Climate change – the impact of aviation and the scope for reducing it

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Air Travel – Greener by Design

Mitigating the Environmental Impact of Aviation:
Opportunities and Priorities

Report of the Greener by Design Science and Technology Sub-Group

Greener
by
DESIGN

GBD S&T Sub Group reports

July 2001 and 2005

Republished

The Aeronautical Journal

February 2002

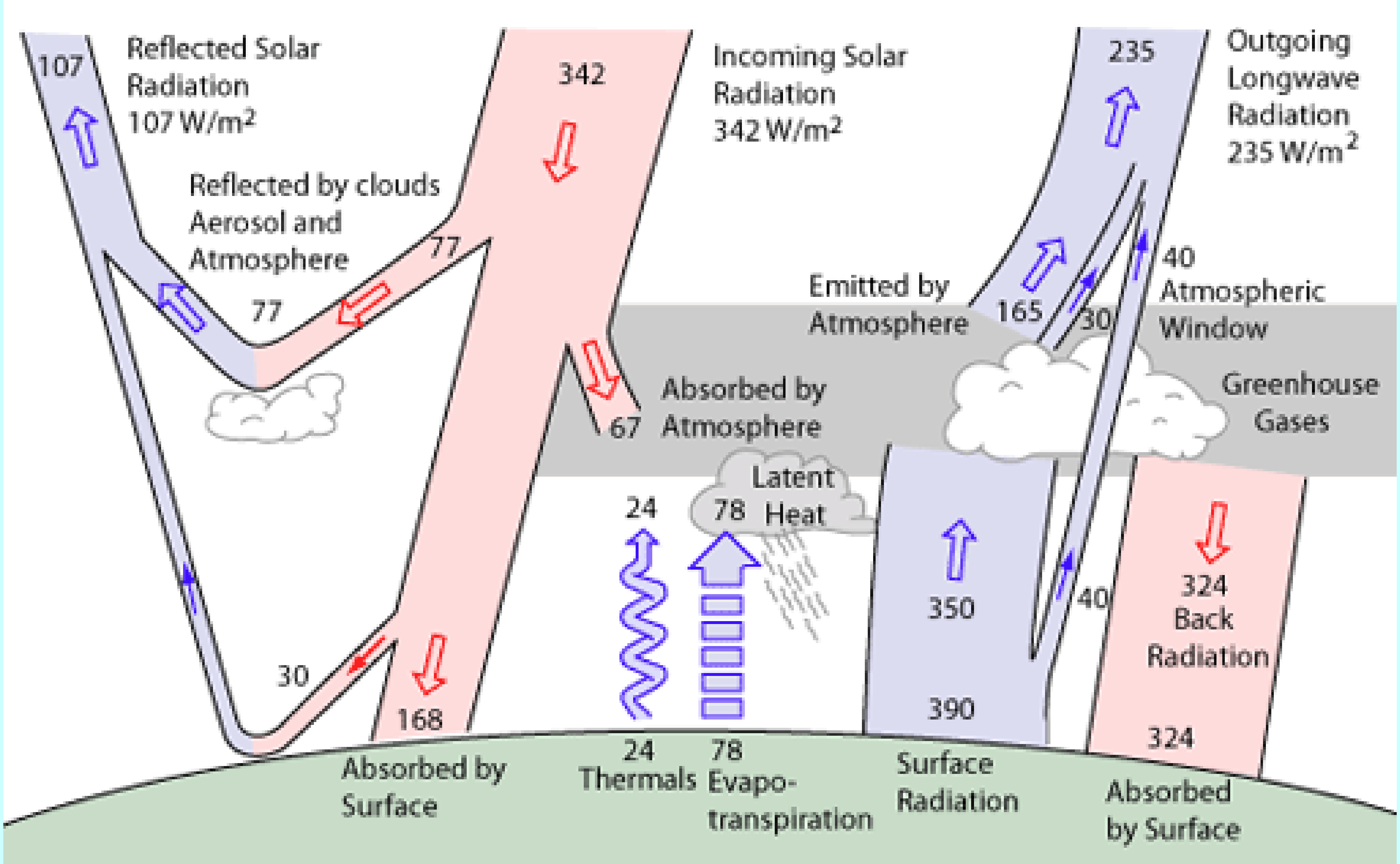
September 2005

All GBD reports available at
www.greenerbydesign.org.uk

Earth’s radiation balance – the greenhouse effect

- The earth’s mean temperature is 15°C
- Without the greenhouse effect it would be - 18°C
- Water (vapour and droplets) provides about 75% of the greenhouse effect
- The other greenhouse gases make up less than 0.04% of the atmosphere at present

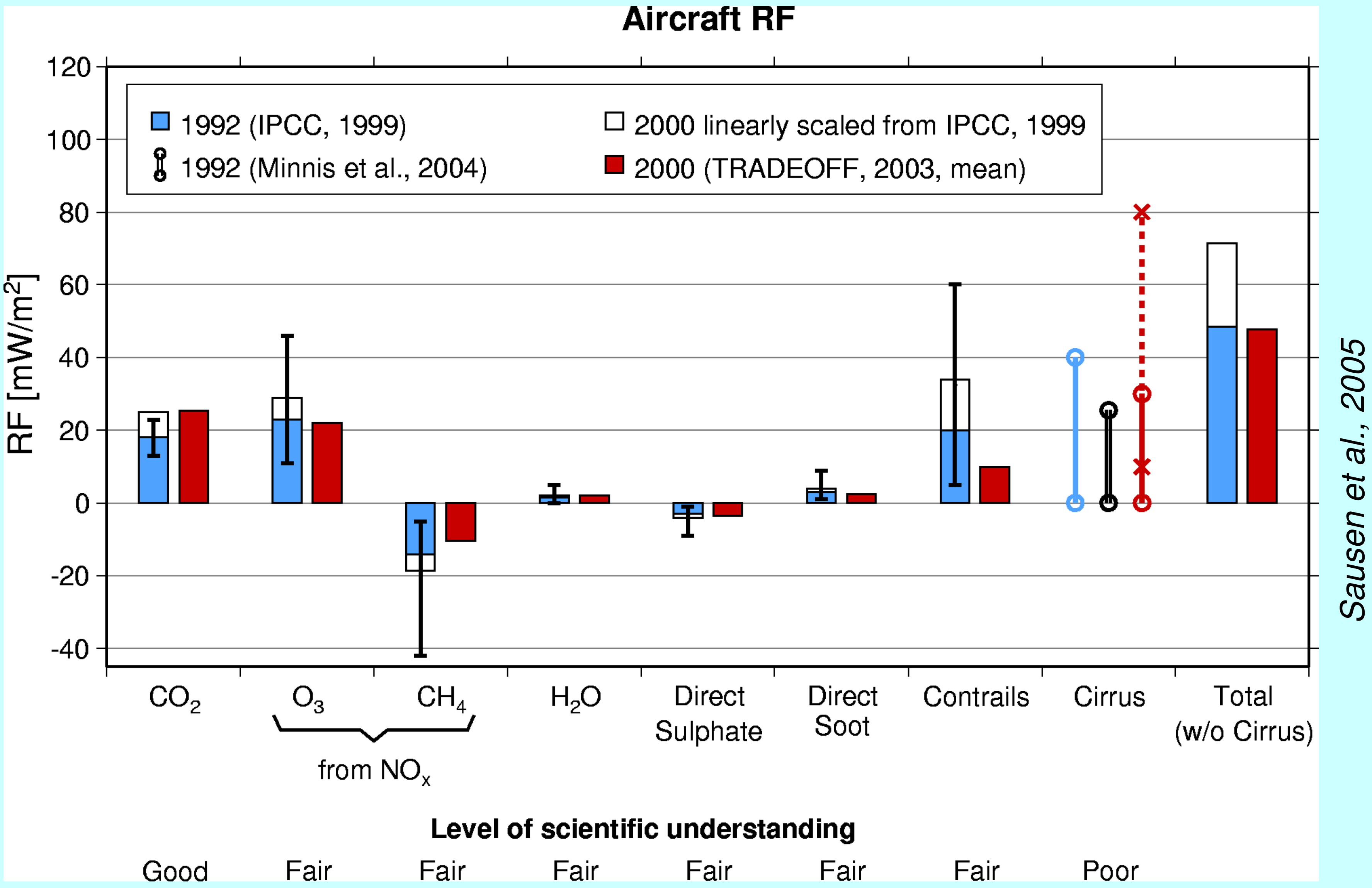
Earth’s energy balance – the greenhouse effect



Anthropogenic greenhouse gas lifetimes and RF

Gas	Concentration (ppm)		Lifetime (years)	Increased RF (W/m^2)
	Pre-1750	Current		
Carbon dioxide (CO_2)	280	380	50-200	1.66
Methane (CH_4)	0.7	1.8	12	0.5
Tropospheric ozone (O_3)	0.025	0.034	months	0.35
Nitrous oxide (N_2O)	0.27	0.32	114	0.16
Halocarbons	0	0.001	5 – 10,000	0.34
Precursors and other main contributors from aviation				
NO_X (NO and NO_2)			weeks	
Contrails and cirrus cloud			hours	

Updated Aviation Radiative Forcing for 2000



Sausen et al., 2005

Impact of aviation on climate

Main contributors	Estimated RF (mW/m^2)
CO_2	25.3 (TRADEOFF 2003)
NO_X (net effect $O_3 - CH_4$)	11.5 (TRADEOFF 2003)
Contrails and cirrus cloud	30 (10 – 80) (IPCC 2007)

Persistent contrails and contrail cirrus

Reducing contrail and contrail cirrus formation

- Reduce traffic through cold, humid air by diverting it under, over or around supersaturated regions
- This will increase fuel burn and costs (and CO_2 and NO_X emissions), disrupt airline schedules and increase the load on air traffic management
- In the long run, this is a price that may have to be paid – in the case of contrail reduction, there is no alternative palliative
- The environmental optimum will not be the complete elimination of contrails but a balance in which the total climate impact of all contributors is minimised
- We cannot frame an operational strategy until the atmospheric science, cost penalties and ATM requirements are better understood

