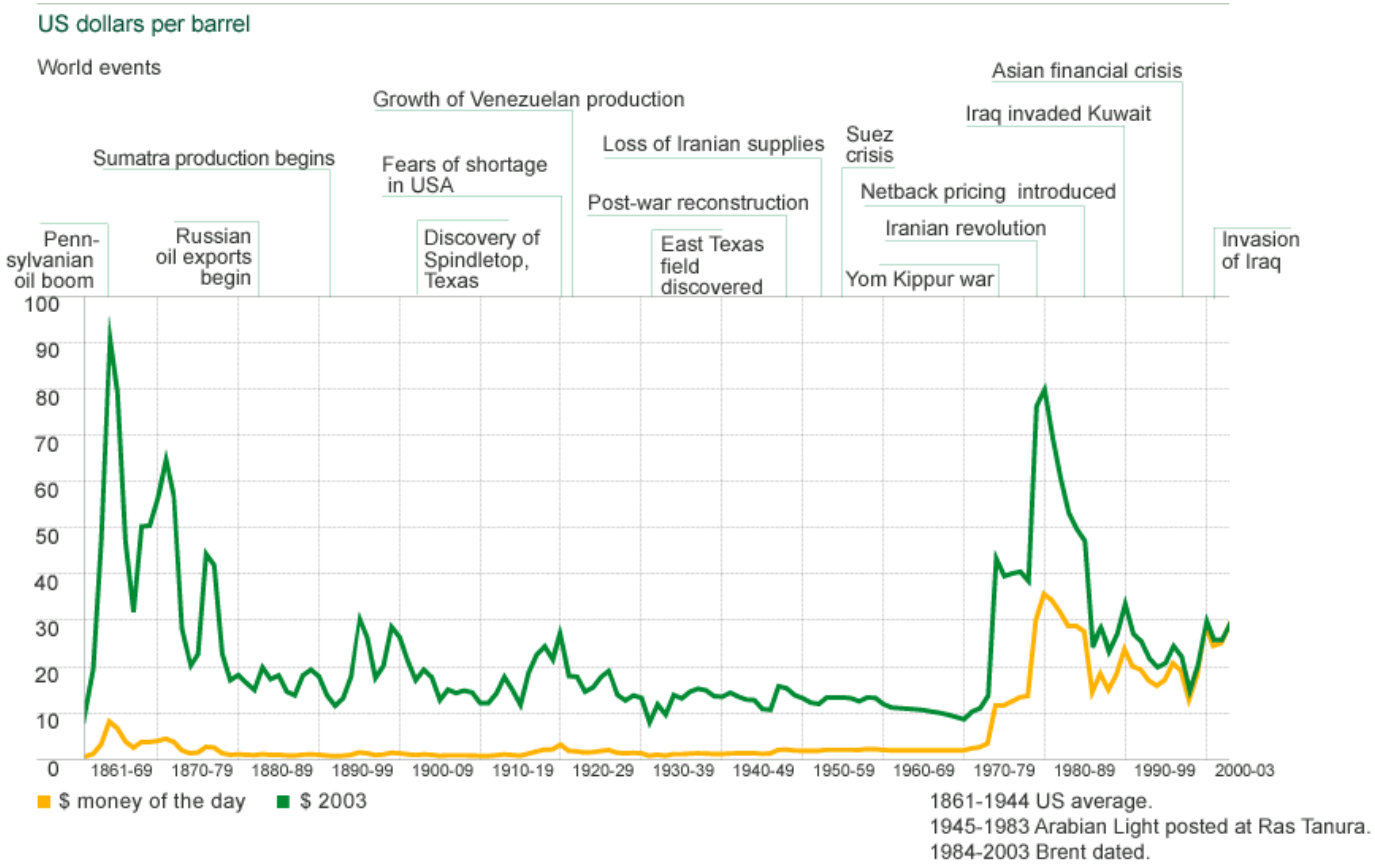
Statorless LP Turbine Design

Why Open Rotors Did Not Succeed in the 1980's?

Difficulty in Achieving Current and Future Noise Margins



Why Open Rotors Did Not Succeed in the 1980's?
Fall in Oil Price



What are the Issues Facing an Open Rotor Aircraft Today?

- Noise requirements have become much more stringent, 1980's Chapter 3, today we have Chapter 4 (-10db cumulative relative to Chapter 3), with the potential of further reductions in the future. The Quota Count - QC system has been introduced at London airports (absolute level).

- Introduction of high bypass ratio turbofans have lead to a dramatic reduction in aircraft noise relative to 1980's aircraft, i.e., the prop fan of 1980's was compared to MD80 JT8D BPR ≈ 2, today's B737/A320's V2500/CFM56 BPR ≈ 5, A380 Trent 900 BPR ≈ 8

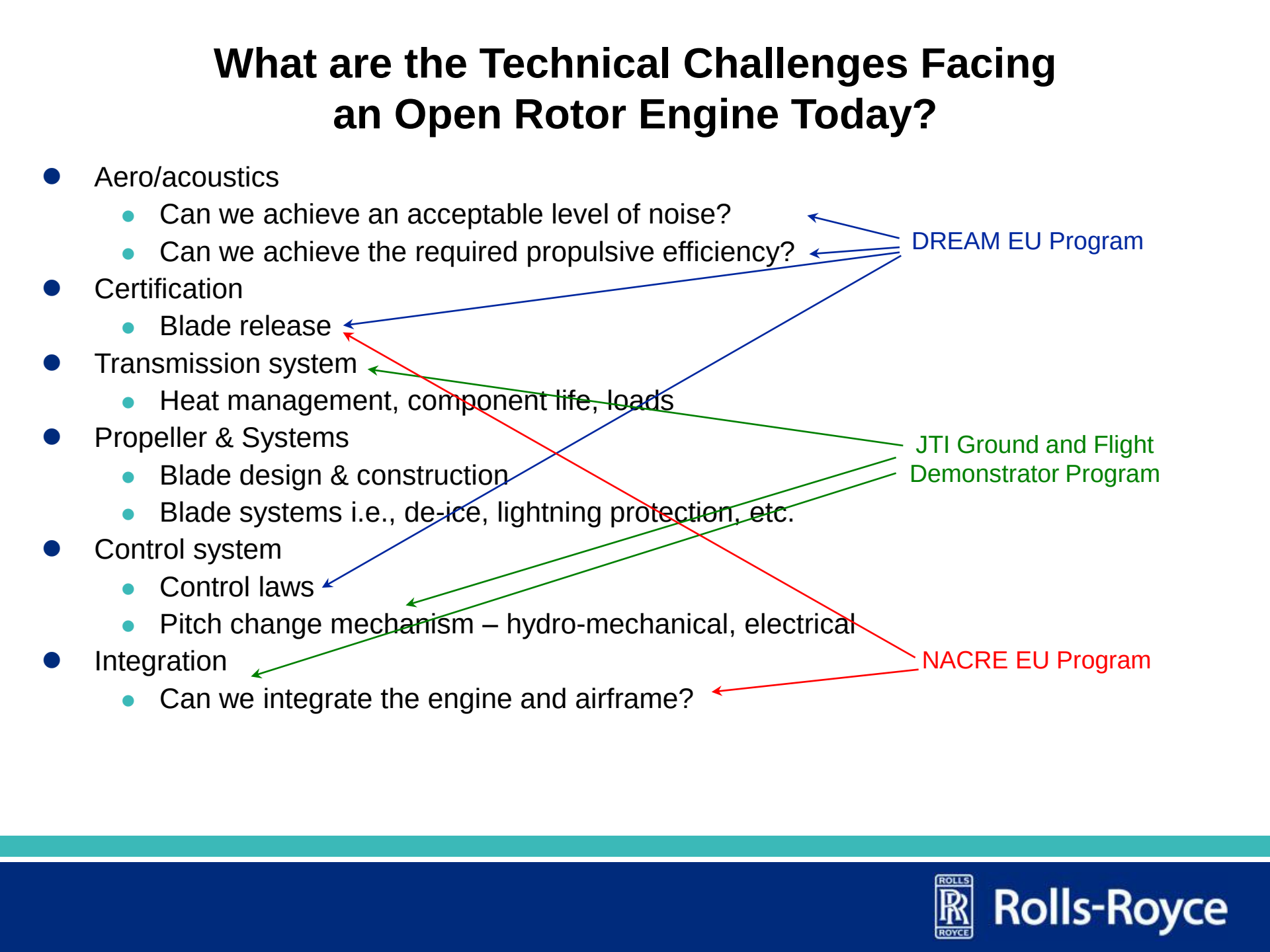
- Fuel has risen again in value - currently around $3 US gallon. Fuel currently makes up an average of 40% of airline operating cost (60% for low cost carrier).

