Climate change, fuel burn targets and the options and limitations facing the designer

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ACARE environmental targets for 2020

- To reduce fuel consumption and CO_2 emissions by 50%
- To reduce perceived external noise by 50%
- To reduce NO_X by 80%

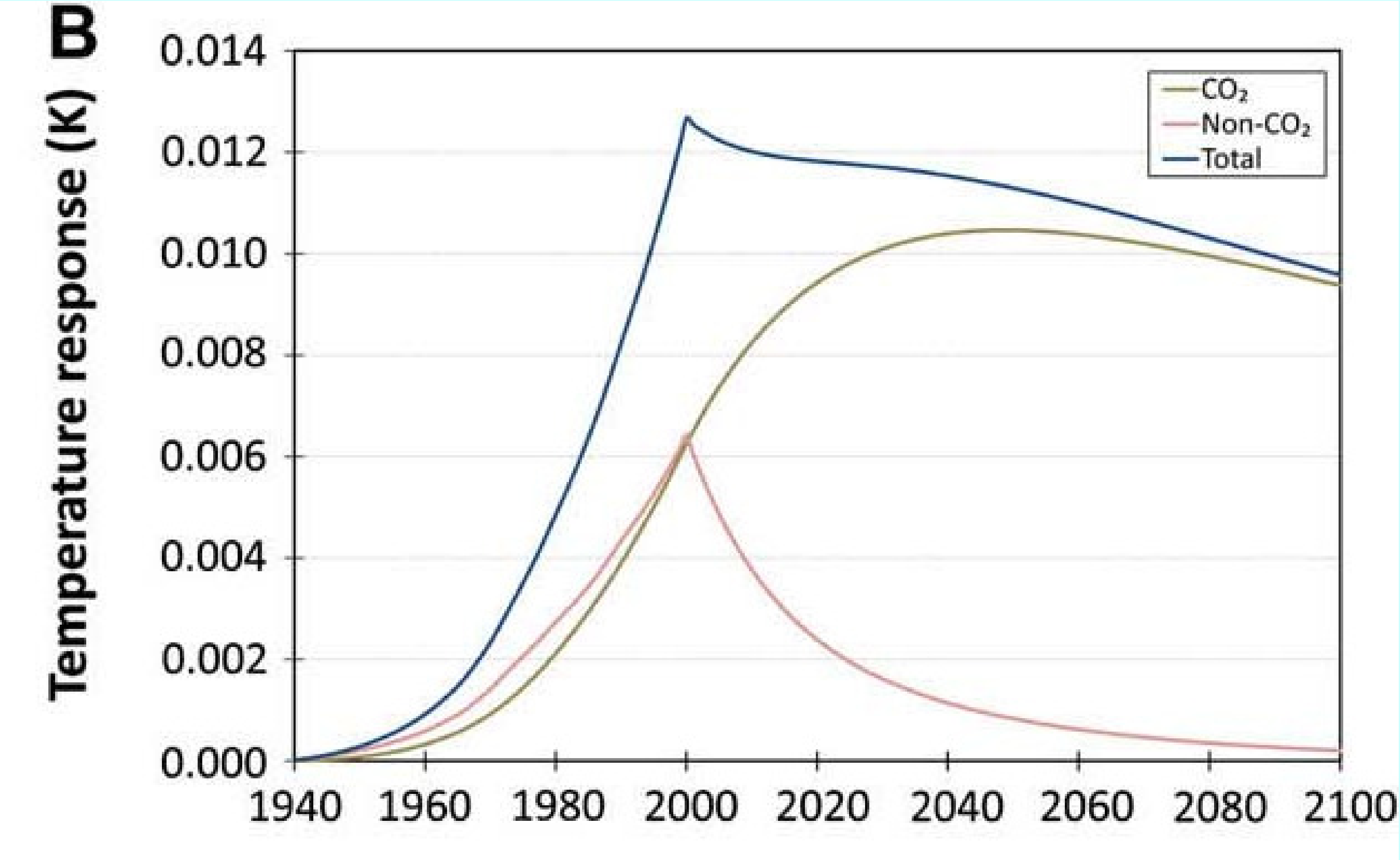
For new aircraft entering service in 2020, using operating procedures current in 2020, relative to new aircraft entering service in 2000 using operating procedures current in 2000

“The objectives are ***not*** achievable ***without important breakthroughs, both in technology and in concepts of operation***” (ACARE emphasis)

Climate priorities – NO_X, contrail/cirrus, CO_2

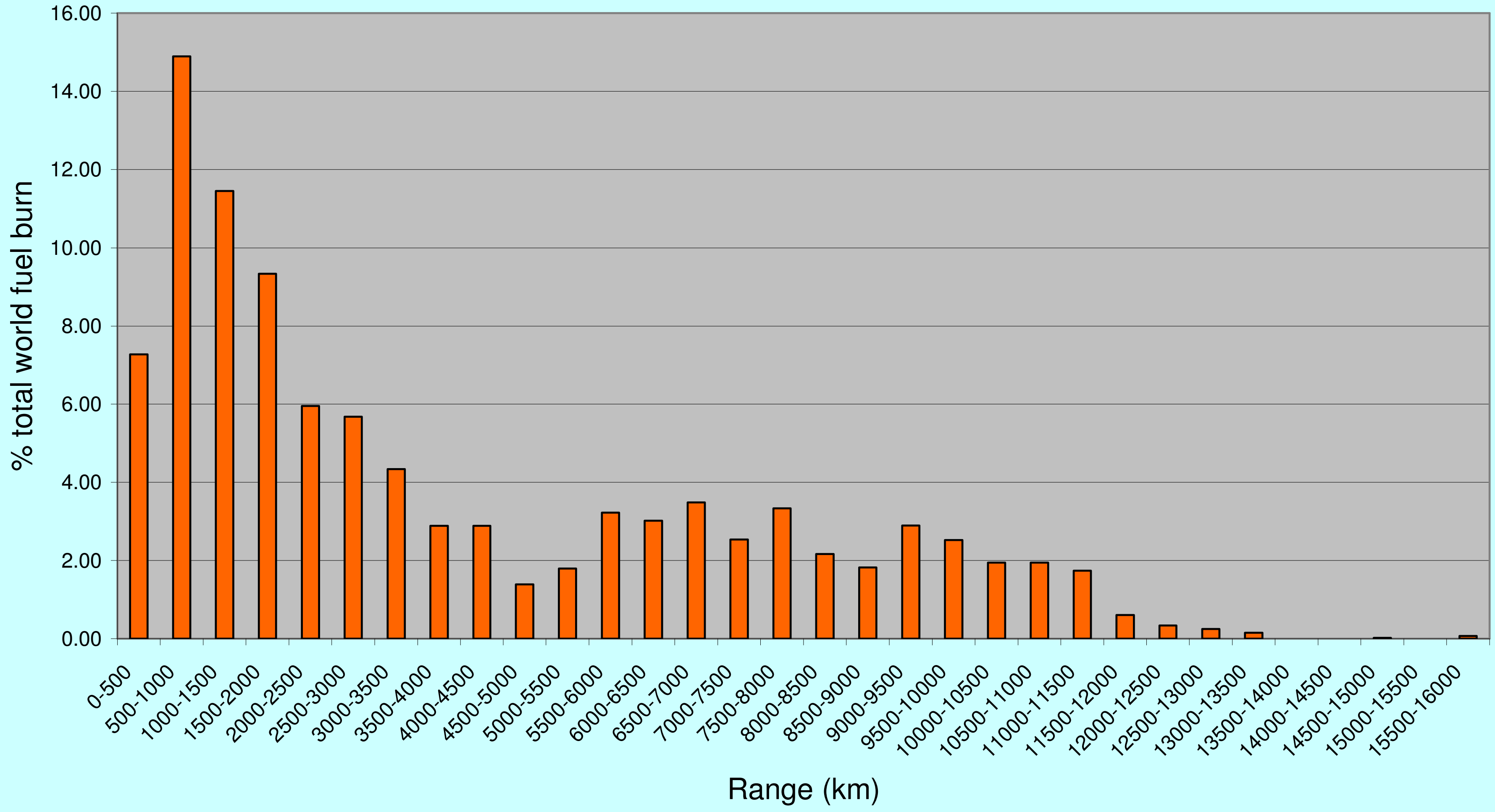
- Impact of NOx at altitude can be reduced substantially by advances in combustor technology
- Impact of contrails and contrail-induced cirrus can be reduced substantially by operational measures to reduce flight through ice-saturated regions
- Because of its longevity and the difficulty of reducing its emission, CO_2 is the main environmental challenge to aviation