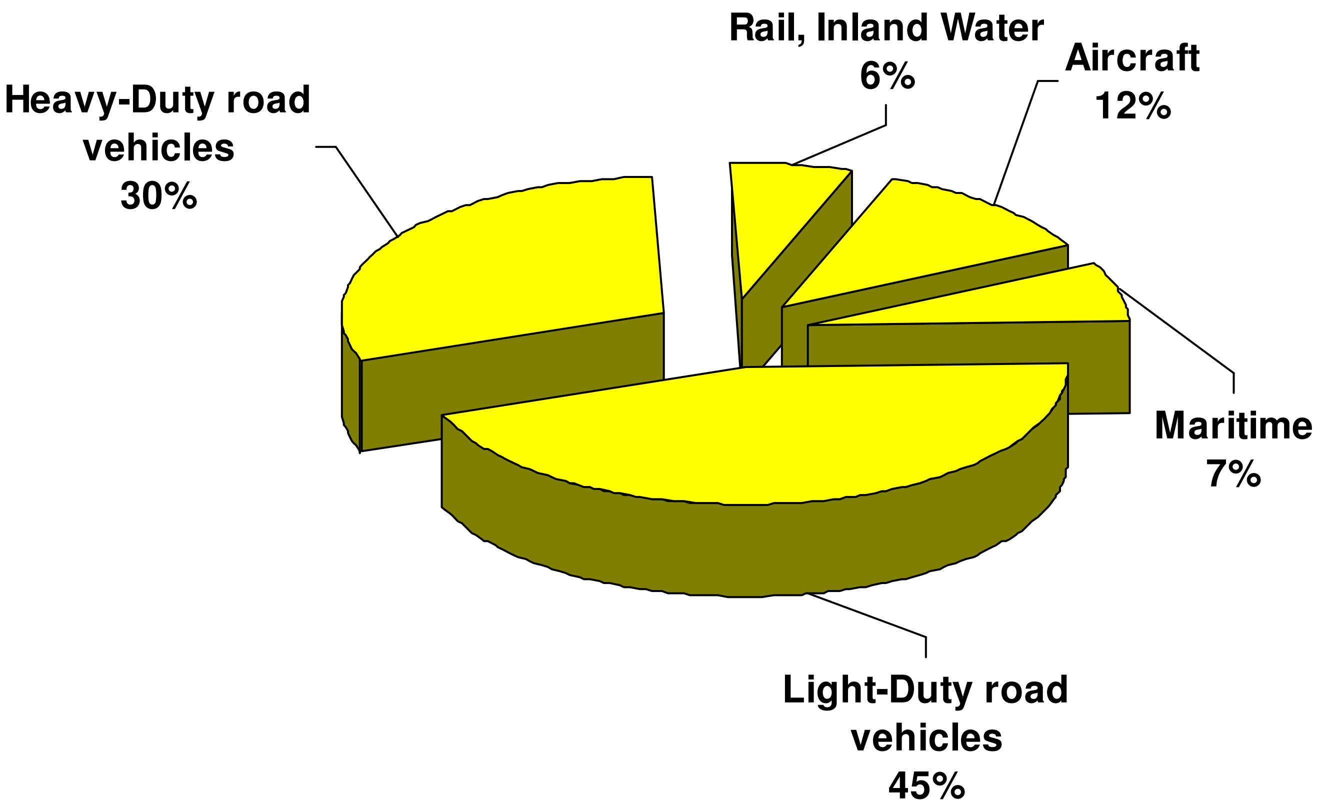
NO_X at altitude

Reducing the climate impact of NO_x

- reduce fuel burn (most measures to reduce fuel burn reduce NO_X proportionately)
- introduce low NO_X technology to reduce $EINO_x$
  - lean burn combustor
  - inter-cooled engine cycle
  - cooled cooling air
- reduce engine overall pressure ratio (future engine design optimisation) – small fuel burn penalty
- reduce cruise altitude (as an operational measure or as part of future aircraft design optimisation) – fuel burn penalty

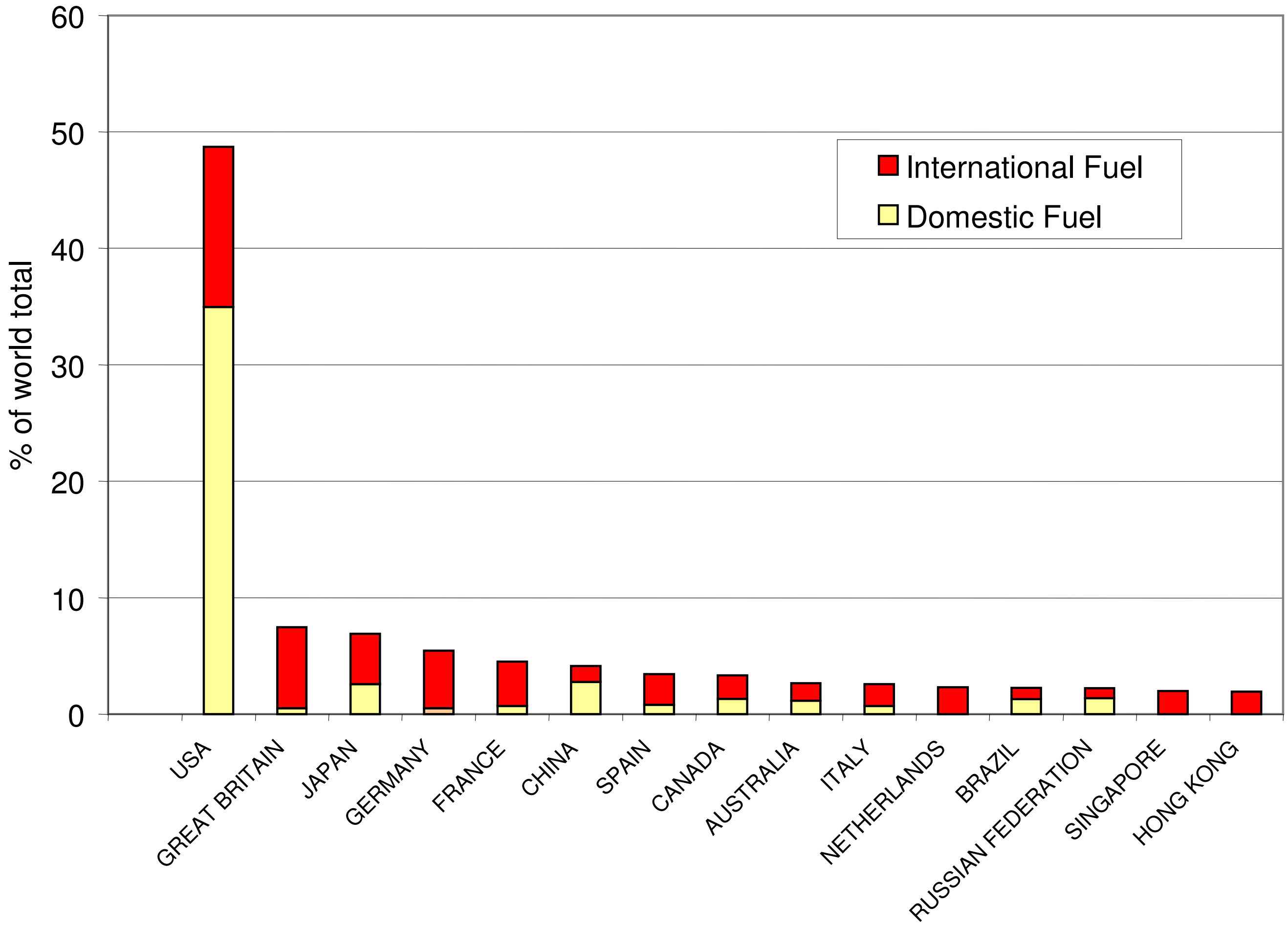
Fuel burn

CO_2 emissions from transport (IPCC 1999)