- Environmental issues have become more prevalent ($C0_2$ & NOx). Strong public, political and media interest in the potential damage from air transportation sector.

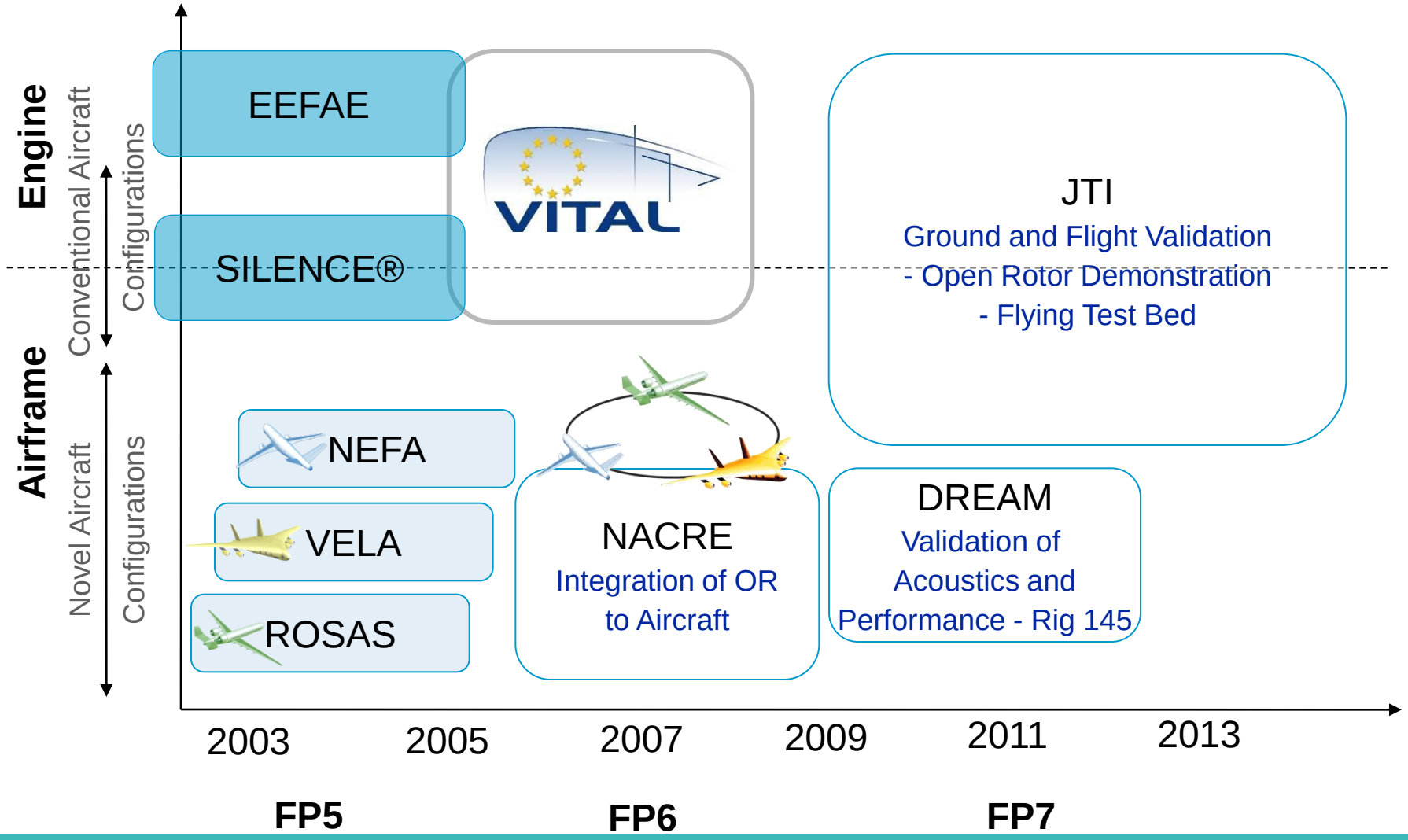
- Environmental taxing in Europe will add 50 cents to a $1 to a gallon of aviation fuel.

What are the Technical Challenges Facing an Open Rotor Engine Today?