Impact on global temperature of total air traffic up to 2000



From Lee et al, j.atmosenv.2009.06.005

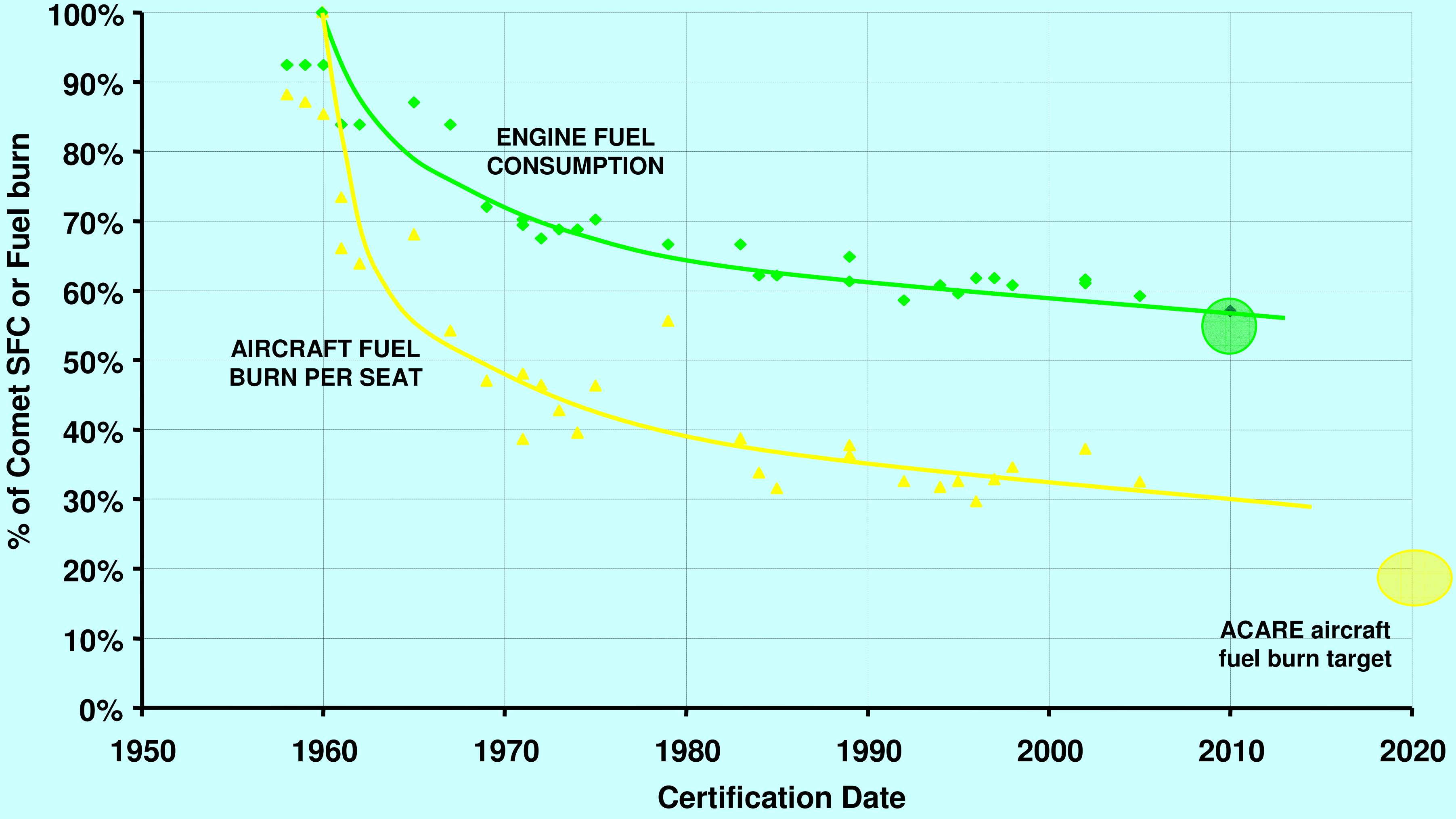
Distribution by stage length of world fuel burn in 2000 (Aero 2K)



Options for reducing CO_2 emissions

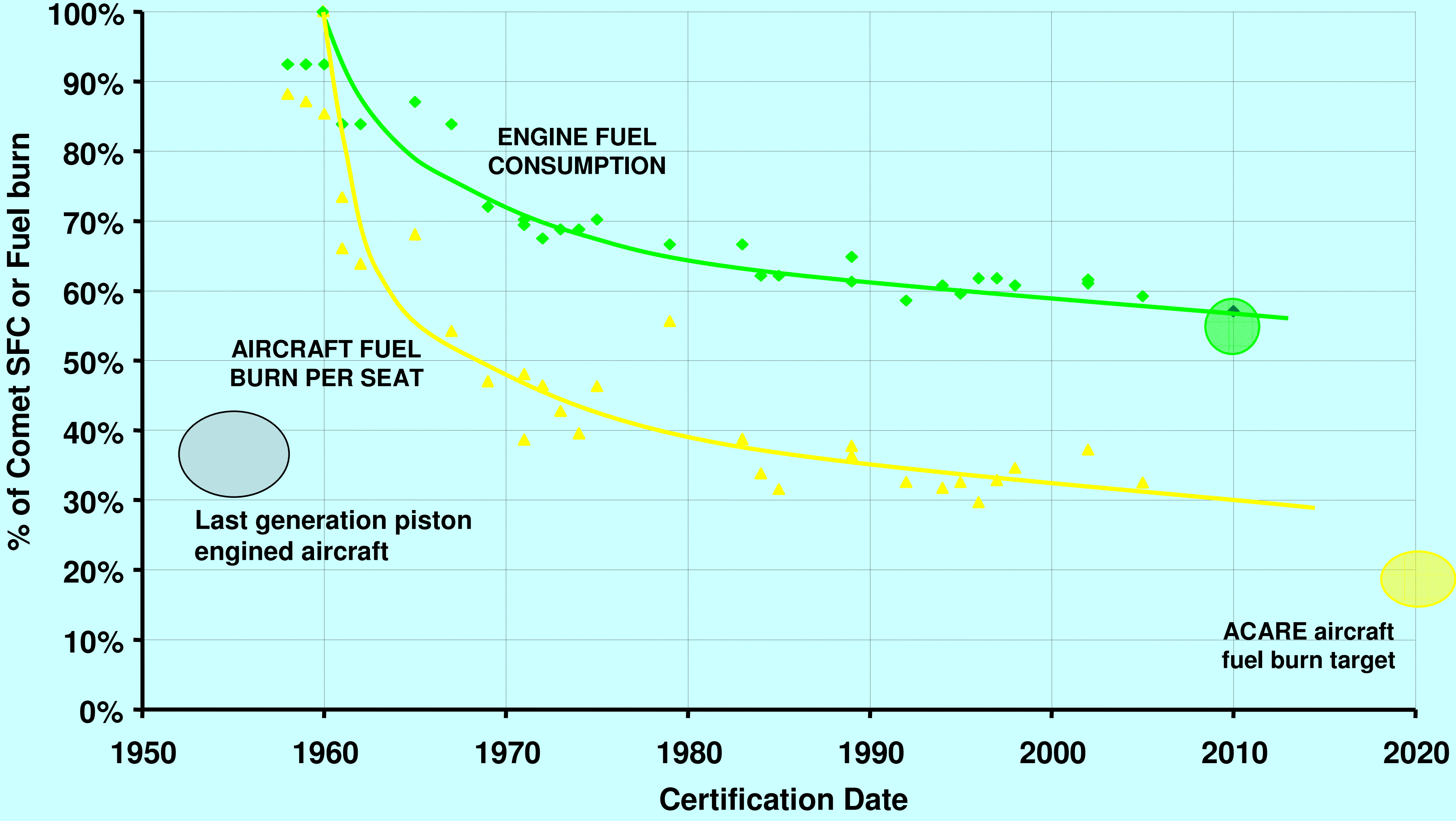
- Operational measures – SESAR and NextGen
- Reduce ratio of empty weight to payload
- Increase propulsive efficiency
- Increase L/D in cruise
- Biokerosine