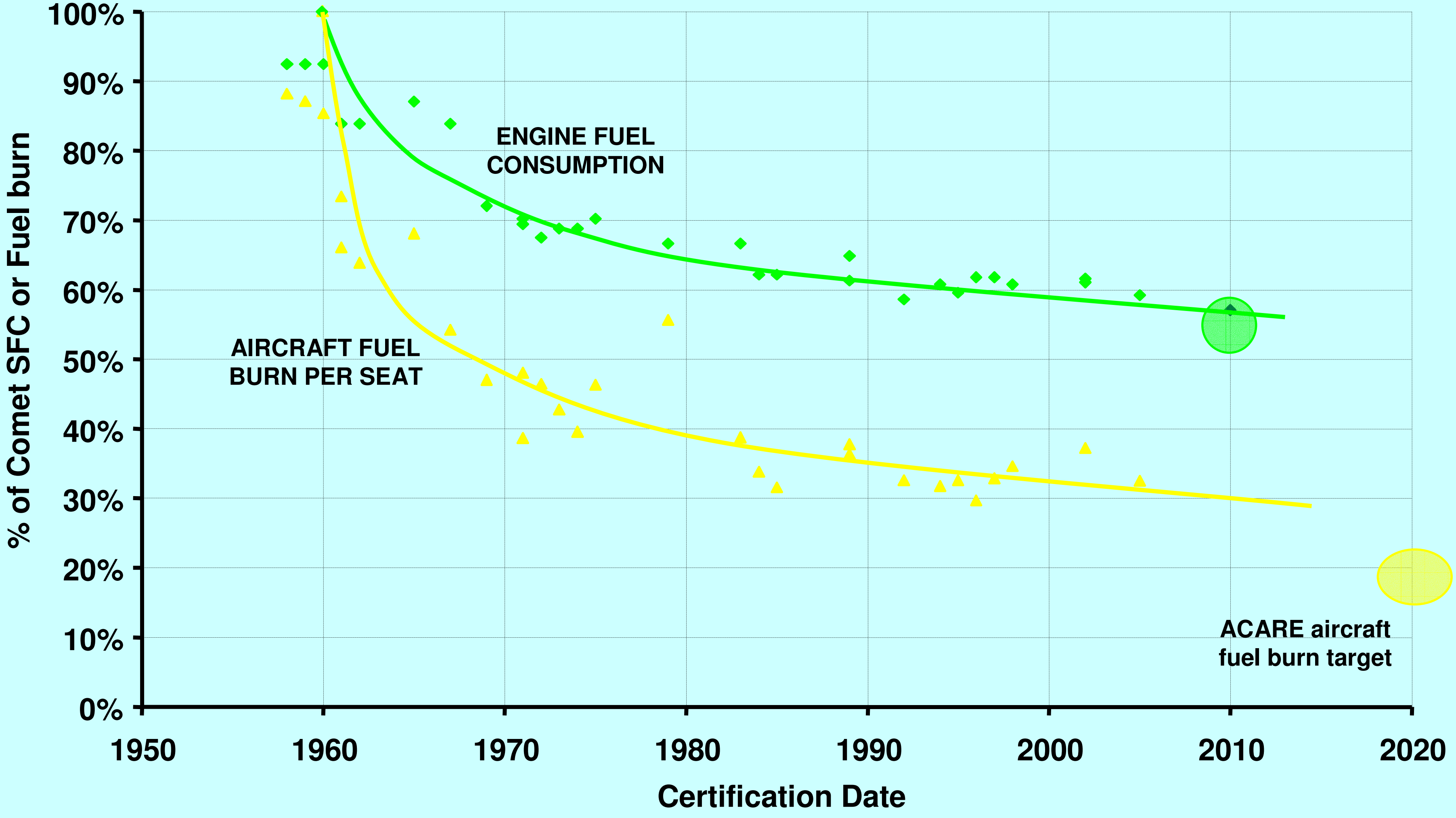
Source:IPCC

World aviation fuel burn in 2000
by country of departure (Aero 2K)



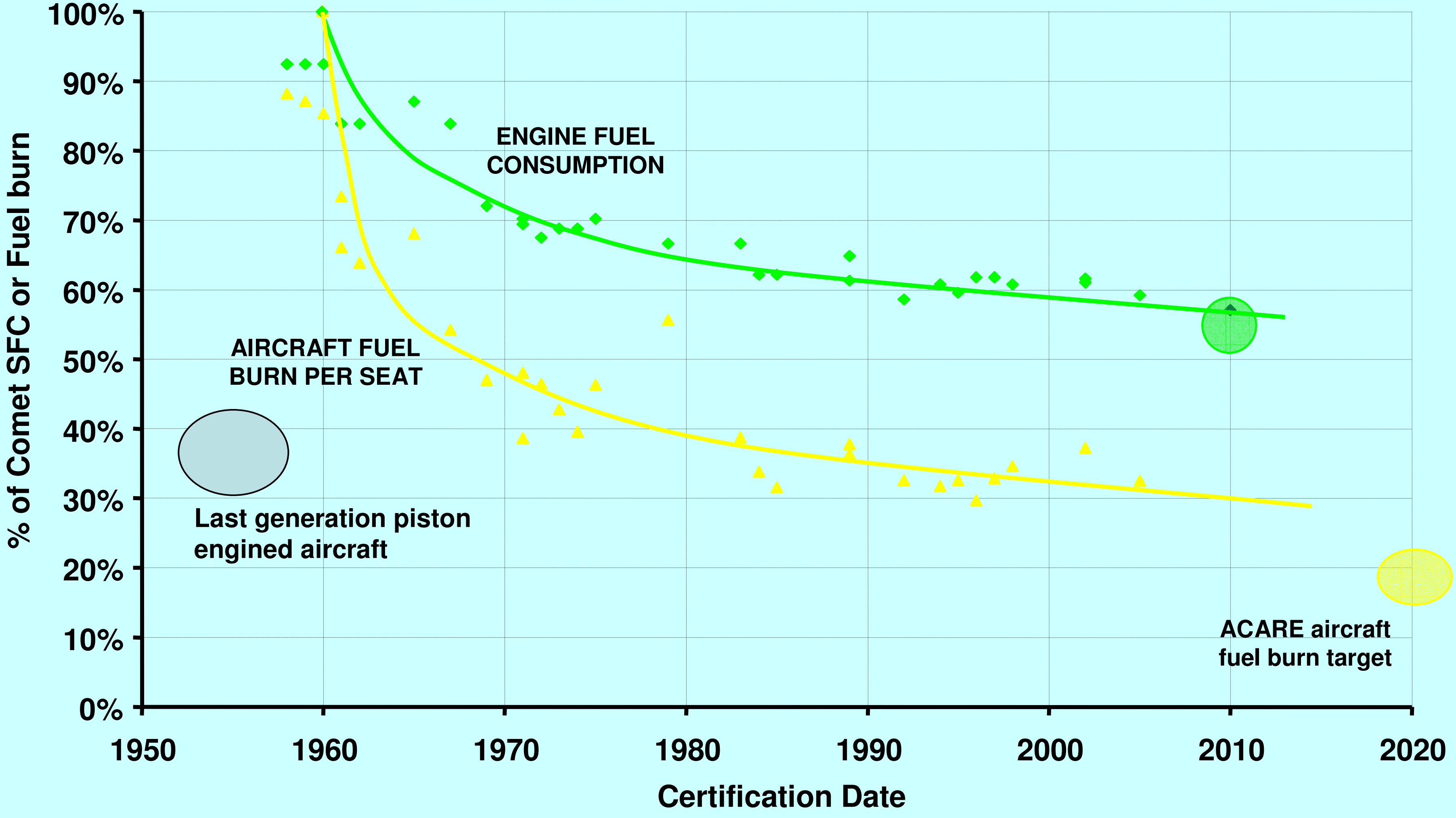
Source:
AERO2K

The ACARE fuel target is a real challenge



AeIGT

The ACARE fuel target is a real challenge



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Options for reducing fuel burn

- Operational measures
- Reduce ratio of empty weight to payload
- Increase propulsive efficiency
- Increase L/D in cruise
- Increase calorific value of fuel

Factors determining fuel burn per passenger-km

Factors determining fuel burn per passenger-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

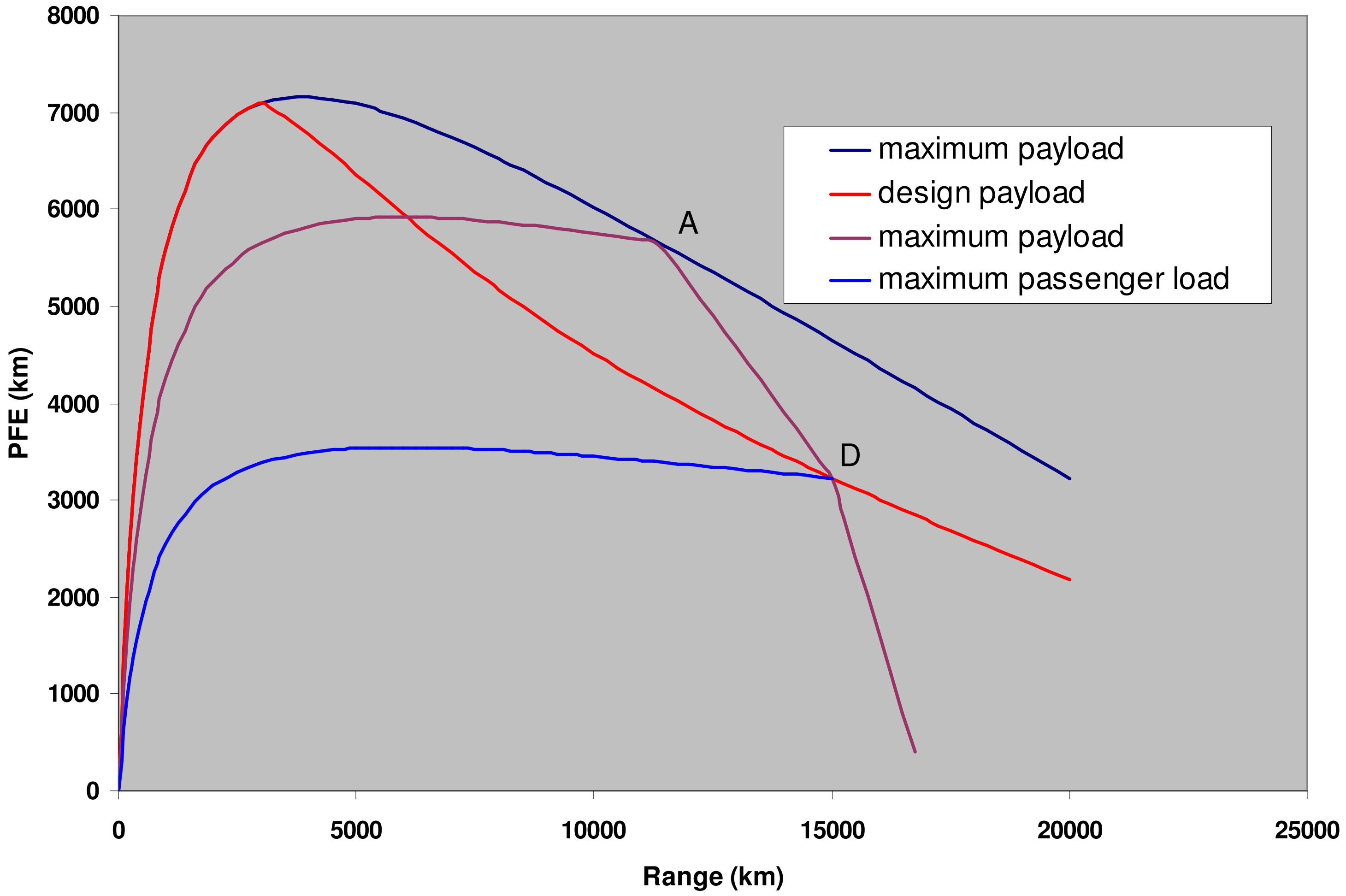
X = HηL/D

H = calorific value of fuel

η = overall propulsion efficiency

L/D = lift/drag ratio

Effect of design range and operating range on payload-fuel efficiency



Effect of design range on fuel burn for long-distance travel

Design range km	Payload tonne	Mission fuel tonne	Reserve fuel tonne	Max TOW tonne	OEW tonne	Fuel for 15,000km tonne
15,000	25.9	120.3	13.5	300.0	140.3	120.3