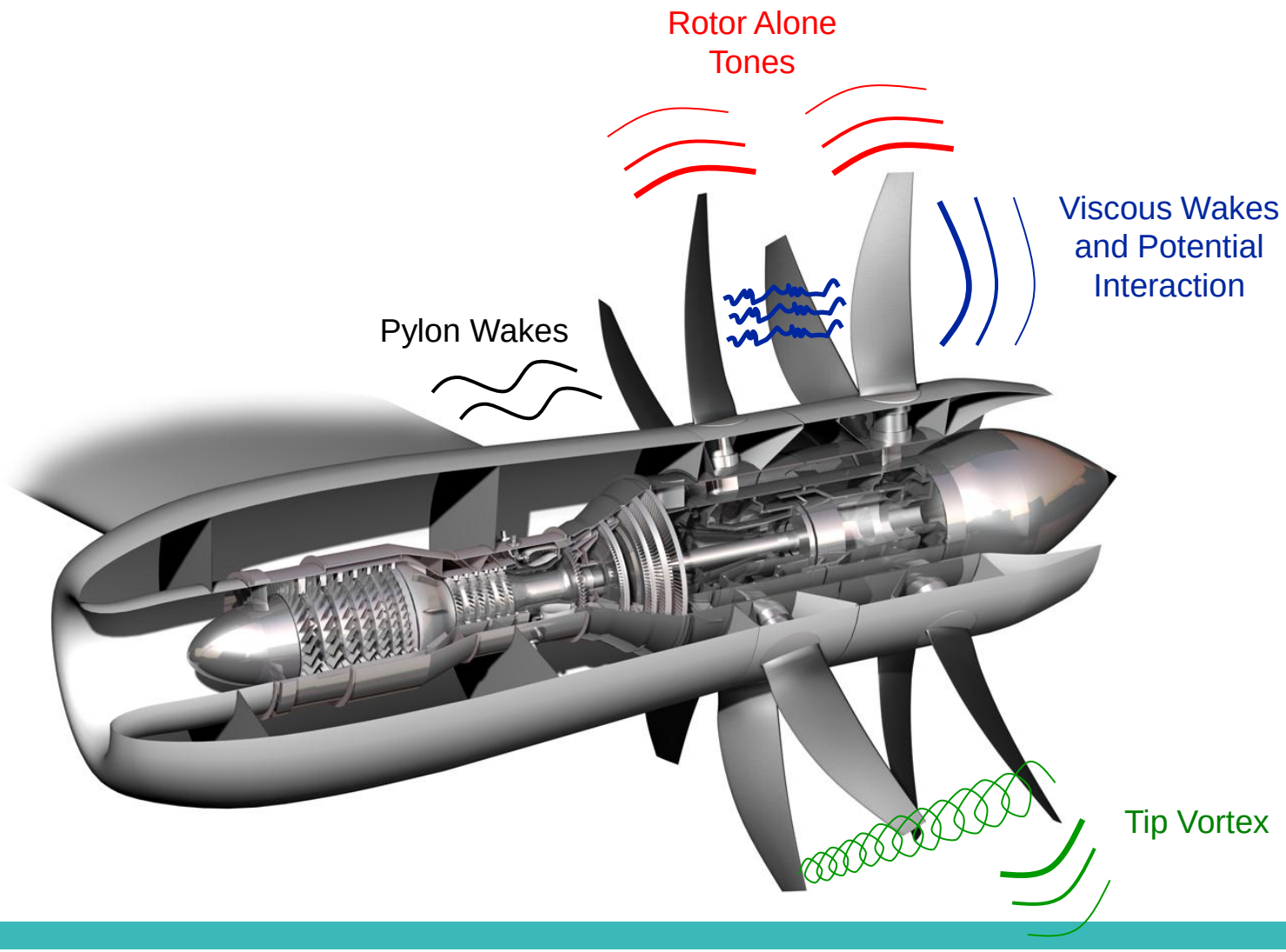
- Aero/acoustics
  - Can we achieve an acceptable level of noise?
  - Can we achieve the required propulsive efficiency?
- Certification
  - Blade release
- Transmission system
  - Heat management, component life, loads
- Propeller & Systems
  - Blade design & construction
  - Blade systems i.e., de-ice, lightning protection, etc.
- Control system
  - Control laws
  - Pitch change mechanism – hydro-mechanical, electrical
- Integration
  - Can we integrate the engine and airframe?



NACRE, DREAM and JTI in the Aeronautics
Research Roadmap

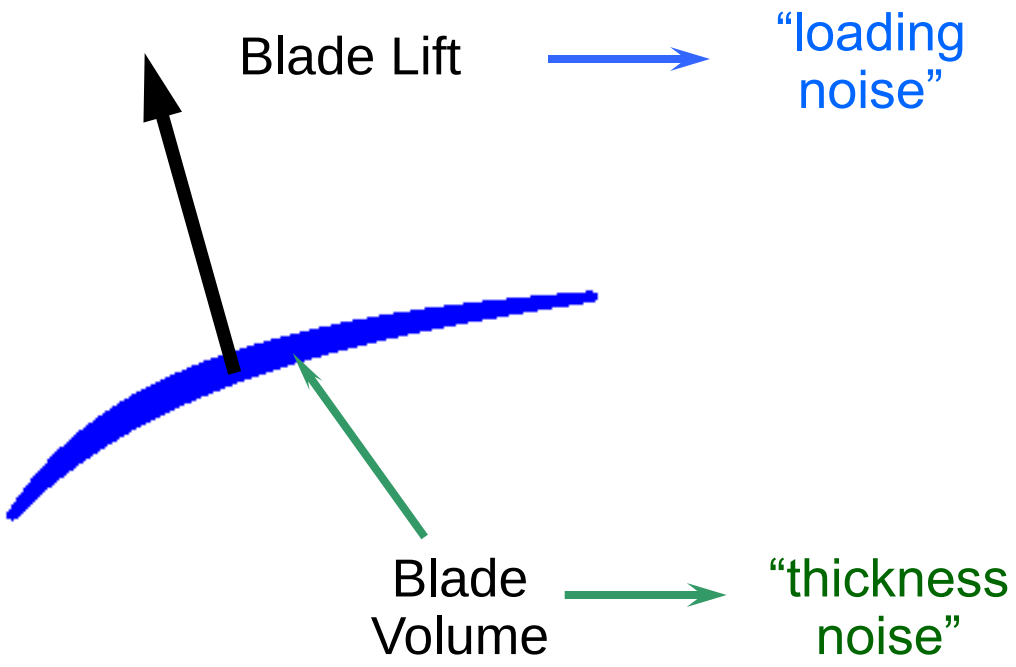


Open Rotor Noise
Additional Noise Sources



Open Rotor Noise

Open Rotors Noise - Single Blade Row Noise Sources



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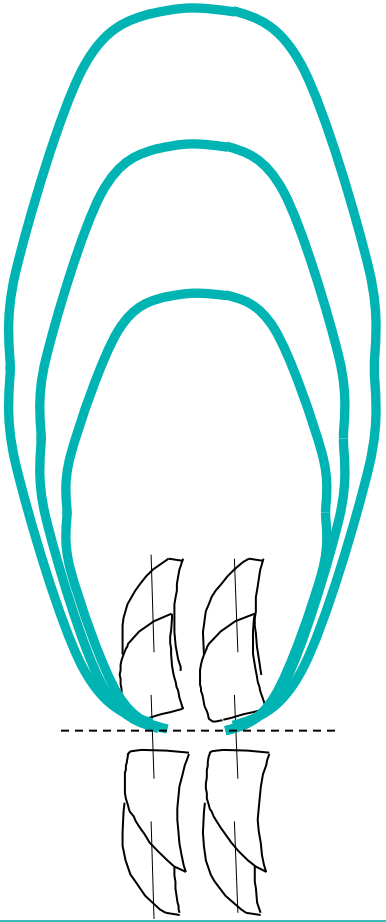