The ACARE fuel target is a real challenge



AeIGT

The ACARE fuel target is a real challenge



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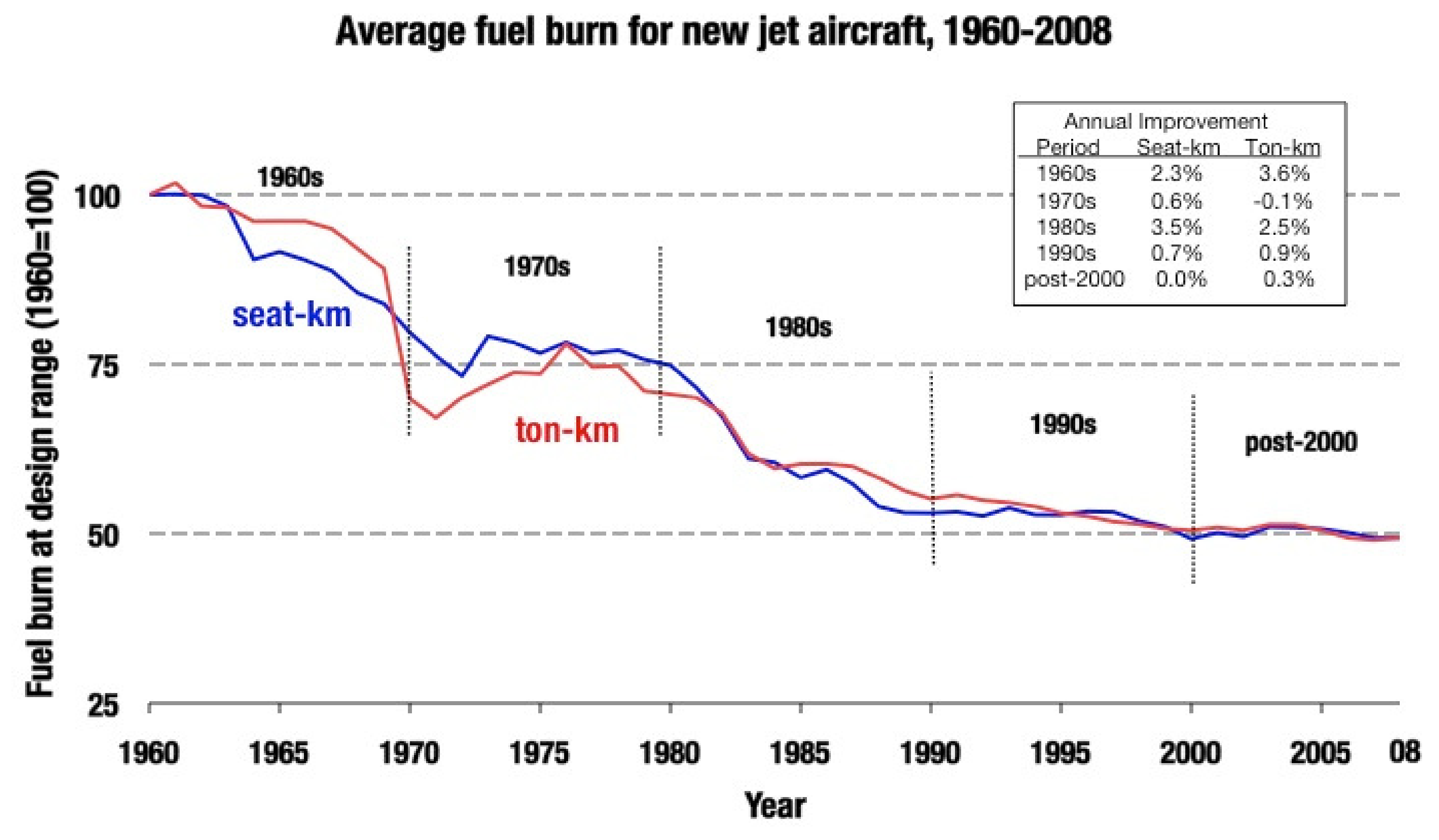


Average fuel burn for new jet aircraft, 1960-2008

Annual Improvement		
Period	Seat-km	Ton-km
1960s	2.3%	3.6%
1970s	0.6%	-0.1%
1980s	3.5%	2.5%
1990s	0.7%	0.9%
post-2000	0.0%	0.3%

From Rutherford, D. and Zeinali, M., Efficiency Trends for New Commercial Jet Aircraft 1960 to 2008, The International Council on Clean Transportation, November 2009.

Fuel burn limits – there is no escape from:

- The Breguet Range Equation
- The Second Law of Thermodynamics
- The stoichiometric limit
- Lanchester-Prandtl formula for induced drag
- Laminar boundary layer stability equations

Basis of the Breguet range equation

Rate of work production by engine

= fuel mass flow rate x calorific value x prop efficiency

= m_f x H x η

= engine thrust x flight velocity

= aircraft drag x flight velocity (in steady flight)

= aircraft weight/(L/D) x flight velocity

whence

Fuel flow rate/flight velocity = aircraft weight/($H\eta L/D$) kg/km

The Breguet range equation

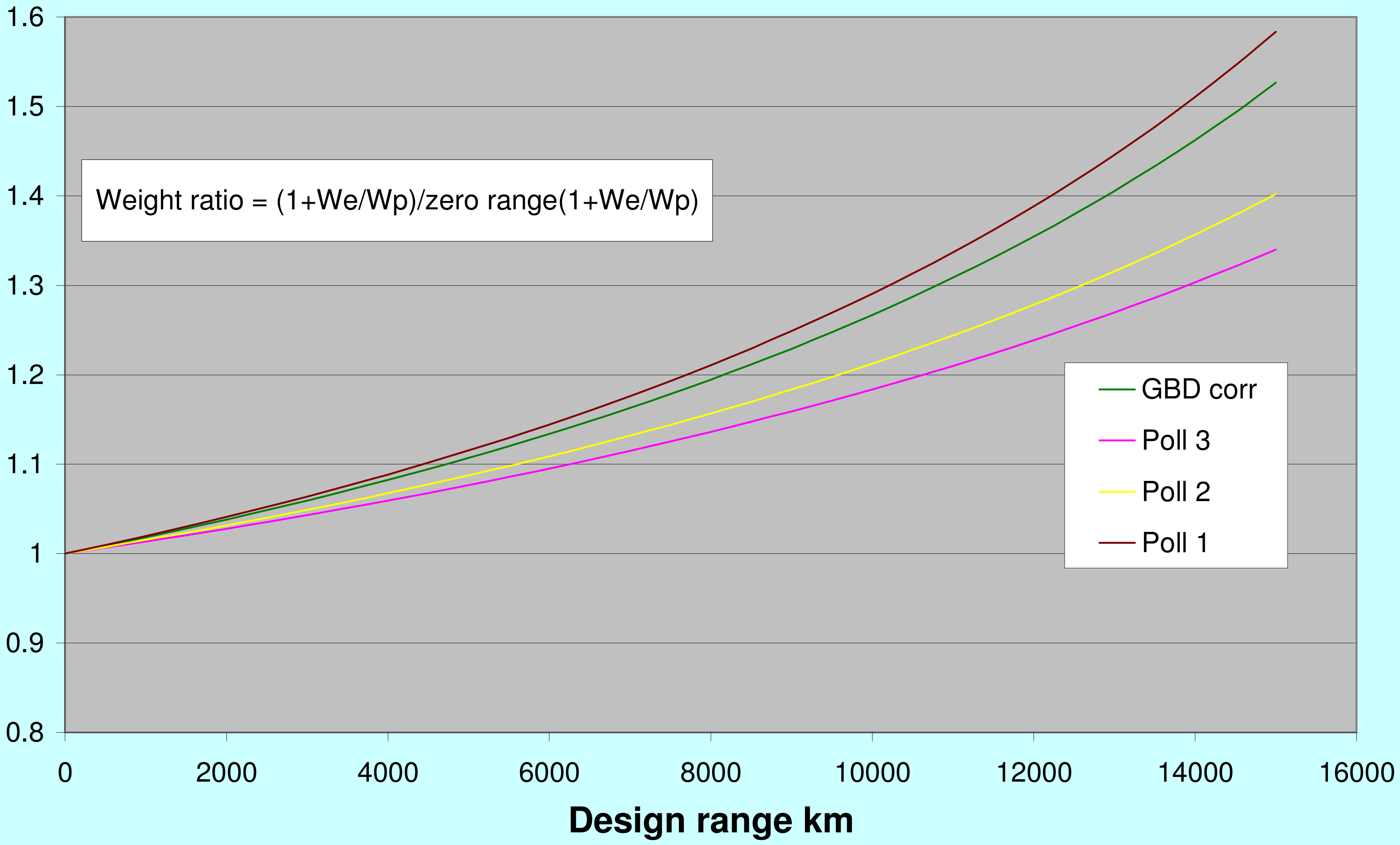
Fuel burn per tonne-kilometre

$$\frac{W_F}{RW_P} = \frac{1}{X}\left(1 + \frac{W_E}{W_P}\right)\left(\frac{1.022\exp\left(\frac{R}{X}\right) - 1}{\left(\frac{R}{X}\right)}\right)$$