Travelling 15,000km in one hop or three

Revision of earlier GBD estimates:

Correction published in August 2006 issue of the Aeronautical Journal

Effect of design range on fuel burn for long-distance travel

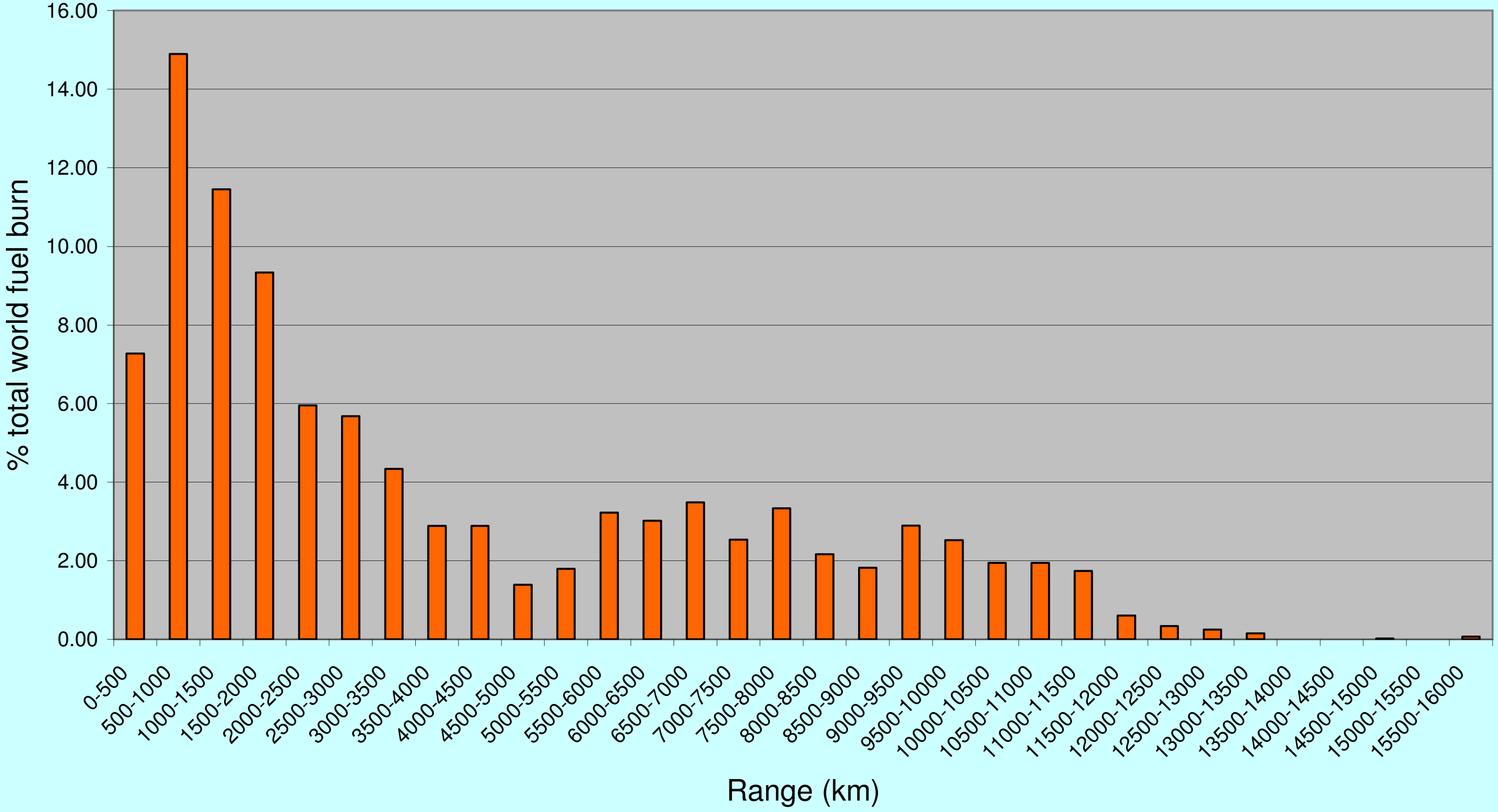
Design range km	Payload tonne	Mission fuel tonne	Reserve fuel tonne	Max TOW tonne	OEW tonne	Fuel for 15,000km tonne
15,000	25.9	120.3	13.5	300.0	140.3	120.3
5,000	25.9	20.4	5.4	120.0	68.4	61.1

Travelling 15,000km in one hop or three

Revision of earlier GBD estimates:

Correction published in August 2006 issue of the Aeronautical Journal

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



Reducing fuel burn by operational changes

- more efficient ATM and other operational measures (applicable to whole fleet and therefore of greater impact, sooner, than new technology)
- Multi-stage long-distance travel
- Air-to-air refuelling??
- Formation flying??

Factors determining fuel burn per passenger-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

Reducing the ratio of empty weight to payload

- Replace structural light alloy by CFRP and other light structural materials (as for B787, A350)
- Further advances in materials and design methods
- Flying wing for larger aircraft
- Less conservative certification requirements for wing strength and fuel reserves
- Reduce design range
- Reduce cruise Mach number

Factors determining fuel burn per passenger-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 = $H\eta L/D$
H = calorific value of fuel
η = overall propulsion efficiency
L/D = lift/drag ratio