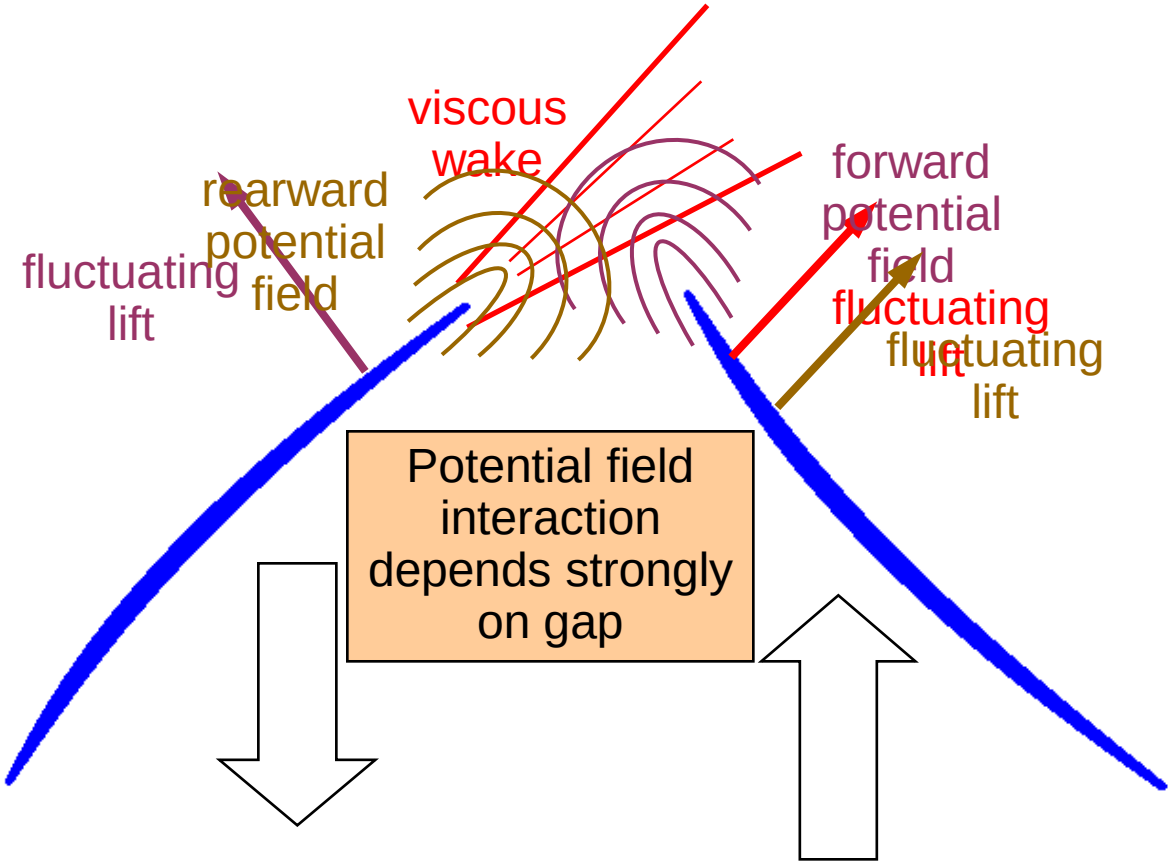
Increase Blade Numbers

and

Decrease Tip Speed (Mn_{rel})

Open Rotor Noise

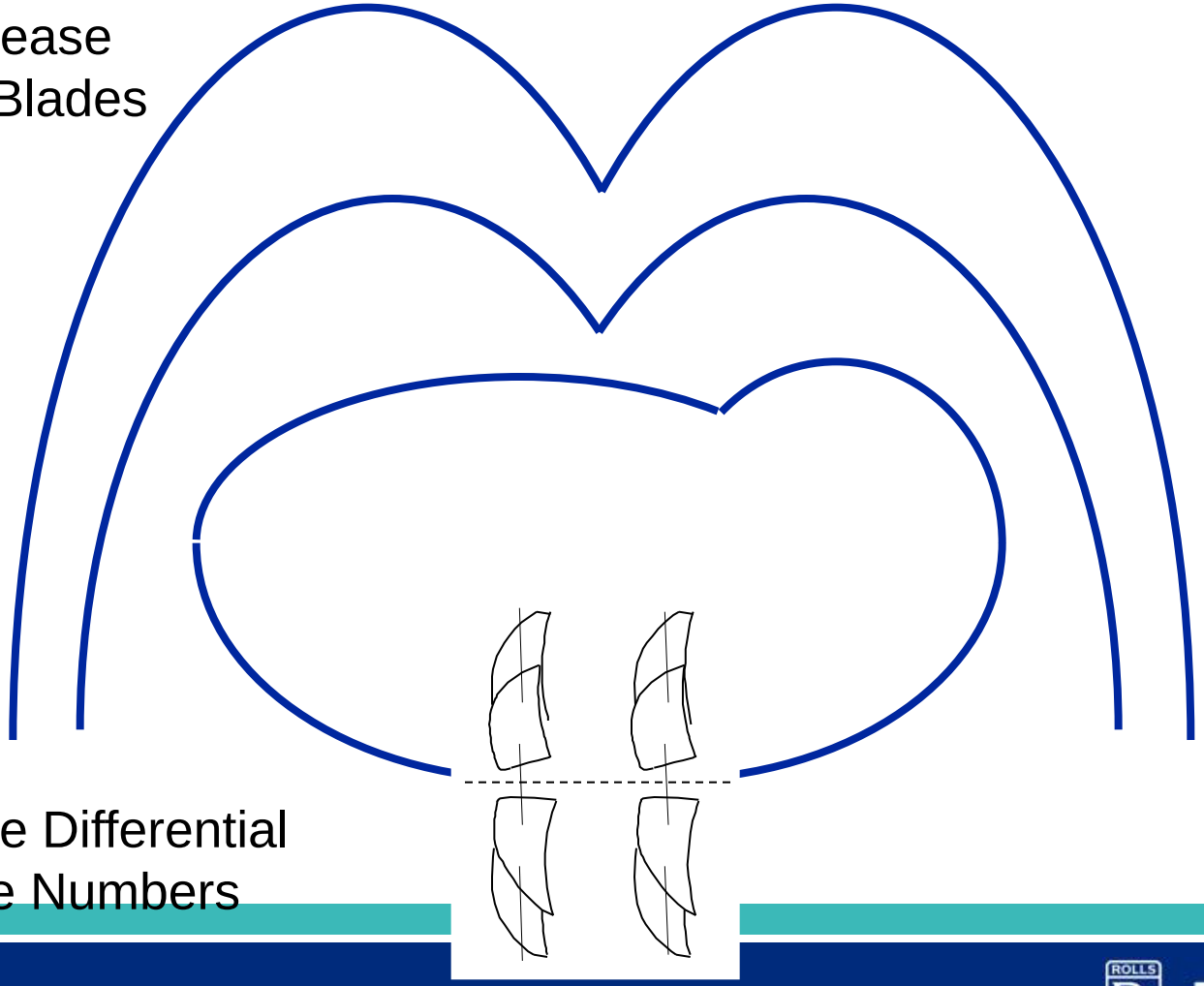
Open Rotors Noise - Blade to Blade Noise Sources