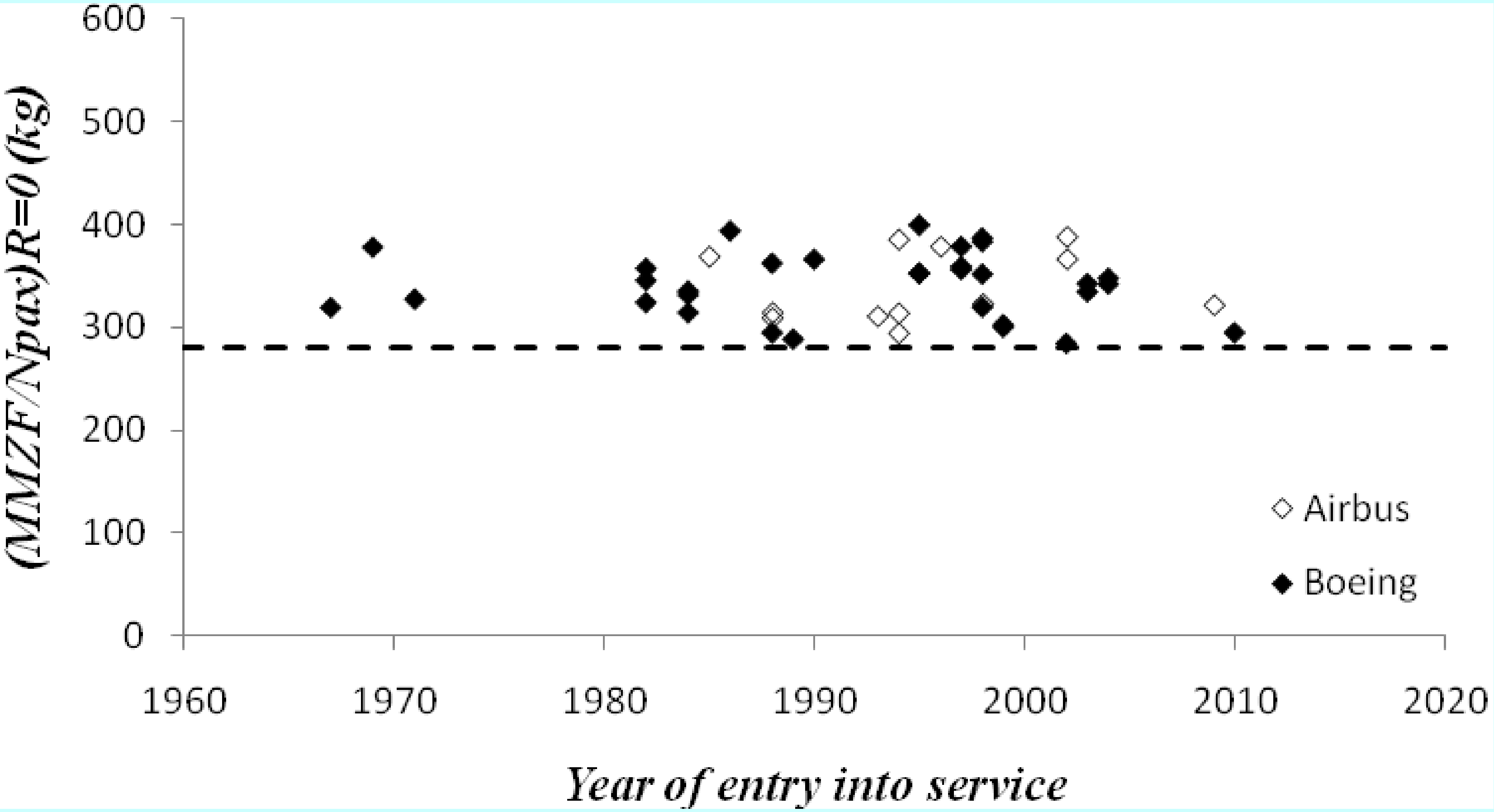
where

X = HηL/D
H = calorific value of fuel
η = overall propulsion efficiency
L/D = lift/drag ratio

Effect of design range on weight ratio



Maximum zero-fuel mass per passenger at zero design range – no significant reduction in best designs over 40 years



From Poll unpublished

The Breguet range equation

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Components of overall propulsion efficiency

Overall propulsion efficiency

$\eta = \eta_{therm}\eta_{trans}\eta_{prop}$

where η_{therm} = thermal efficiency

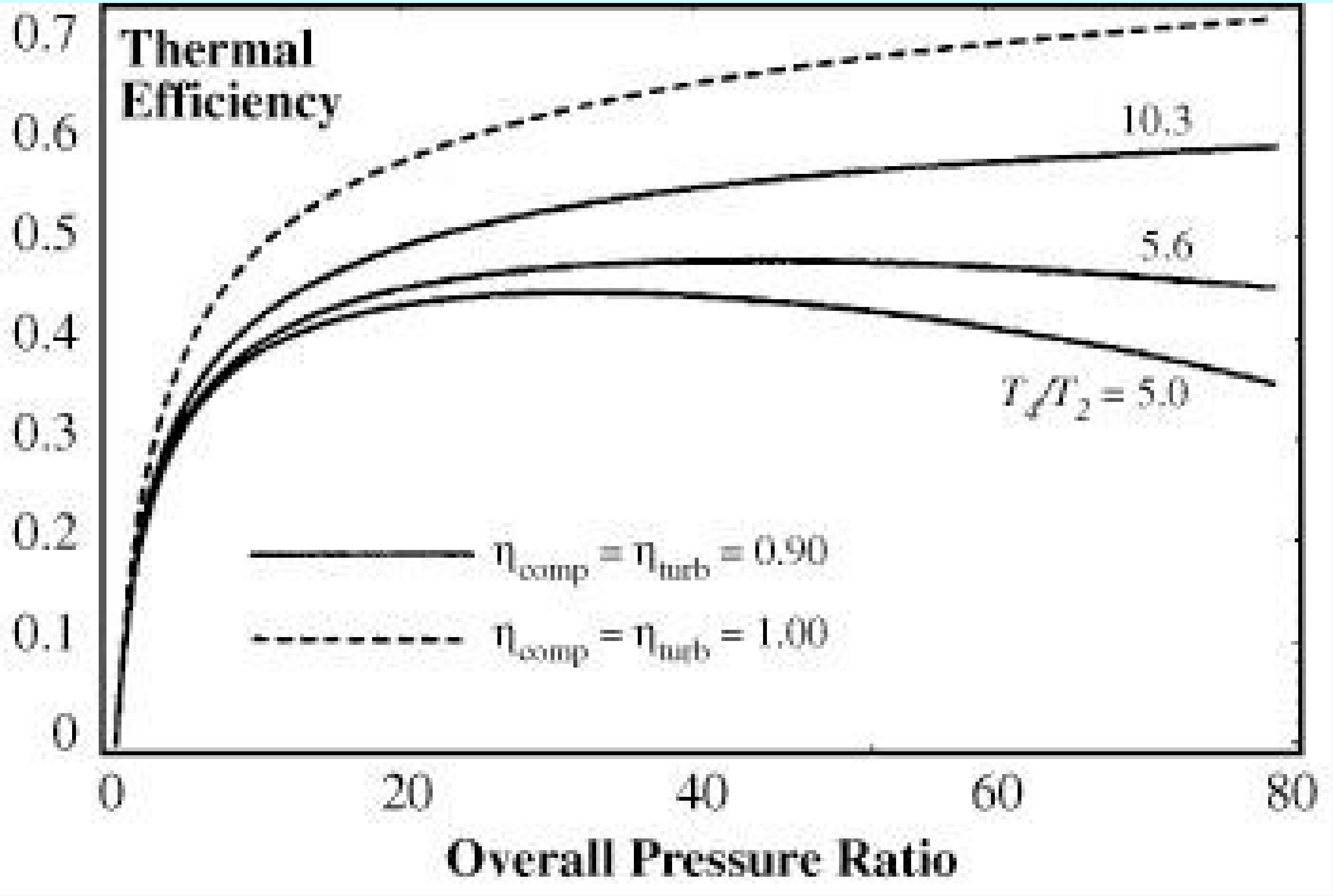
η_{trans} = transfer efficiency

η_{prop} = propulsive efficiency of jet (Froude efficiency)