Reducing fuel burn by increasing propulsion efficiency

Reducing fuel burn by increasing propulsion efficiency

Overall propulsion efficiency

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

where η_{therm} = thermal efficiency

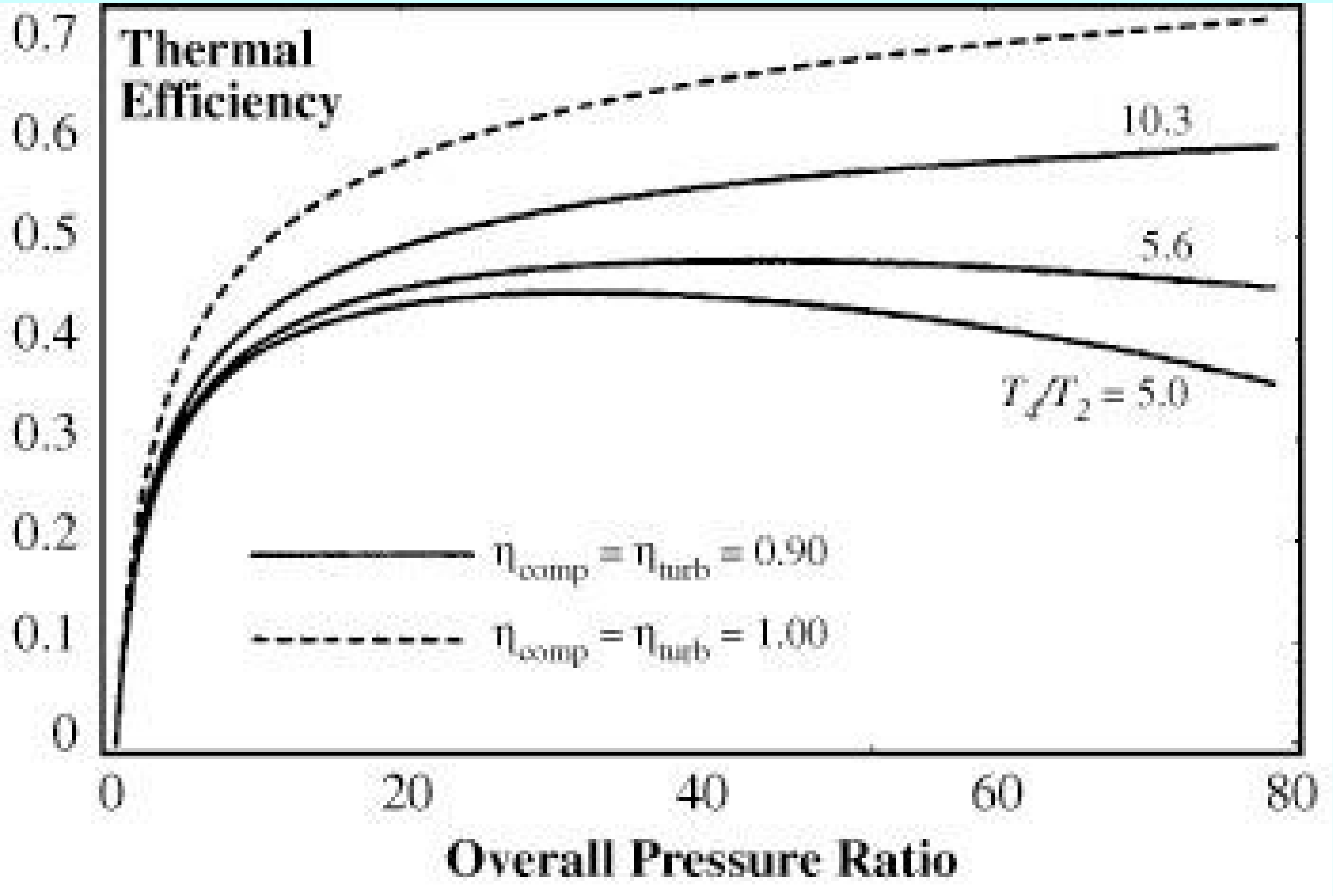
η_{trans} = transfer efficiency

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

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

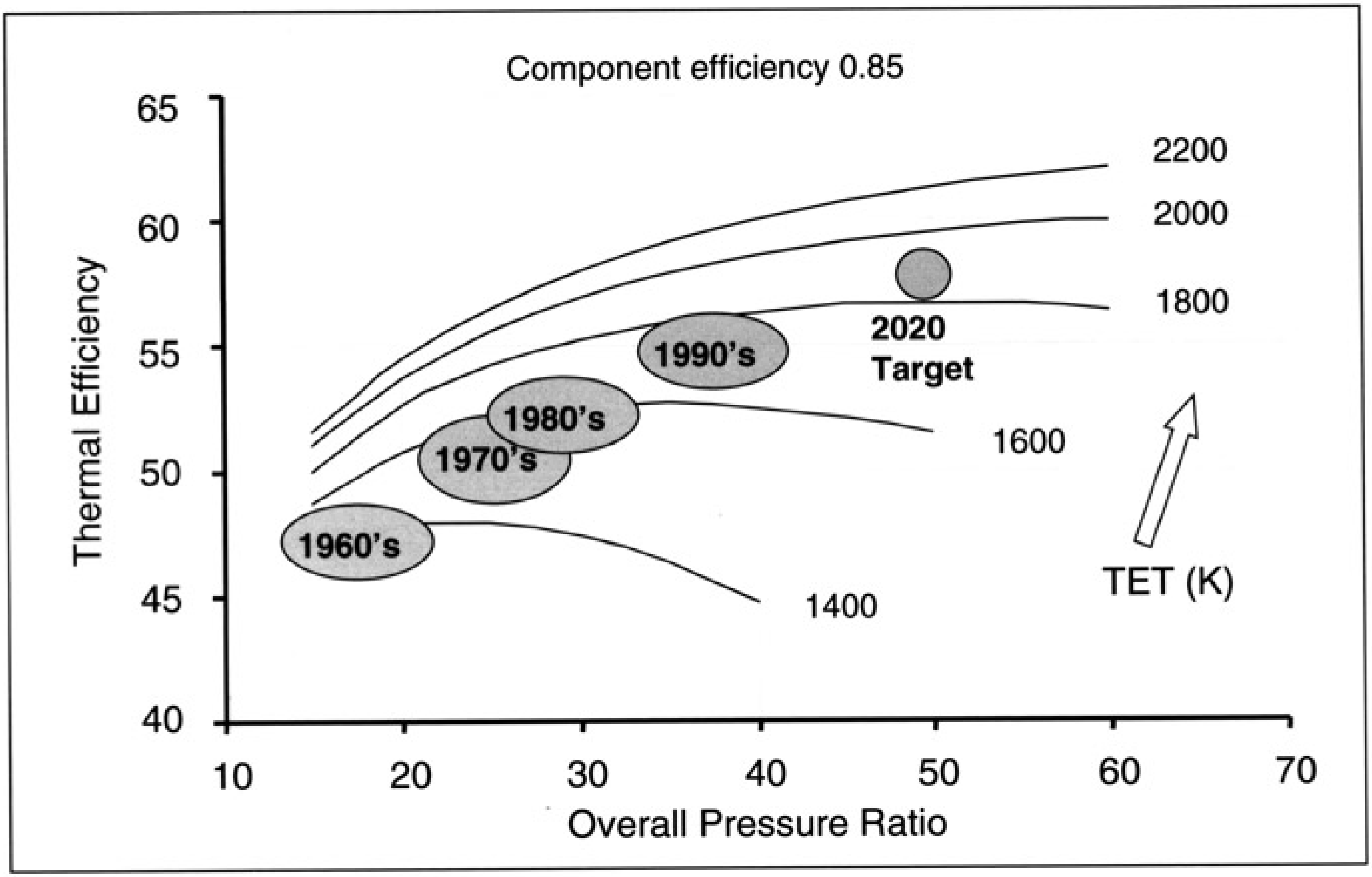
where V is flight velocity and Th_S is specific thrust

Variation of thermal efficiency with overall pressure ratio and turbine entry temperature (1)



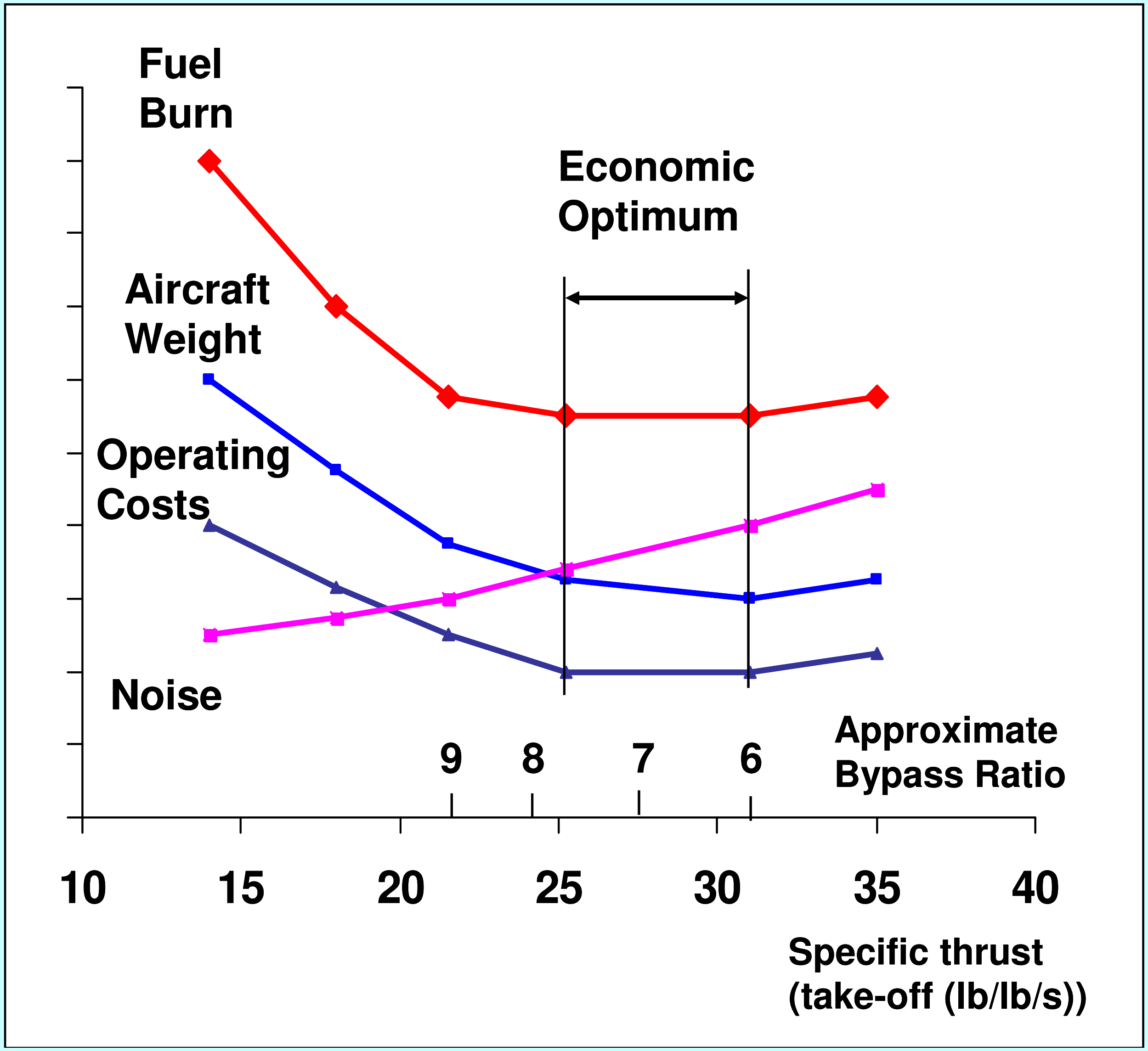
Source IPCC

Variation of thermal efficiency with overall pressure ratio and turbine entry temperature (2)



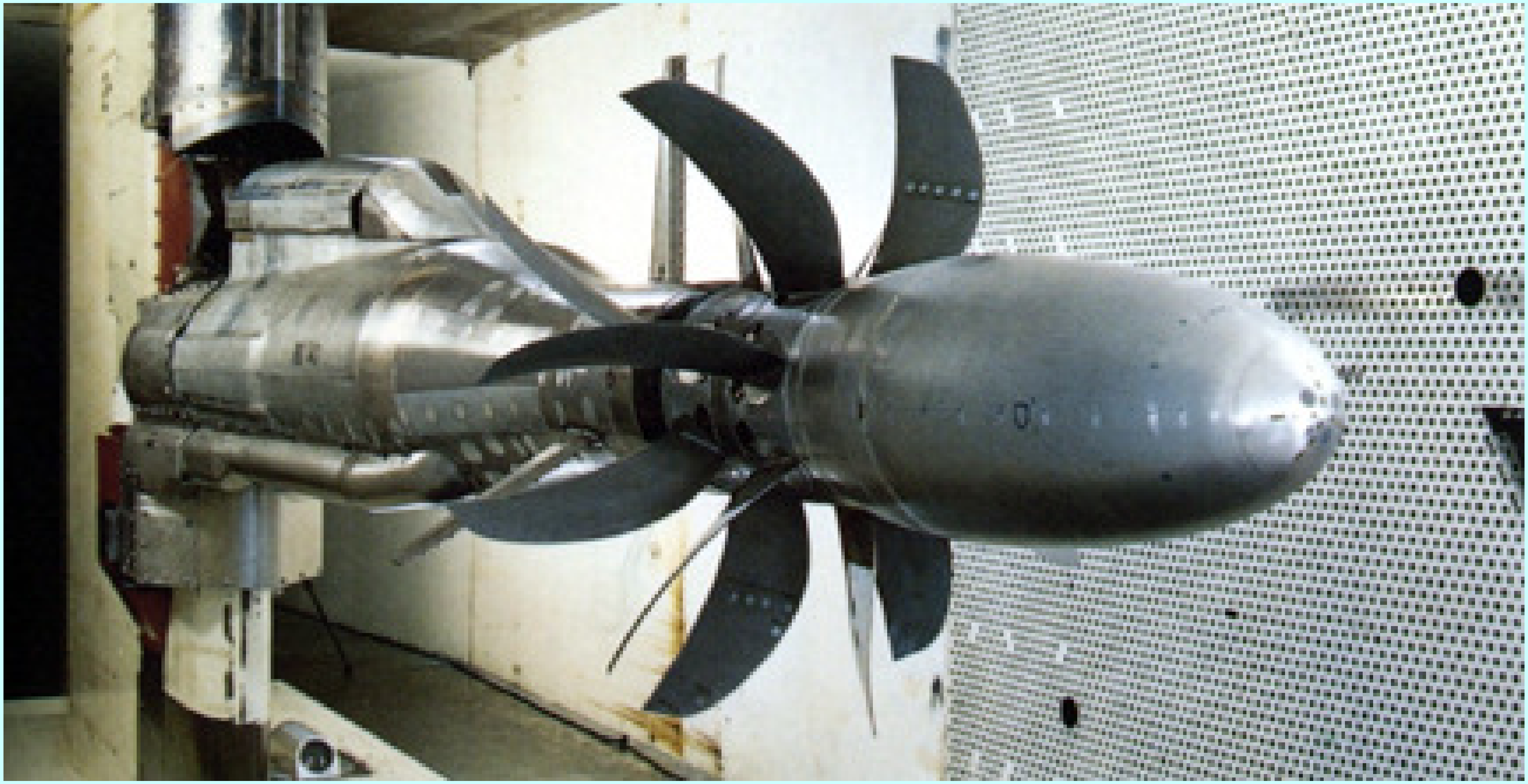
Source Rolls-Royce

Variation of aircraft characteristics with engine specific thrust



Source Rolls-Royce

Eliminating nacelle weight and drag – an advanced open rotor



Source ARA

Factors determining fuel burn per passenger-km

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Fuel burn per tonne-kilometre