Open Rotor Noise

Open Rotors Noise - Blade to Blade Noise Sources

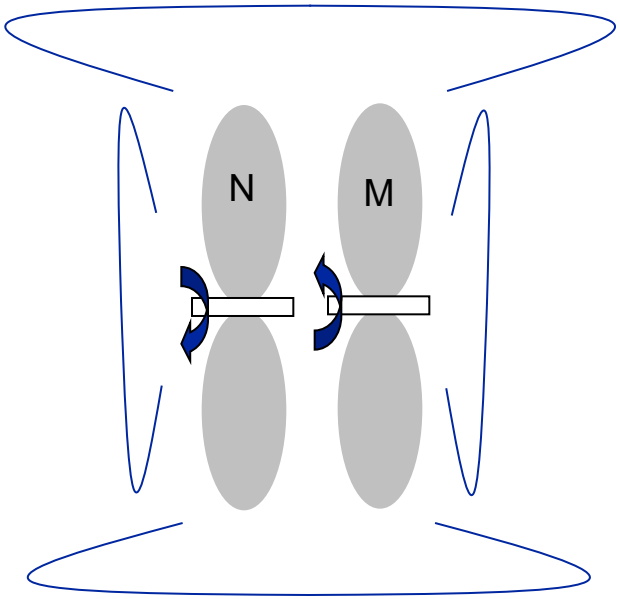
Increase Gap/Blades



and Use Differential Blade Numbers

Open Rotor Noise

Open Rotors Noise - Blade to Blade Noise Sources



$N \neq M$

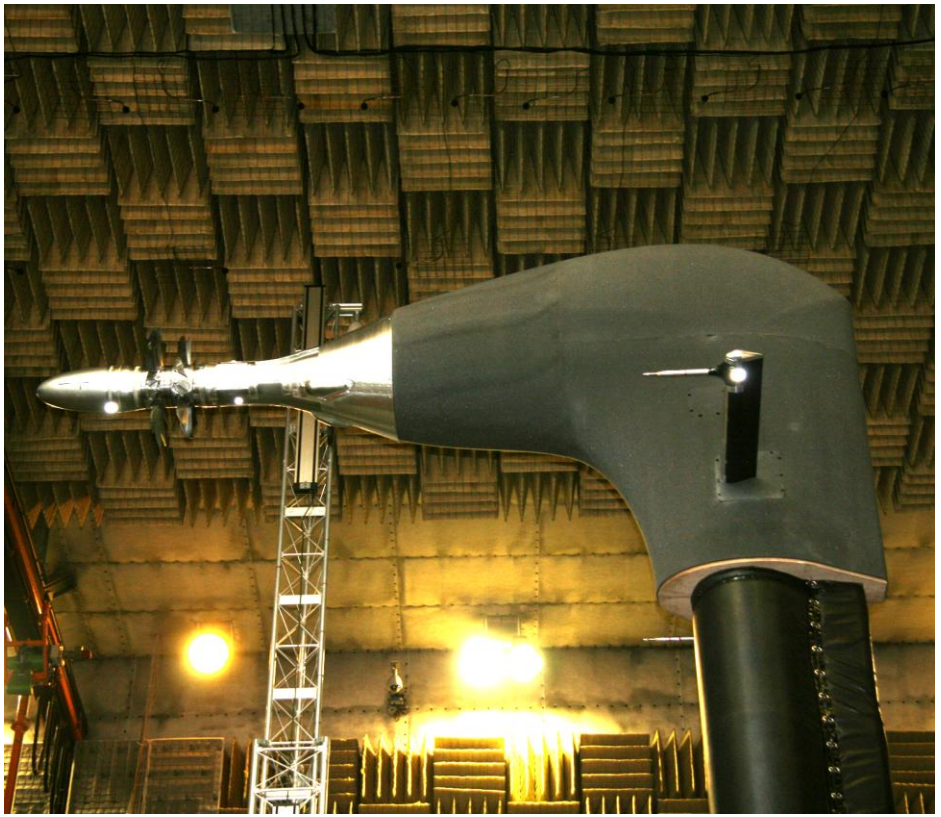
- N & M are large numbers
- Gap between N & M is optimised

+ extra stuff I can't talk about

DREAM Open Rotor Noise Testing

Rig 145 at DNW Test Facility

- 1/6th scale rig (28” diameter)
- Multiple configurations run to optimise performance and noise