$$= \frac{1}{1 + g\frac{Th_S}{2V}}$$

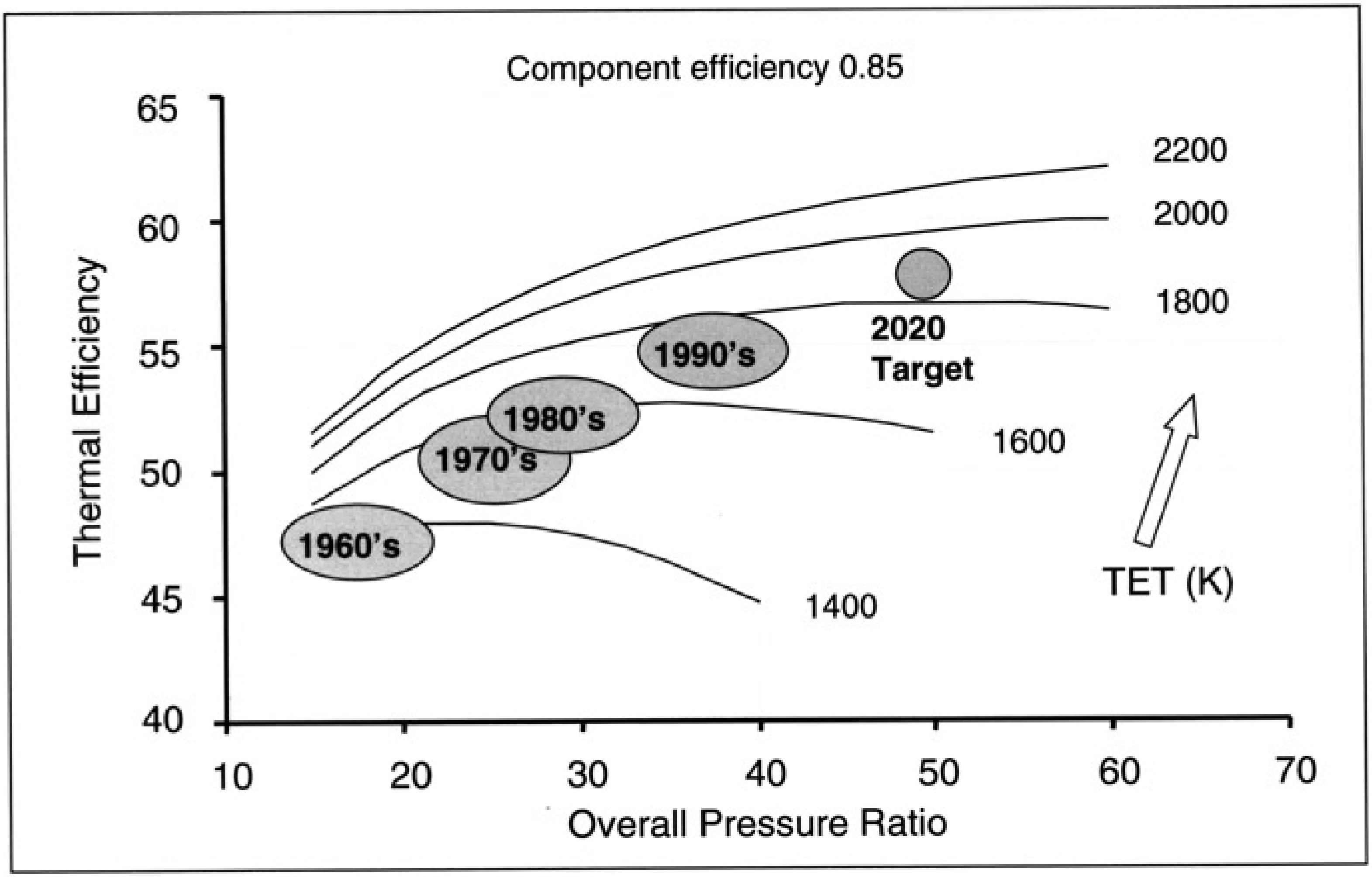
where V is flight velocity and Th_S is specific thrust

Thermal efficiency and the stoichiometric limit



Source IPCC 1999

Thermal efficiency and the 2nd Law of Thermodynamics



Source Rolls-Royce

Factors determining propulsive (Froude) efficiency

Overall propulsion efficiency

$$\eta = \eta_{therm}\eta_{trans}\eta_{prop}$$

where η_{therm} = thermal efficiency

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η_{prop} = propulsive efficiency of jet (Froude efficiency)