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where

X = HηL/D
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η = overall propulsion efficiency
L/D = lift/drag ratio

Maximising lift-to-drag ratio in cruise

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

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

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

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

Reducing fuel burn by increasing L/D

- Increase span
  - Increasing span increases wing weight. Dominant configuration close to optimum

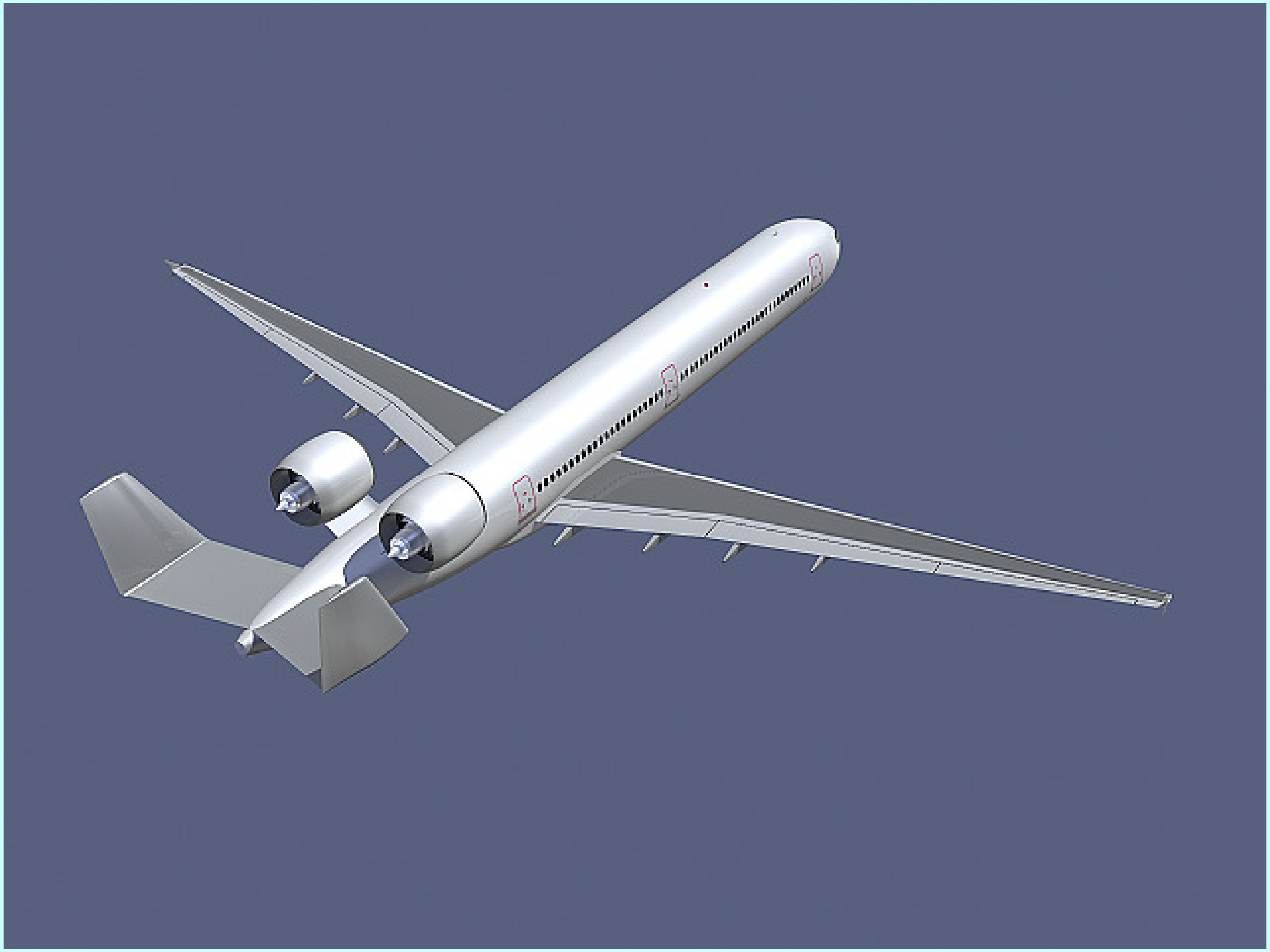
- Reduce vortex drag factor κ
  - Dominant configuration highly developed. Very limited scope without change of configuration

- Reduce zero lift drag area S_{DO}
  - Very limited possibilities for dominant configuration except for introduction of laminar flow control. Greater drag reductions possible with change of configuration

Reducing zero-lift drag area $S_{\mathbf{DO}}$

- Natural laminar flow control (NLFC)
- Hybrid laminar flow control (HLFC)
- Blended wing-body
- Full (all-over) laminar flow control