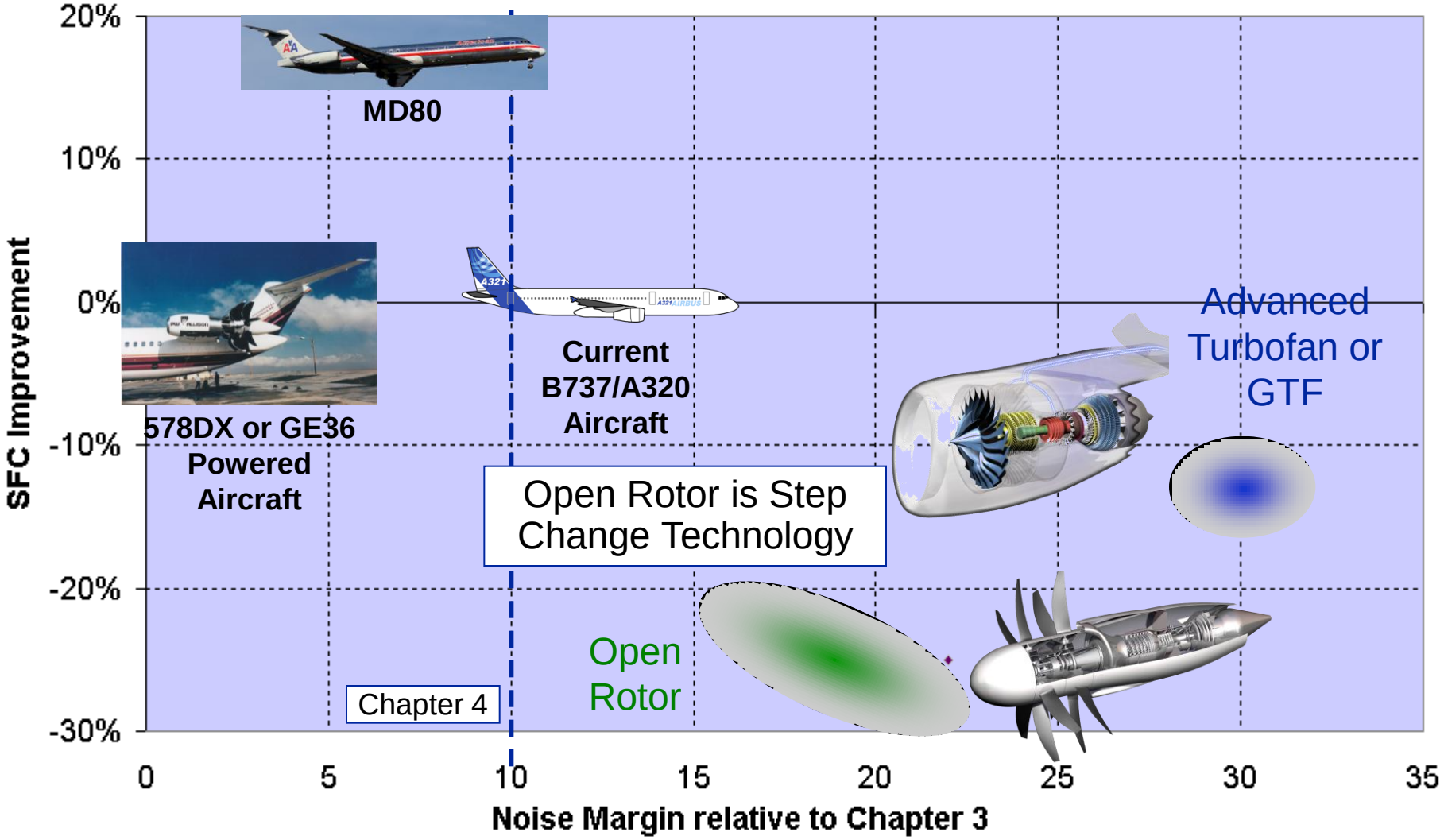


DREAM Open Rotor Noise Testing
Results So Far

- Rig 145 recently completed successfully low speed acoustic test campaign in DNW facility in the Netherlands
- Rig145 now being transported to the ARA facility in Bedford for high speed performance testing
- Testing funded under EU framework 7 DREAM project
- Initial results are in line with expectation
- Based on this new and innovative technology Rolls-Royce believes a quiet and efficient open rotor engine is realisable

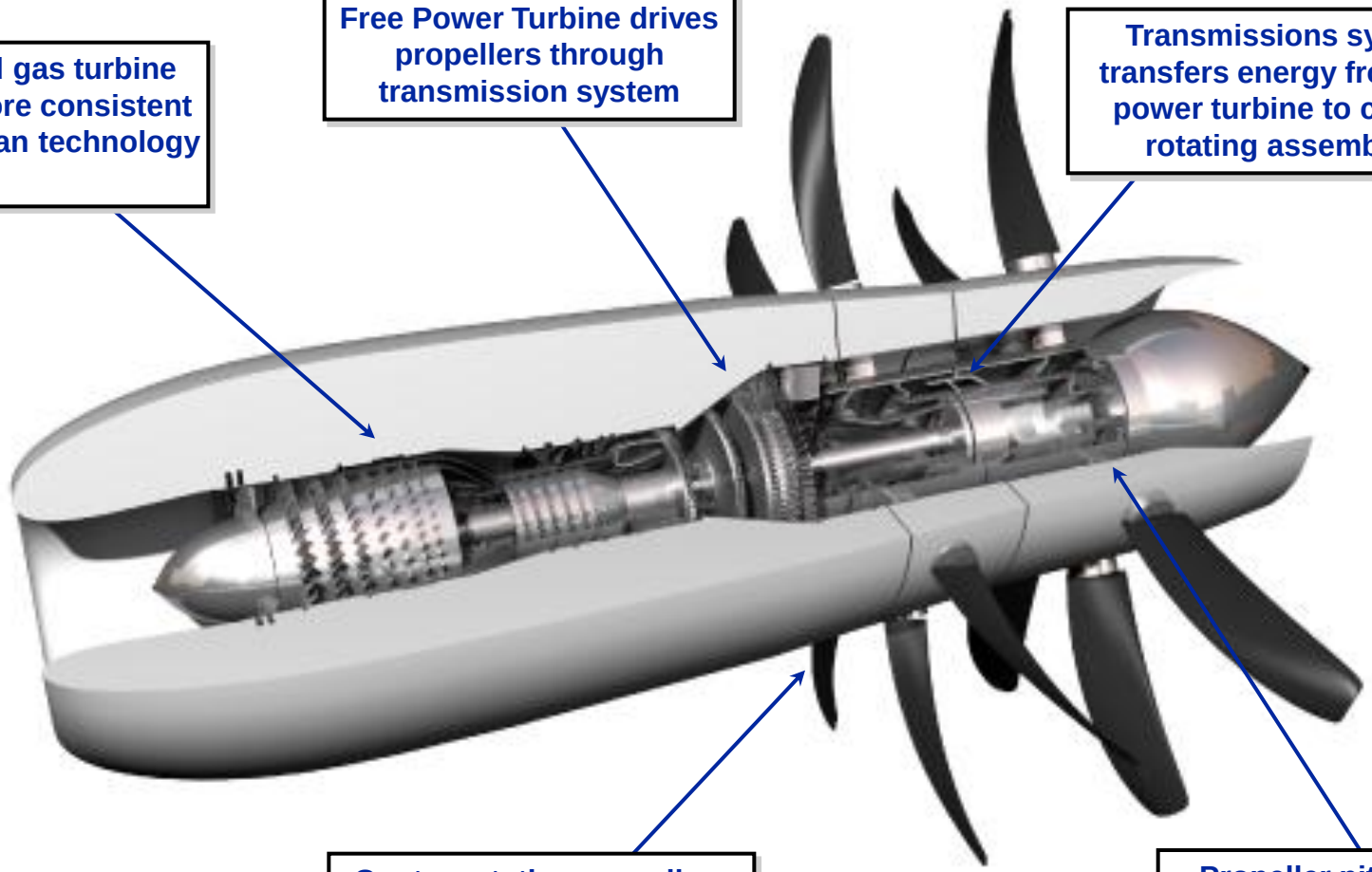
Local and Environmental Trade-Offs

A320/737 Aircraft Sector



Rolls-Royce RB2011 Open Rotor

Baseline Pusher Concept



Advanced gas turbine 2 spool core consistent with turbofan technology

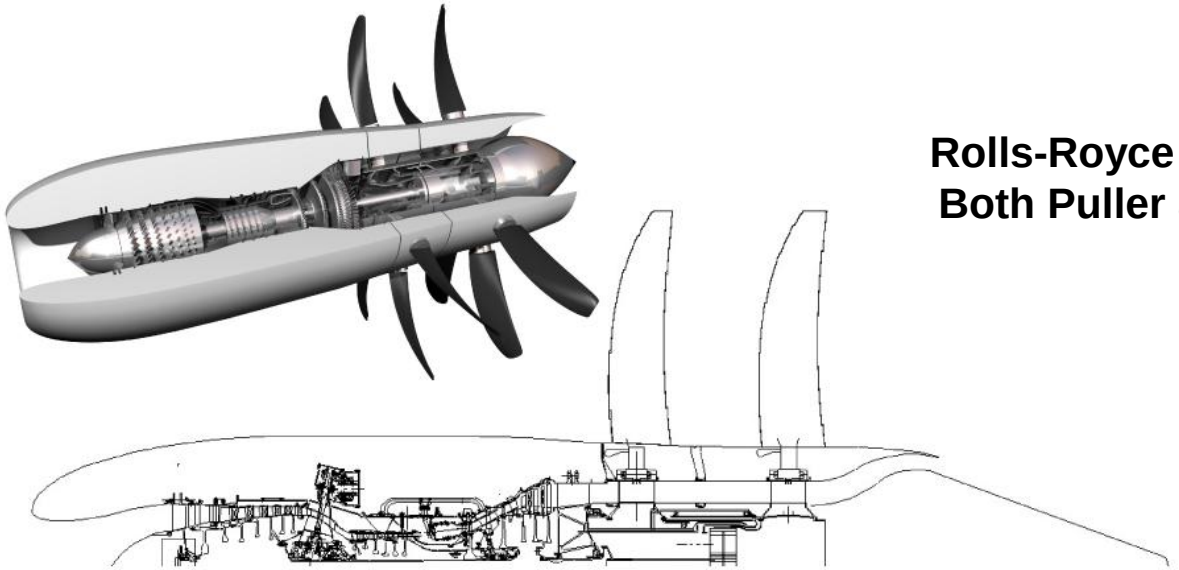
Free Power Turbine drives propellers through transmission system