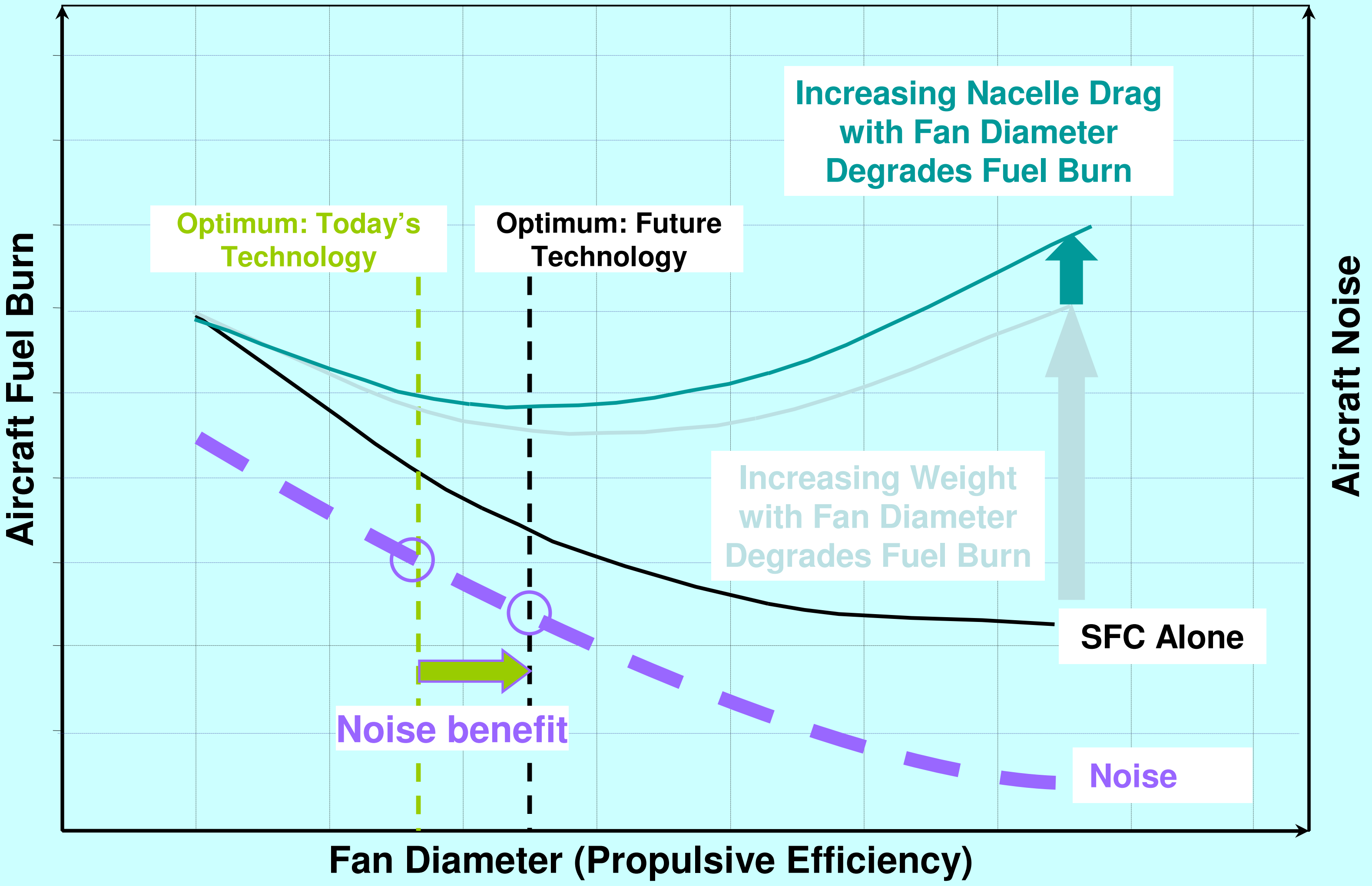
$$= \frac{1}{1 + g\frac{Th_S}{2V}}$$

where V is flight velocity and Th_S is specific thrust

Next generation ducted fan

Potential reduction in aircraft fuel burn for advanced ducted fan

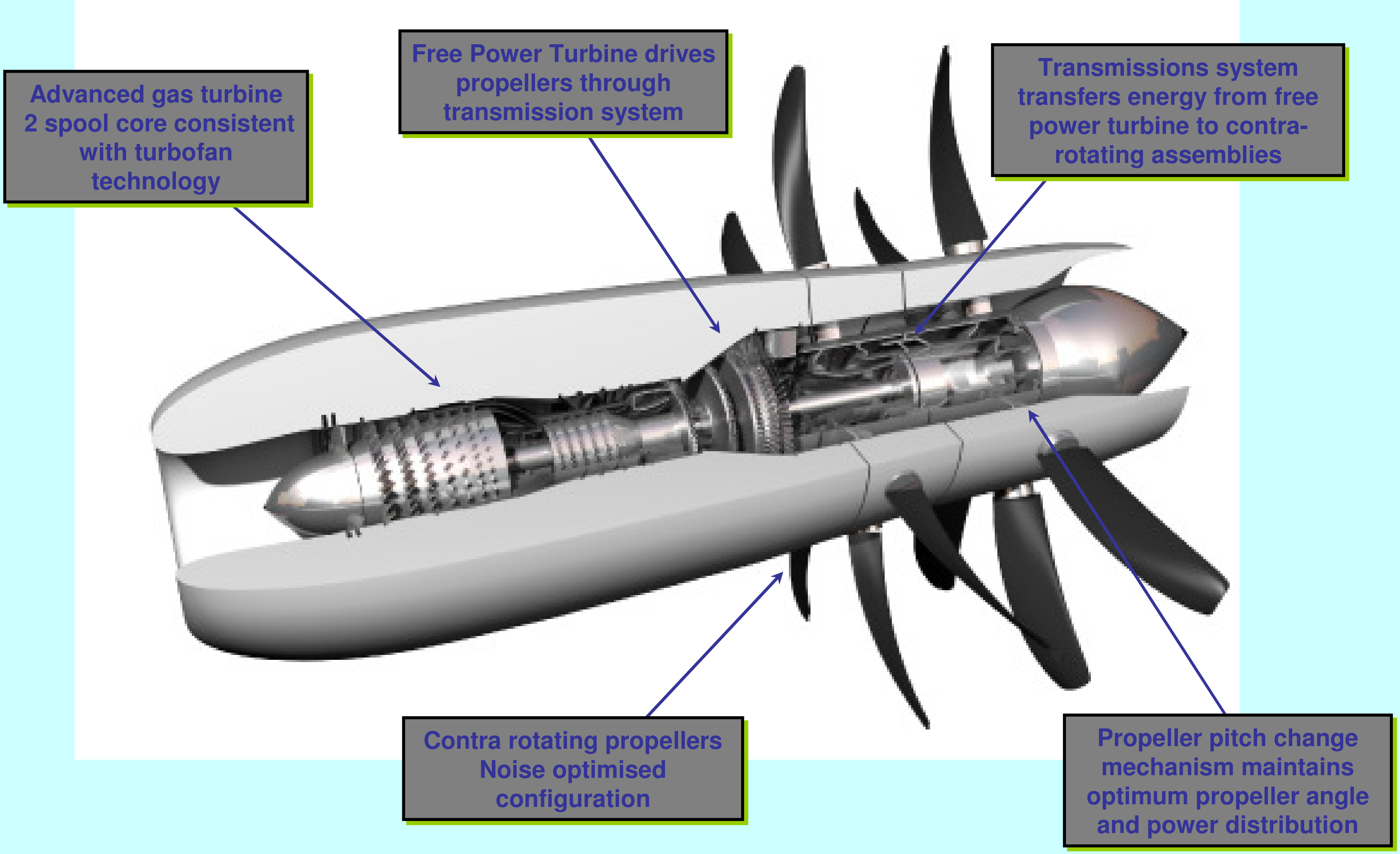
Optimised Fan Diameter – Advanced Turbofan & Geared Turbofan



Source Rolls-Royce

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

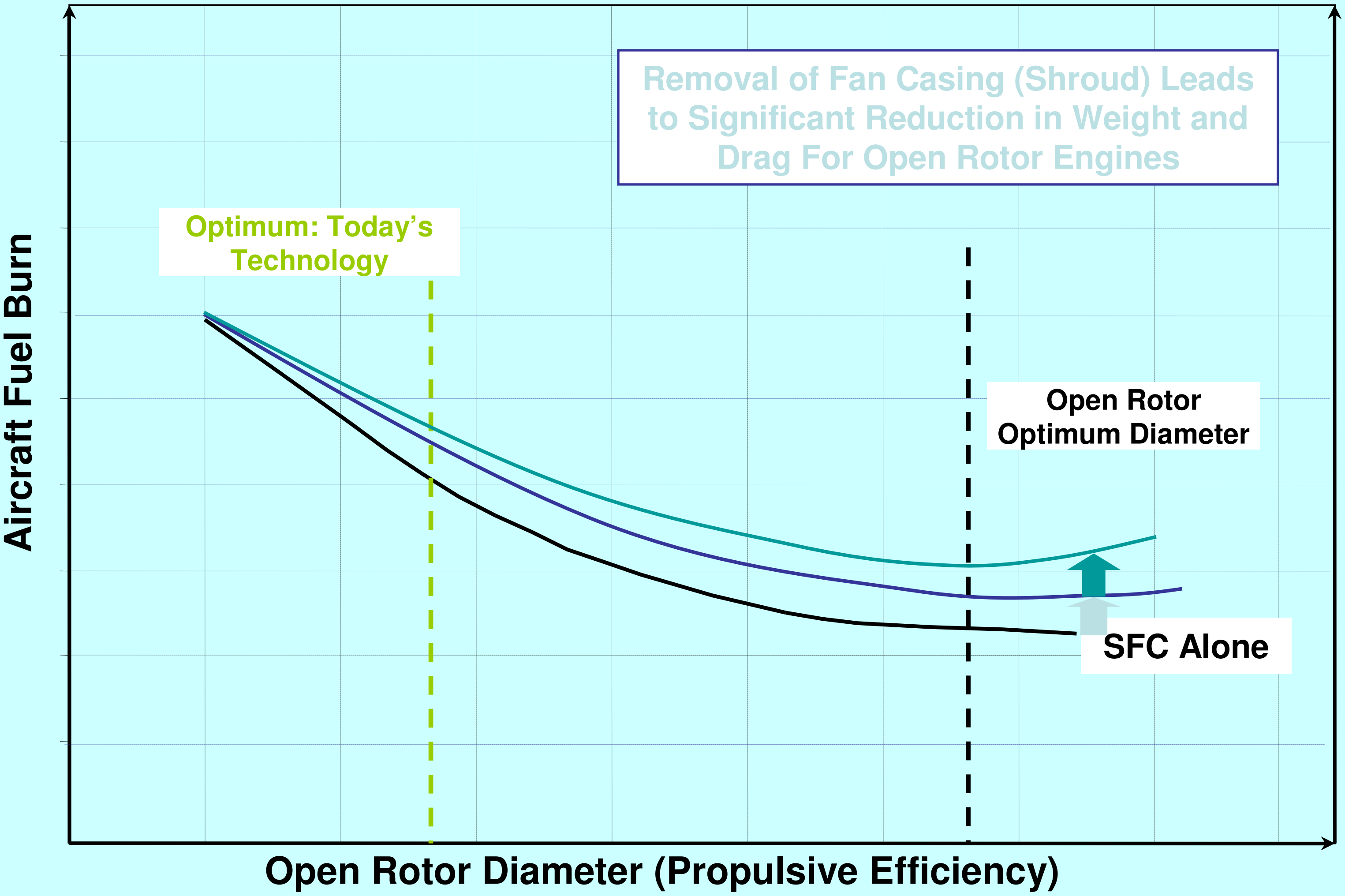
Transmissions system transfers energy from free power turbine to contra-rotating assemblies

Contra rotating propellers Noise optimised configuration

Propeller pitch change mechanism maintains optimum propeller angle and power distribution