The Proactive Green aircraft of the EC NACRE project

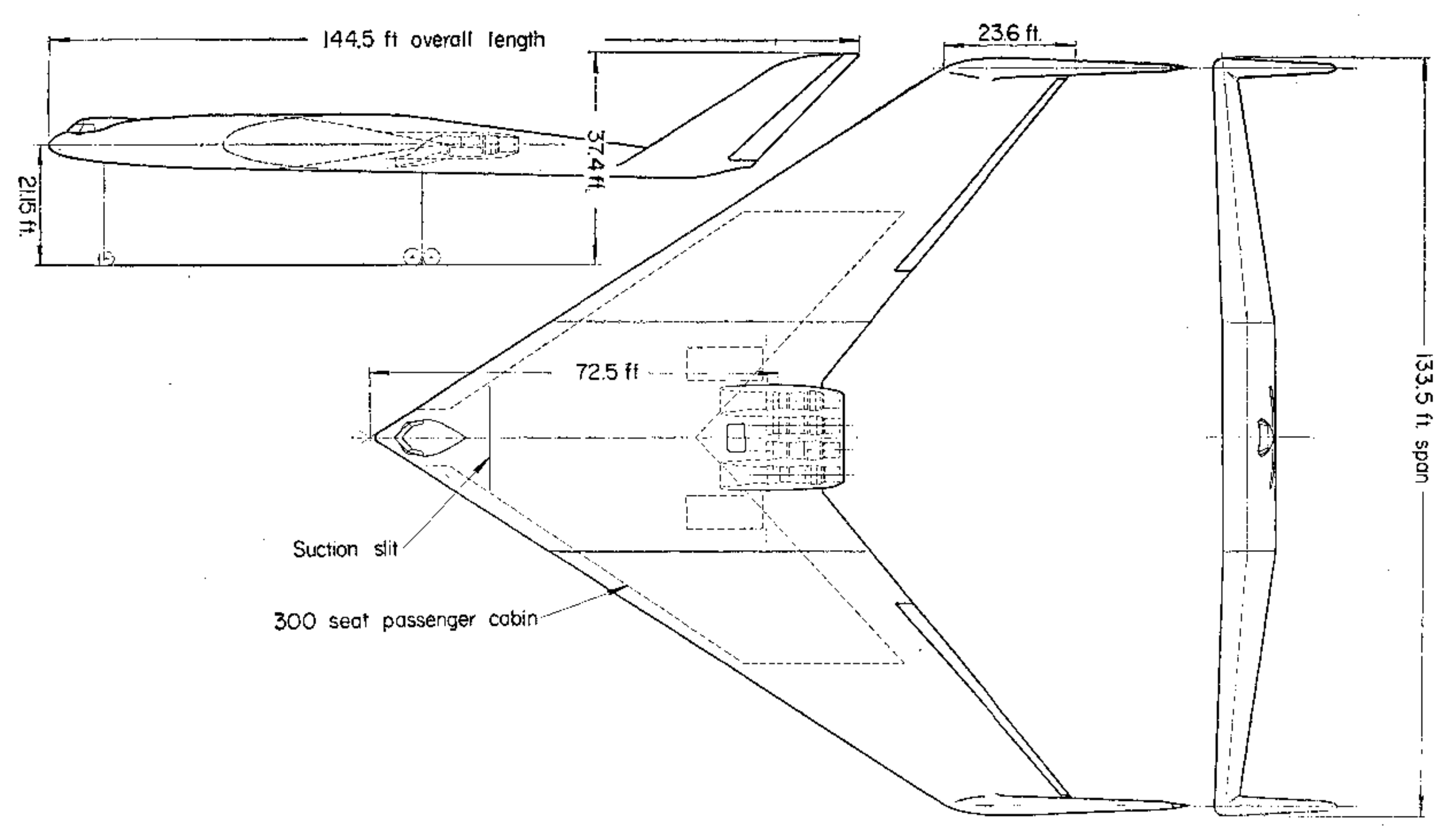


Source: Airbus

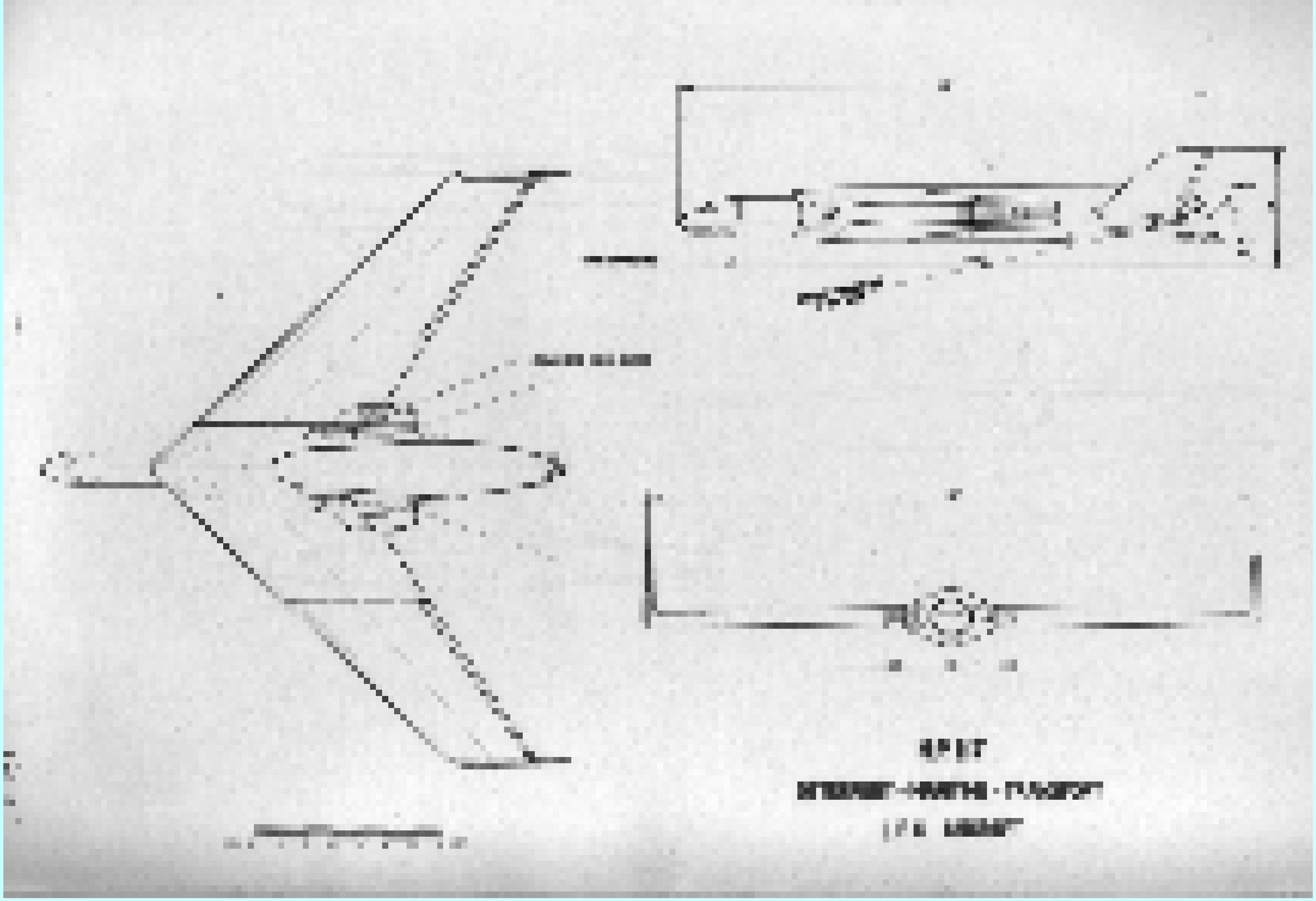
The large blended wing-body of the EC NACRE project

Source: Airbus

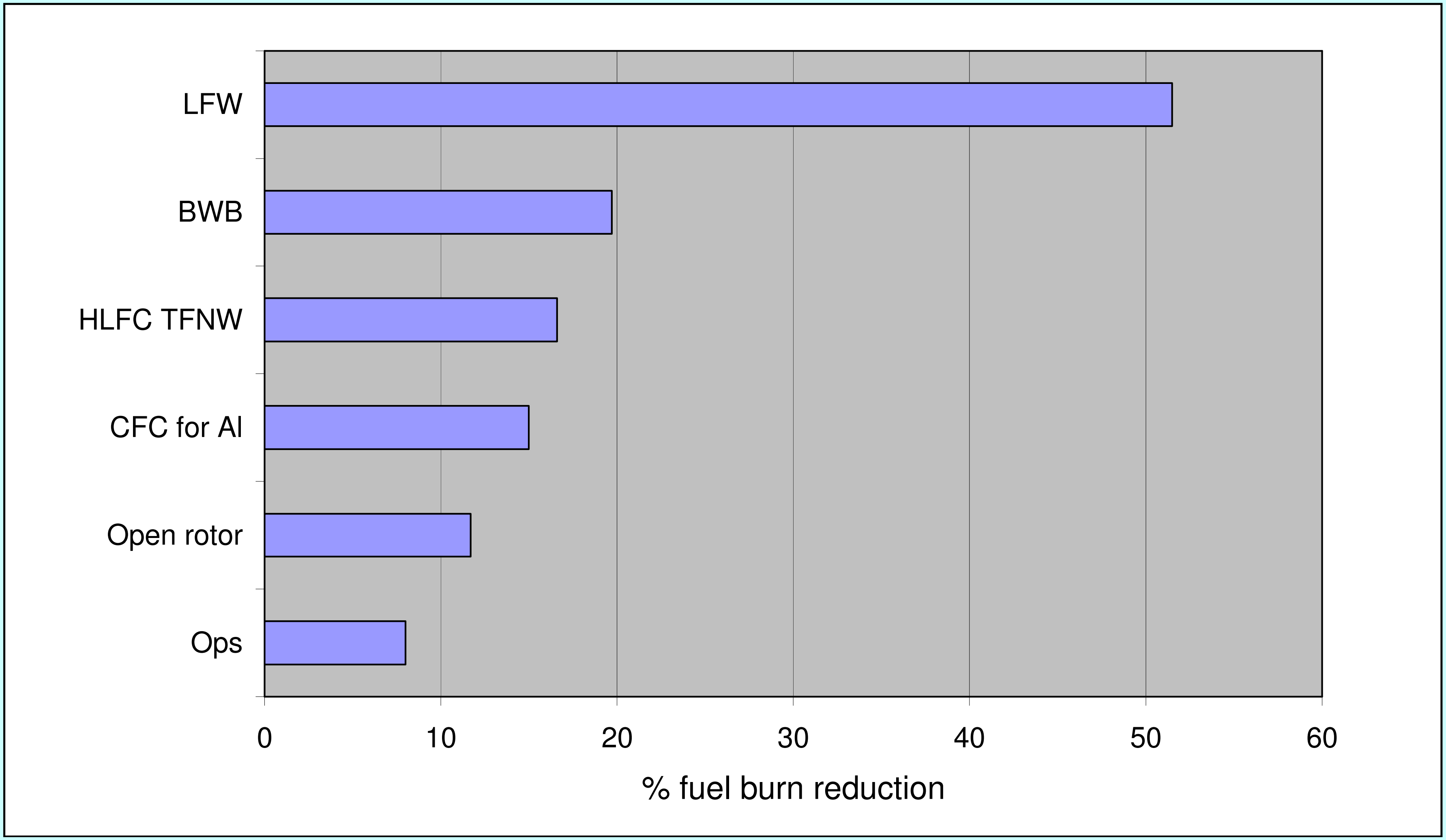
Handley-Page projected 300-seat laminar flow airliner (1961)



Handley Page HP.117 laminar flow military project (1962)



Potential reductions in fuel burn: GBD 2005 report



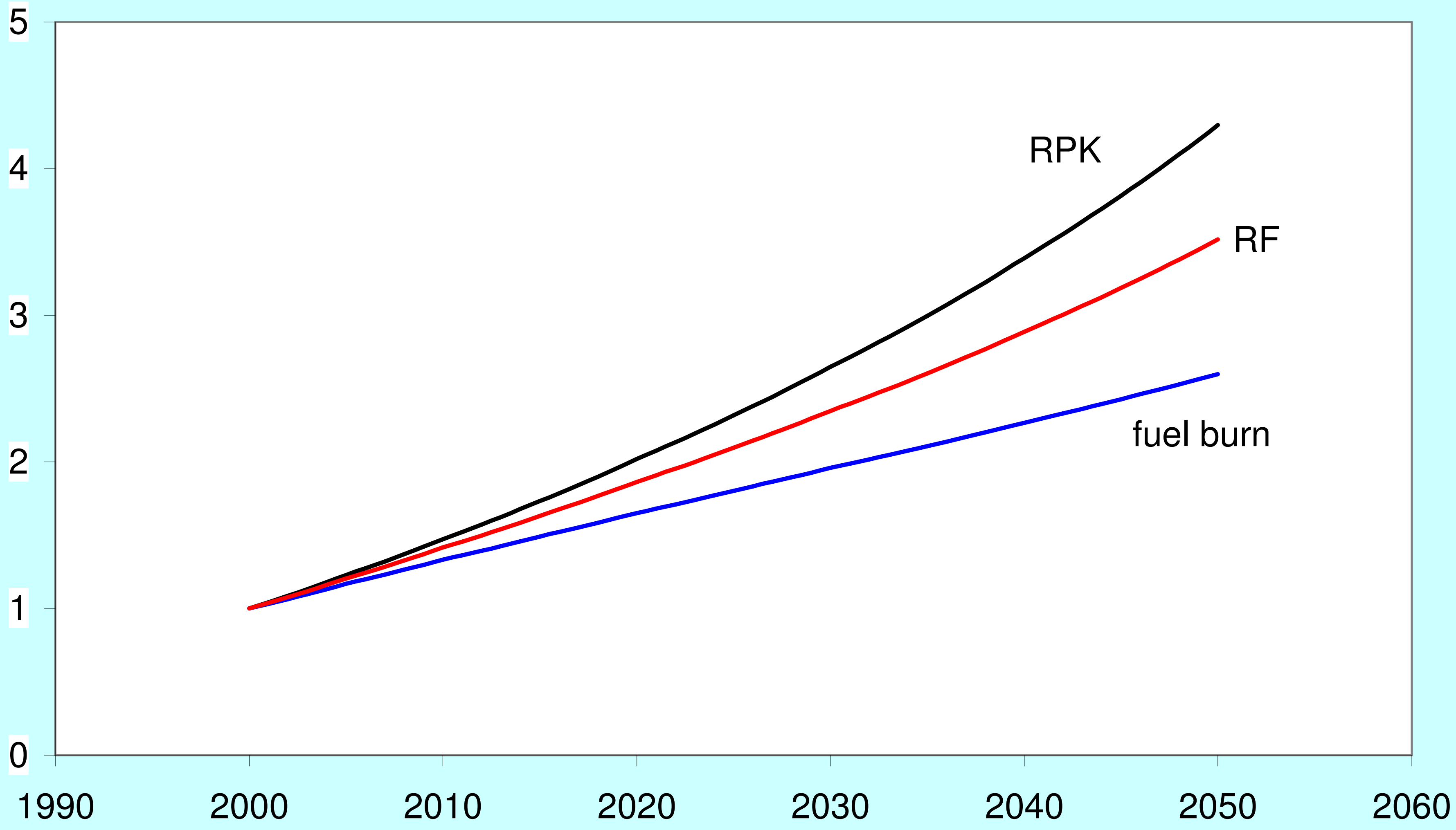
GBD S&T Sub Group Report, July 2005

"Technologies can and will be deployed in combination. The report has identified a number of specific avenues of advance in the reduction of weight, drag and NO_X *emission, increase in propulsion efficiency and operational improvement."*