Transmissions system transfers energy from free power turbine to contra-rotating assemblies

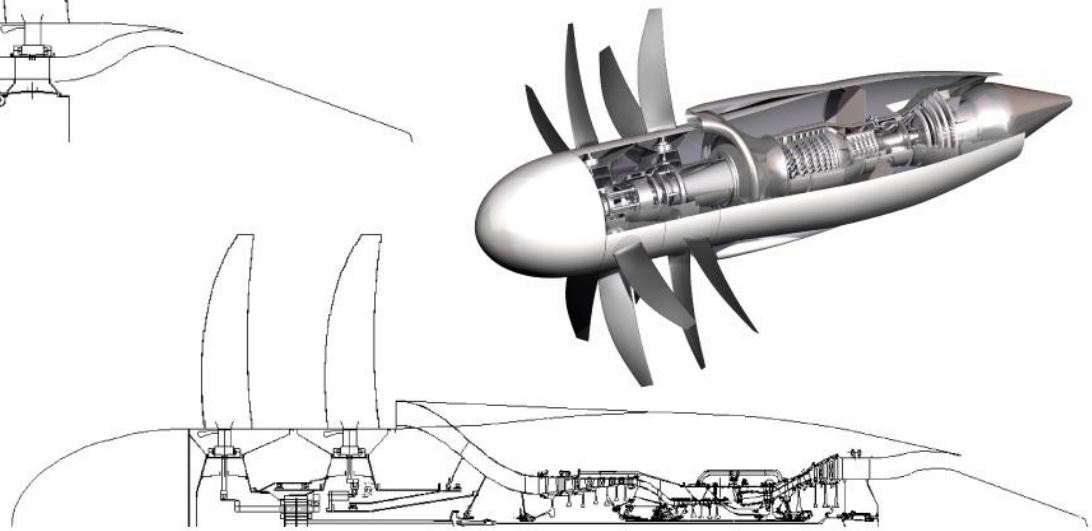
Contra rotating propellers Noise optimised configuration

Propeller pitch change mechanism maintains optimum propeller angle and power distribution

Rolls-Royce RB2011 Open Rotor
Pusher and Puller Configurations



Rolls-Royce Generic Studies Consider Both Puller and Pusher Configuration



Overall ACARE* Environmental Targets for 2020

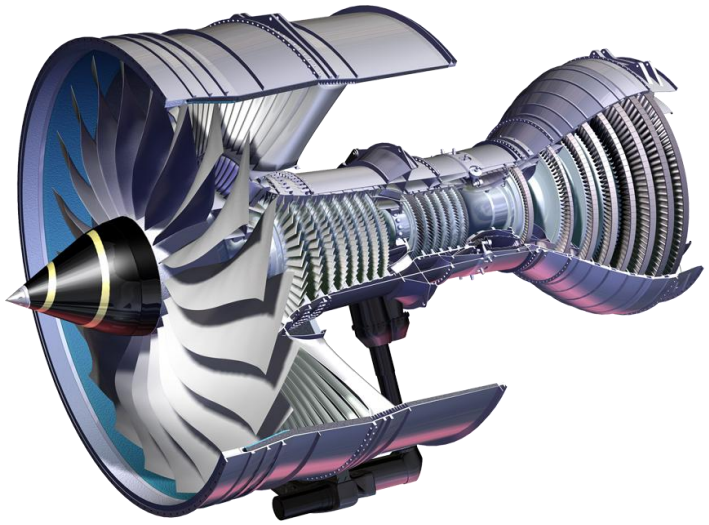
Reduce Perceived External Noise by 50% (30db Cumulative)

Reduce Perceived External Noise by 18 dB Cumulative

Reduce NO_X Emissions by 80%

Reduce NO_X Emissions by 80%

Targets are for new aircraft and whole industry relative to 2000….



……..and represent a doubling of the historical rate of improvement

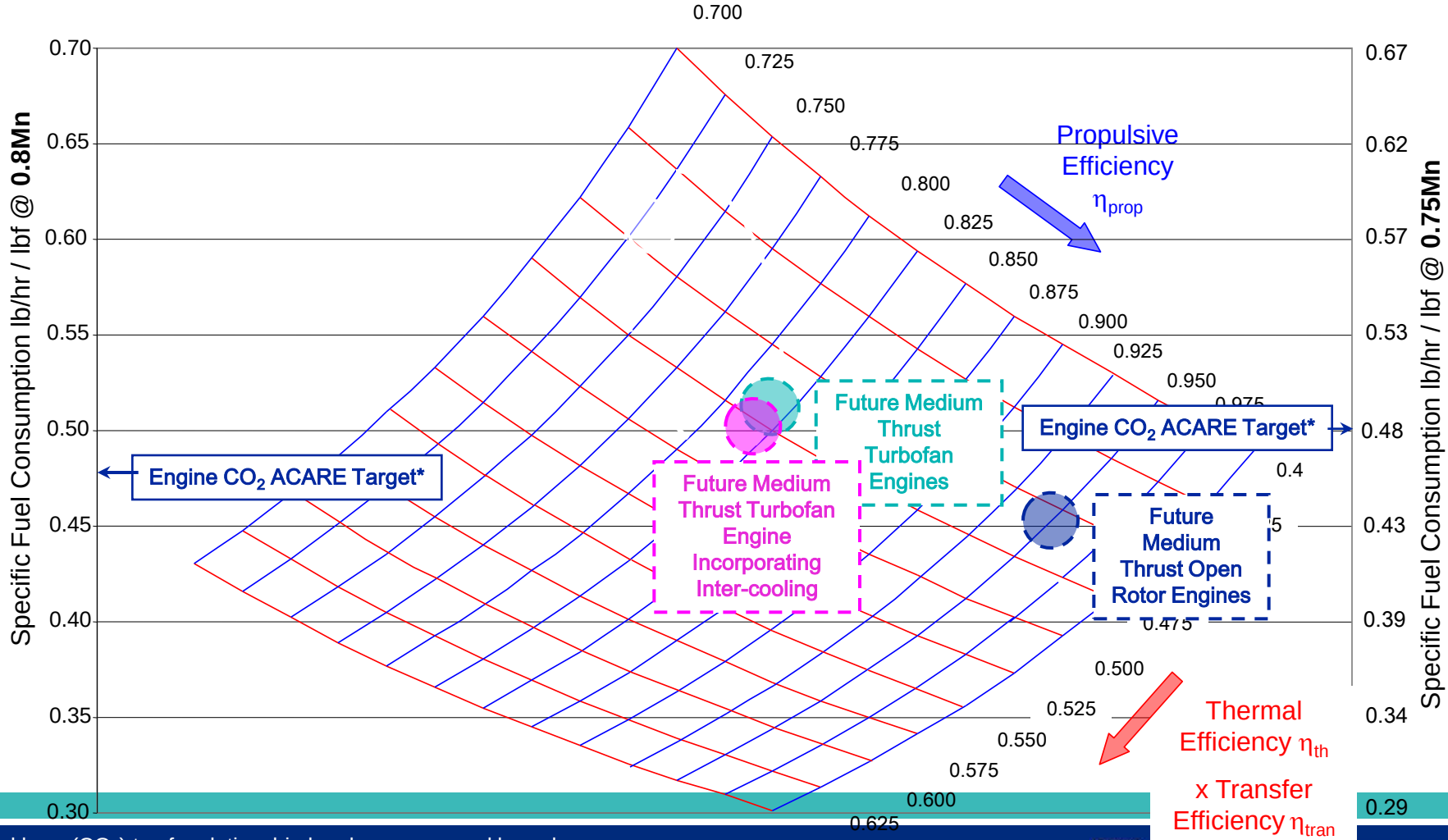
Reduce Fuel Consumption and CO_2 Emissions by 50%