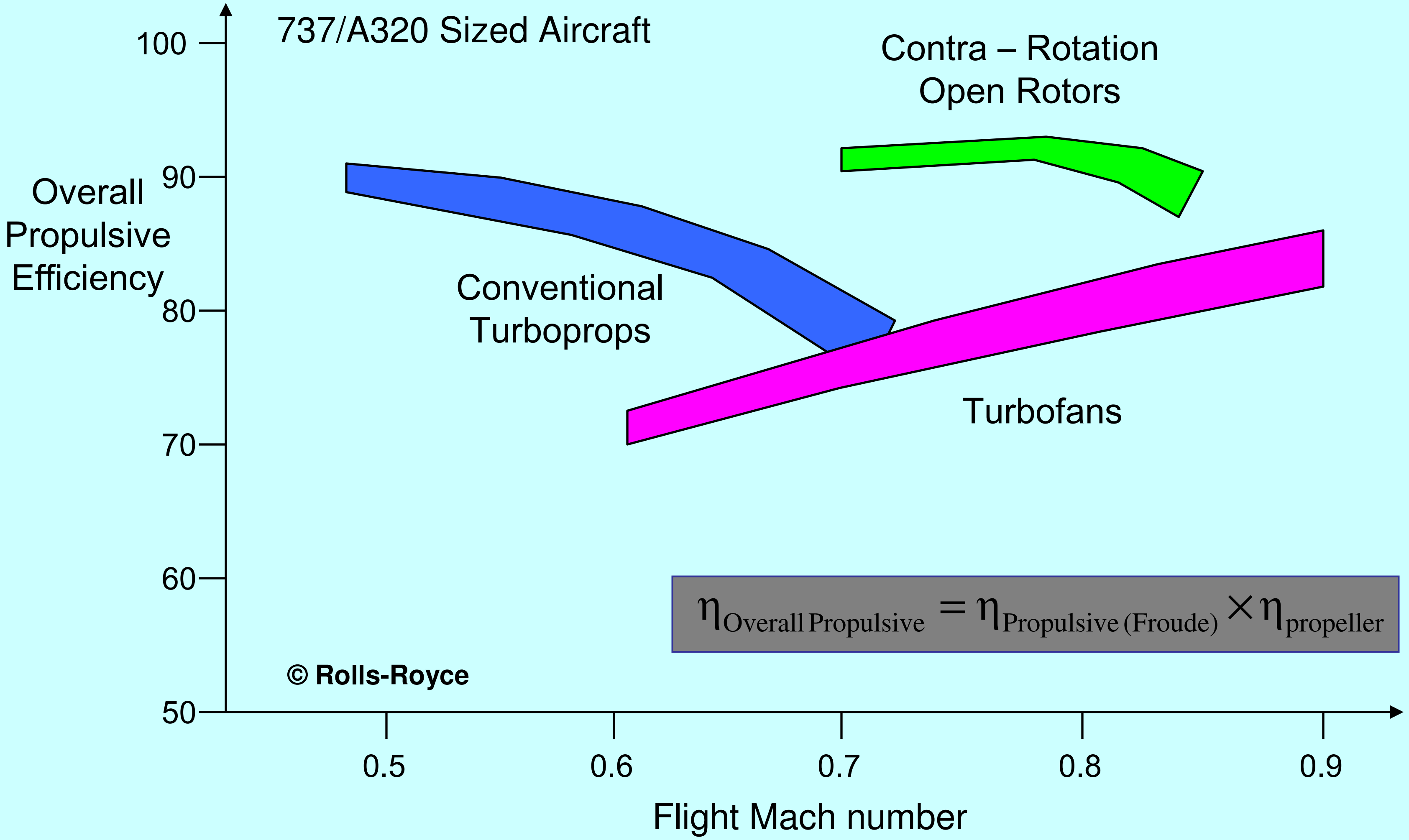
Potential reduction in aircraft fuel burn with an open rotor

Optimised Diameter – Open Rotor



Source Rolls-Royce

Propulsive efficiency of alternative forms of propulsor



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

Source Rolls-Royce

The Breguet range equation

Fuel burn per tonne-kilometre

$$\frac{W_F}{RW_P} = \frac{1}{X}\left(1 + \frac{W_E}{W_P}\right)\left(\frac{1.022\exp\left(\frac{R}{X}\right) - 1}{\left(\frac{R}{X}\right)}\right)$$

where
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η = overall propulsion efficiency
L/D = lift/drag ratio

Lanchester-Prandtl and the components of drag

$$\text{Drag} = qS_{DO} + \frac{\kappa}{\pi q}\left(\frac{W}{b}\right)^2$$

L/D is a maximum when the two components of drag are equal, giving

$$\left(\frac{L}{D}\right)_{MAX} = b\sqrt{\frac{\pi}{4\kappa S_{DO}}}$$

$$\text{when } q = W\sqrt{\frac{\kappa}{\pi b^2 S_{DO}}}$$

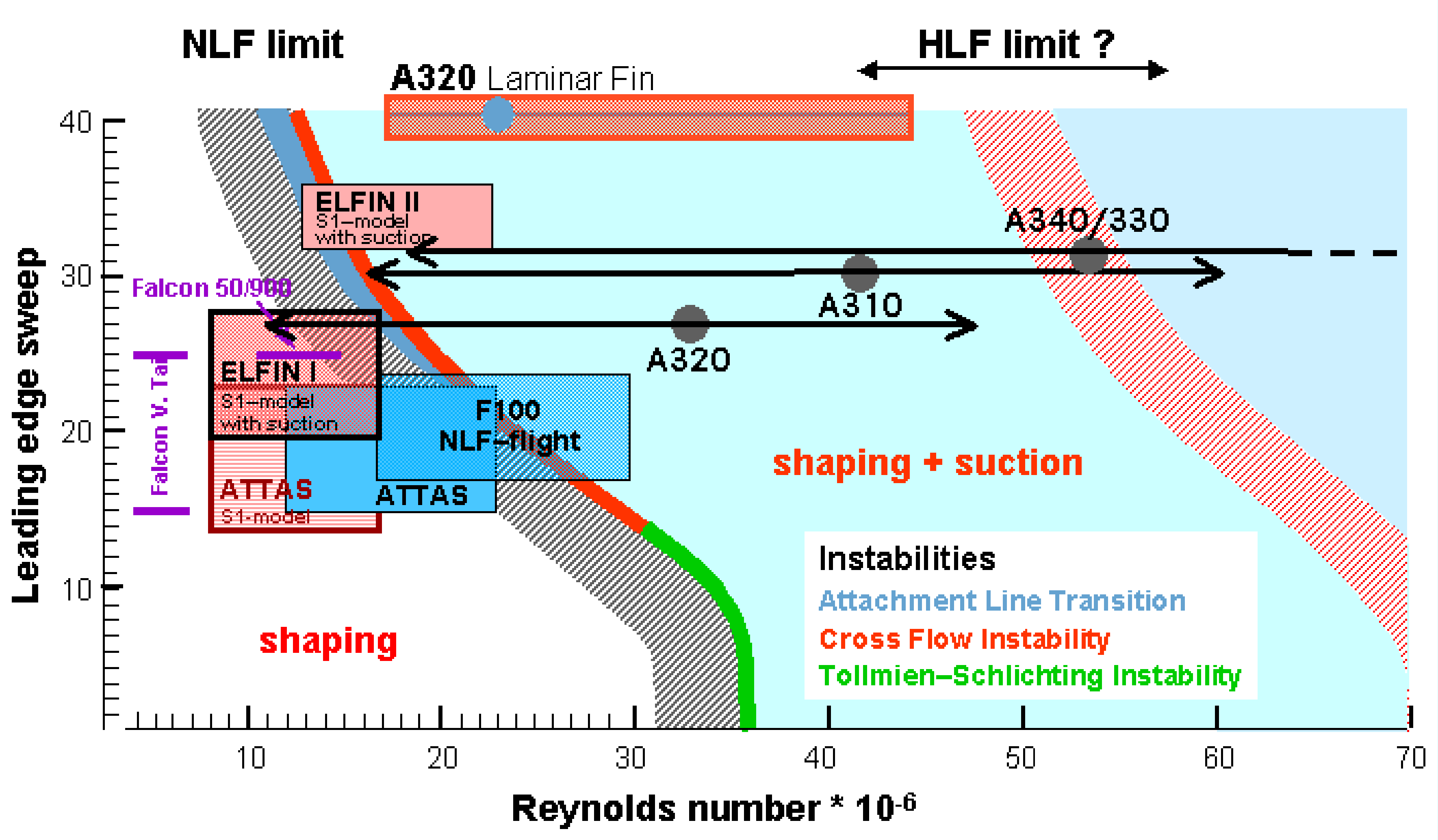
Options for increasing L/D

- Increase span
  - Increasing span increases wing weight. Dominant configuration close to optimum. Composite wing and reduced cruise M (reduced sweep/increased wing thickness) could enable re-optimisation at greater span