Reduce Fuel Consumption and CO_2 Emissions by 20%

Engine level targets

* Advisory Council for Aerospace Research in Europe

Potential Specific Fuel Burn Improvements for Medium Thrust Engines – 2020 EIS

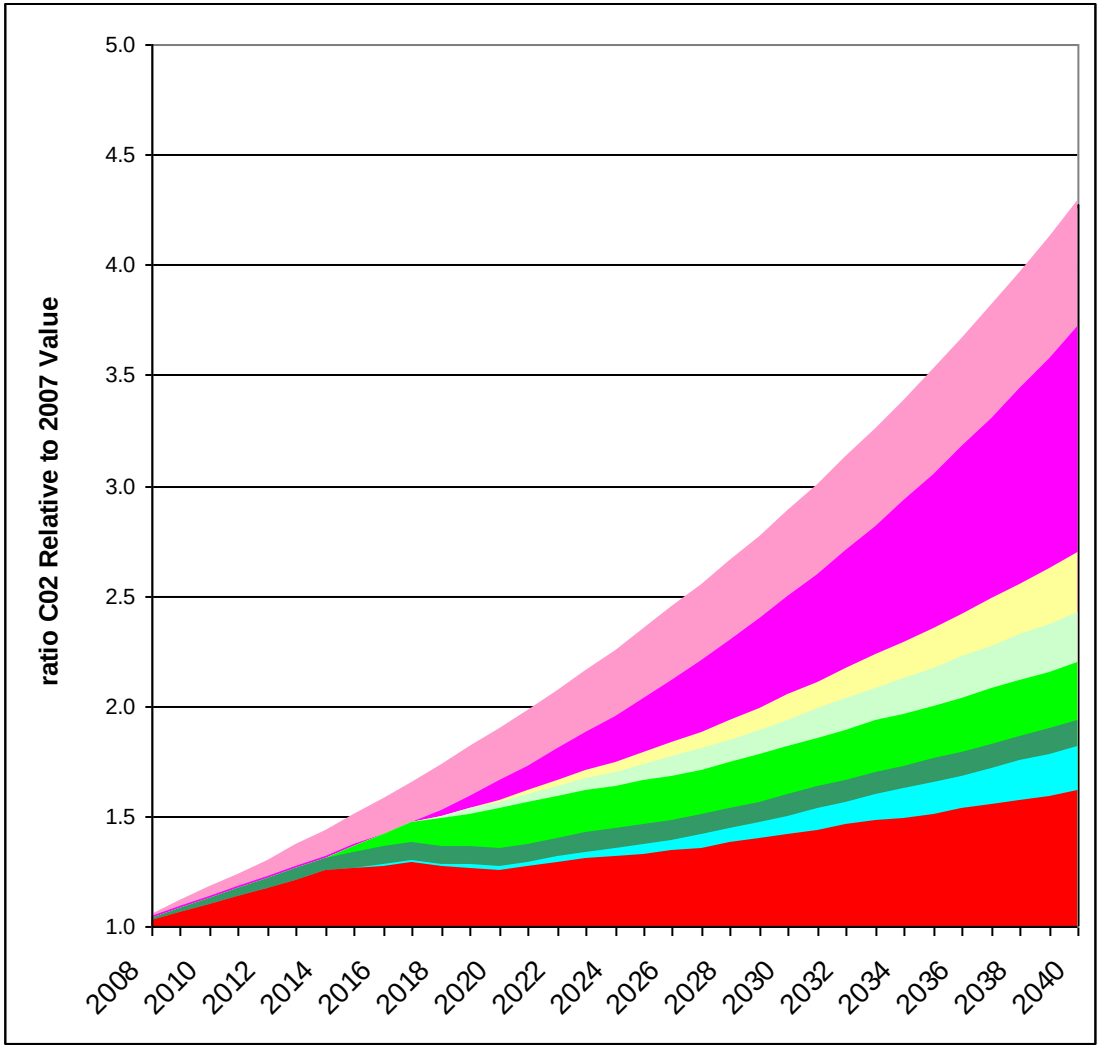


* Fuel burn (CO_2) to sfc relationship has been assumed based on predicted future engine weight and drag reductions.

Rolls-Royce

100 to 200 Seat Sector

The Solution is at the Enterprise Level



Today's fleet

Current products (replacing old aircraft)

Option 30 - 30% Reduction in 2018

Incremental engine - 0.5% pa

Upgauge aircraft size by 12 seats

ATM improvement of 12%

Airline operations improve by 6%

Alternate fuel

50% alternate fuel by 2050

30% less CO_2 per gallon

Datum

Summary

- Open rotor powered aircraft have the potential to offer significant fuel burn advantages relative to advanced or geared turbofan powered aircraft.
- In order to realise this potential may technical challenges need to be overcome, i.e., noise, certification, integration with the airframe, etc.
- Rolls-Royce has recently completed the first part of a comprehensive experimental program to validate a low noise high efficiency open rotor.
- Initial results are in line with expectation and based on this new and innovative technology, Rolls-Royce believes a quiet and efficient open rotor engine is realisable.
- Over the last few year a number of EU framework programmes have been configured to help fund the technology required to develop a successful open rotor engine and airframe.
- In terms of benefits to the aircraft operator and the environmental impact, relative to today's aircraft a future open rotor powered aircraft could save approximately $3 million and 10,000 tonnes of $C0_2$ per year - per aircraft.

Summary

- Further consideration needs to be given to the trade-off between fuel burn (global) and noise (local).
- Rolls-Royce is currently developing the technologies and engine options to address the 150 seater replacement market in a changing world.

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