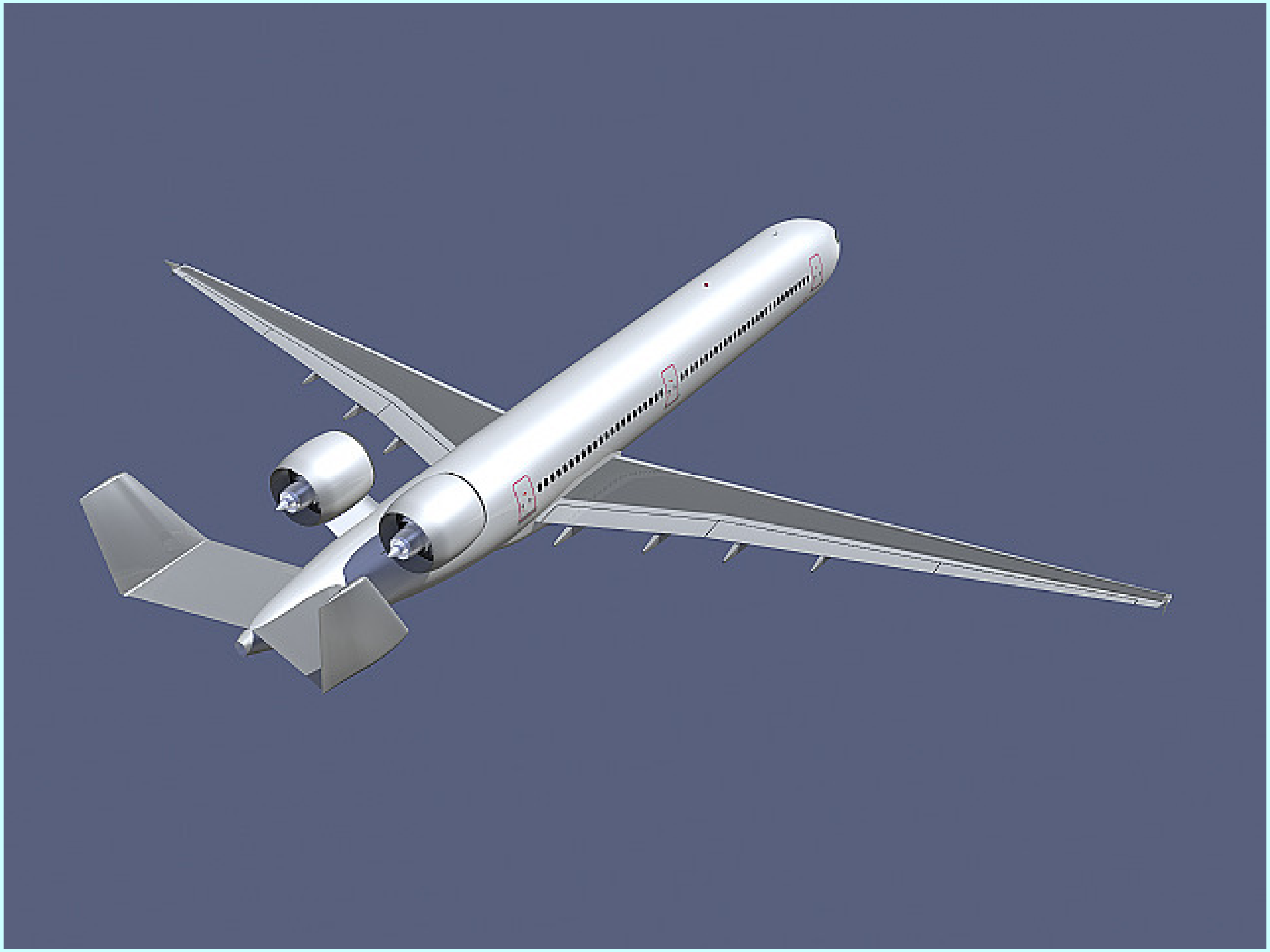
- Reduce vortex drag factor κ
  - Dominant configuration highly developed. Very limited scope without change of configuration

- Reduce zero lift drag area S_{DO}
  - Minimal potential for tube/wing layout with turbulent boundary layers
  - Blended wing body
  - Laminar flow control
    - Natural
    - Hybrid
    - Total

Laminar boundary layer stability and the limits of laminar flow control technologies (Schrauf and Kühn)



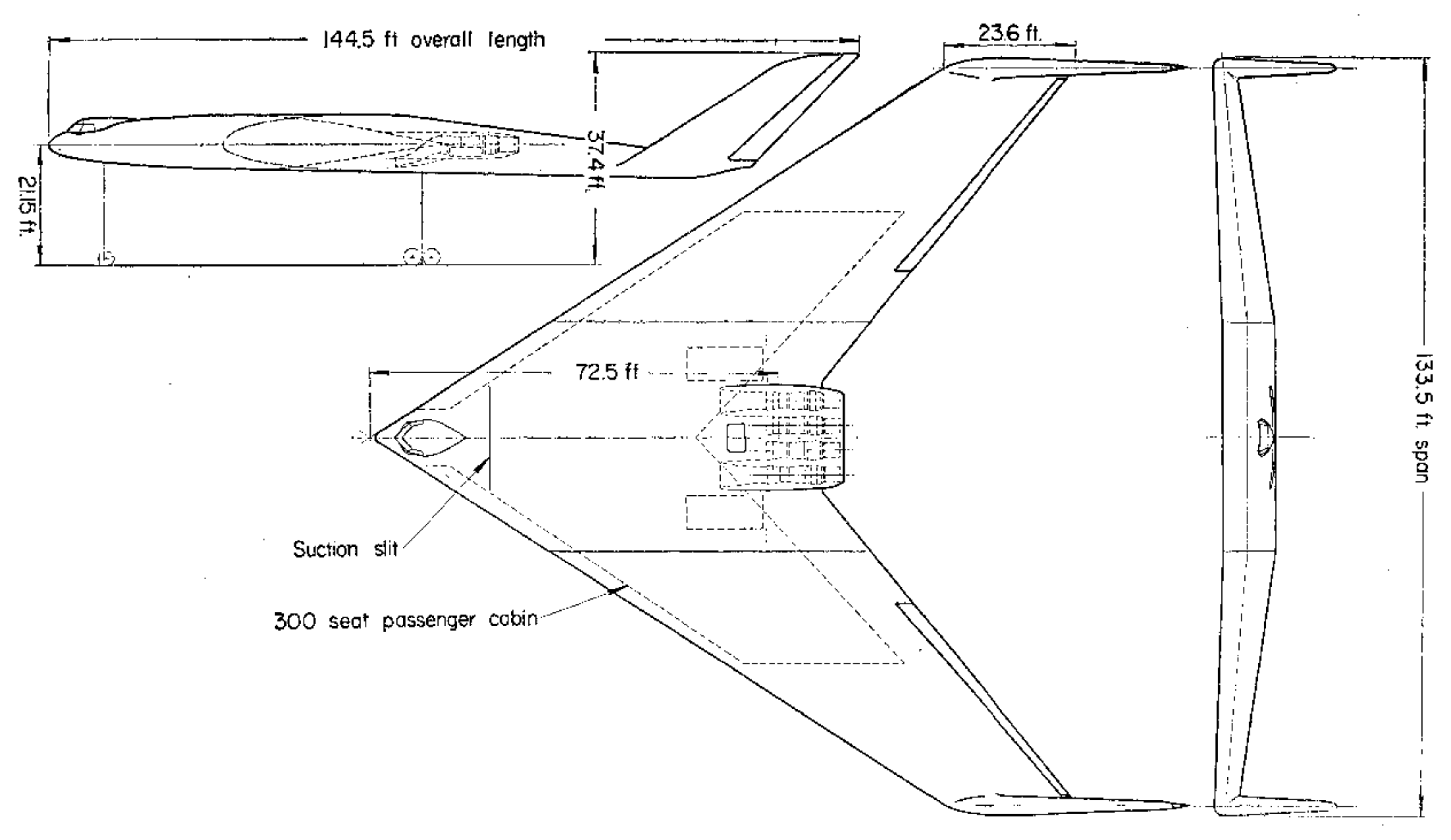
The Proactive Green aircraft of the EC NACRE project



Source:
Airbus

X-48B
Blended wing-body at
NASA Dryden

Handley-Page projected 300-seat laminar flow airliner (1961)



Conclusions

- Reducing fuel burn is emerging as the overriding environmental priority
- The laws of physics seriously limit what can be achieved
- Reducing aircraft weight is an important but apparently elusive goal – designing for shorter maximum range appears the most powerful tool available to the designer
- There are limits to further gains in propulsion efficiency – only the open rotor offers a substantial increase
- For the tube-wing layout only laminar flow control offers a significant improvement in L/D
- ACARE was right to assert that its goals are not achievable without important breakthroughs, both in technology and in concepts of operation
- We do not know when the airlines and travelling public will be ready to accept the changes implicit in giving real priority to reducing fuel burn (slower, possibly noisier aircraft, limited to medium range non-stop)

When will biokerosine come riding over the horizon to our rescue?