"Taken together, these hold out the prospect that, in the long run, technological, design and operational progress will enable environmental impact per passenger-kilometre to be reduced faster than air traffic increases."

Conjecture

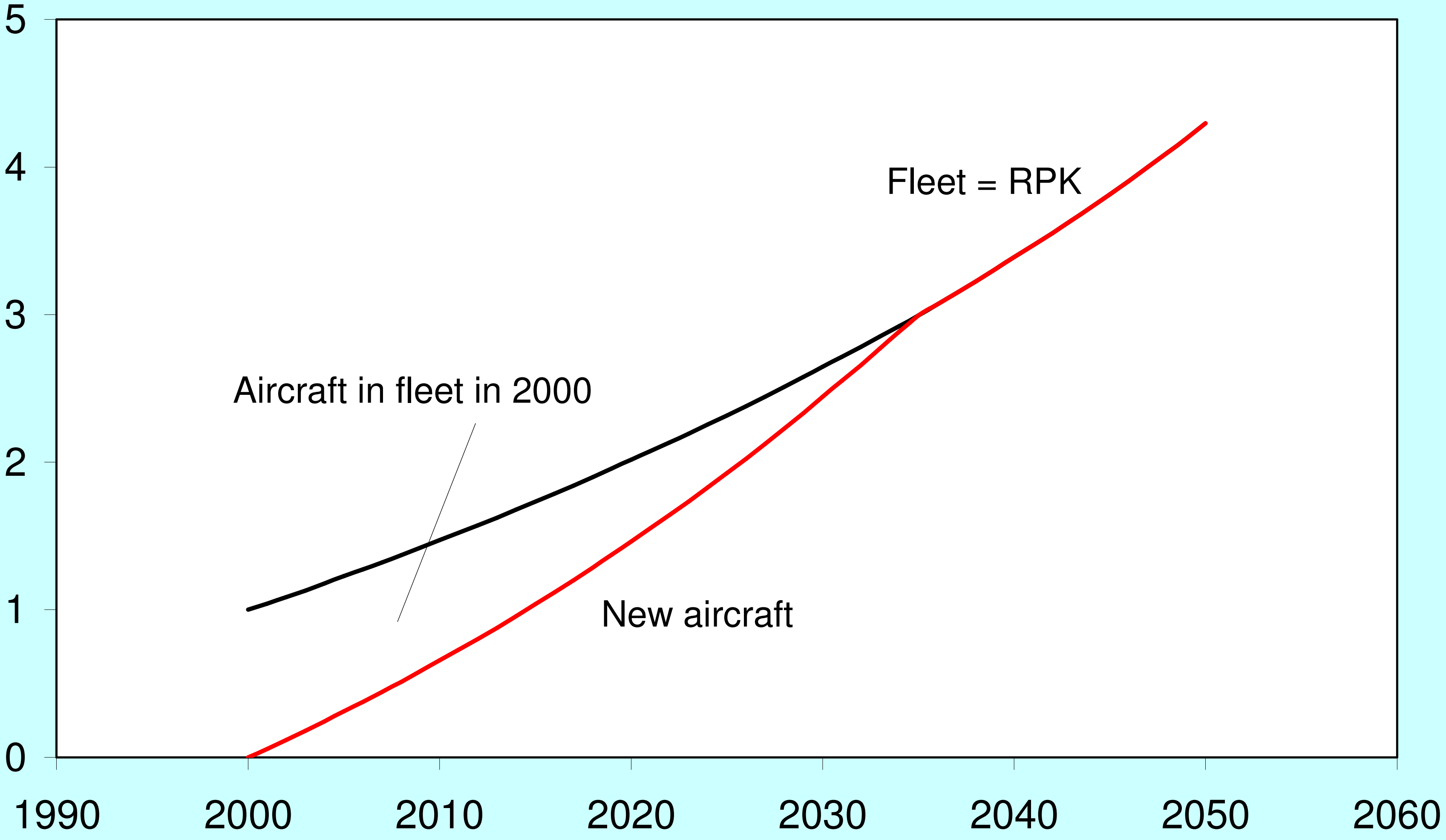
- Reasoned conjecture in defence of an assertion in GBD S&T Sub Group report
- A personal view, not reviewed by the Sub Group but based on material in the Sub Group report
- Addresses emissions solely in the context of climate change
- Attempts not to be unduly optimistic in timing of new technology
- Two important caveats
  - Still important uncertainties in the atmospheric science
  - There is not a linear relationship between rates of emission and contribution to climate change



IPCC FESGa projections of RPK, fuel burn and RF

Assumptions

- World RPK grows as in FESG scenario a
- World fleet grows in proportion to RPK
- Fleet retirement rate is 1.5% per annum
- Fuel efficiency of existing fleet improves at a rate of 1% per annum
- Specific technologies identified in the GBD July 2005 report are introduced at specific dates and are assumed to take 30 years fully to penetrate the relevant sector of the fleet
- Specific operational procedures are assumed to take a shorter but still protracted time to become universally adopted

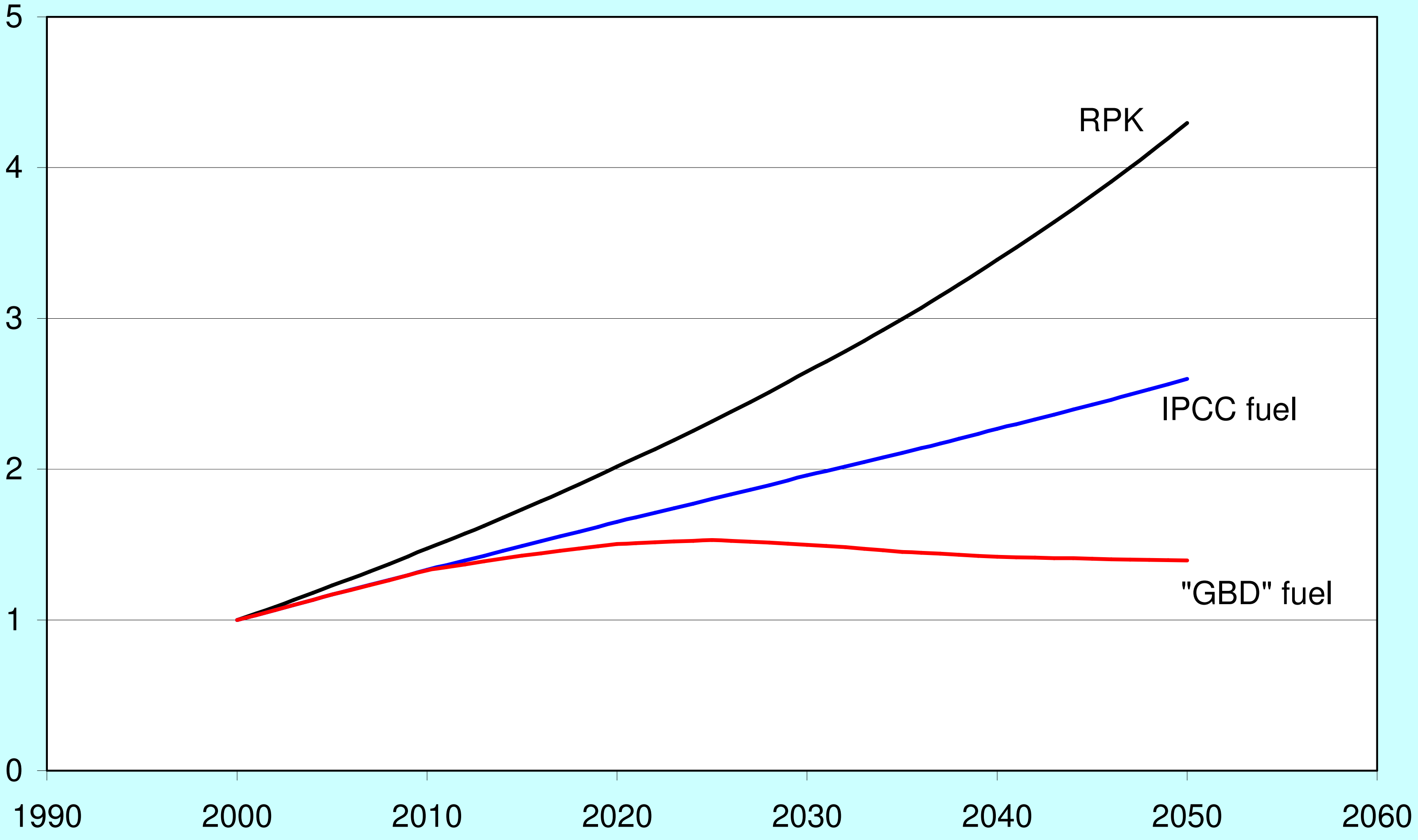


Assumed make up of world fleet, 2000 - 2050

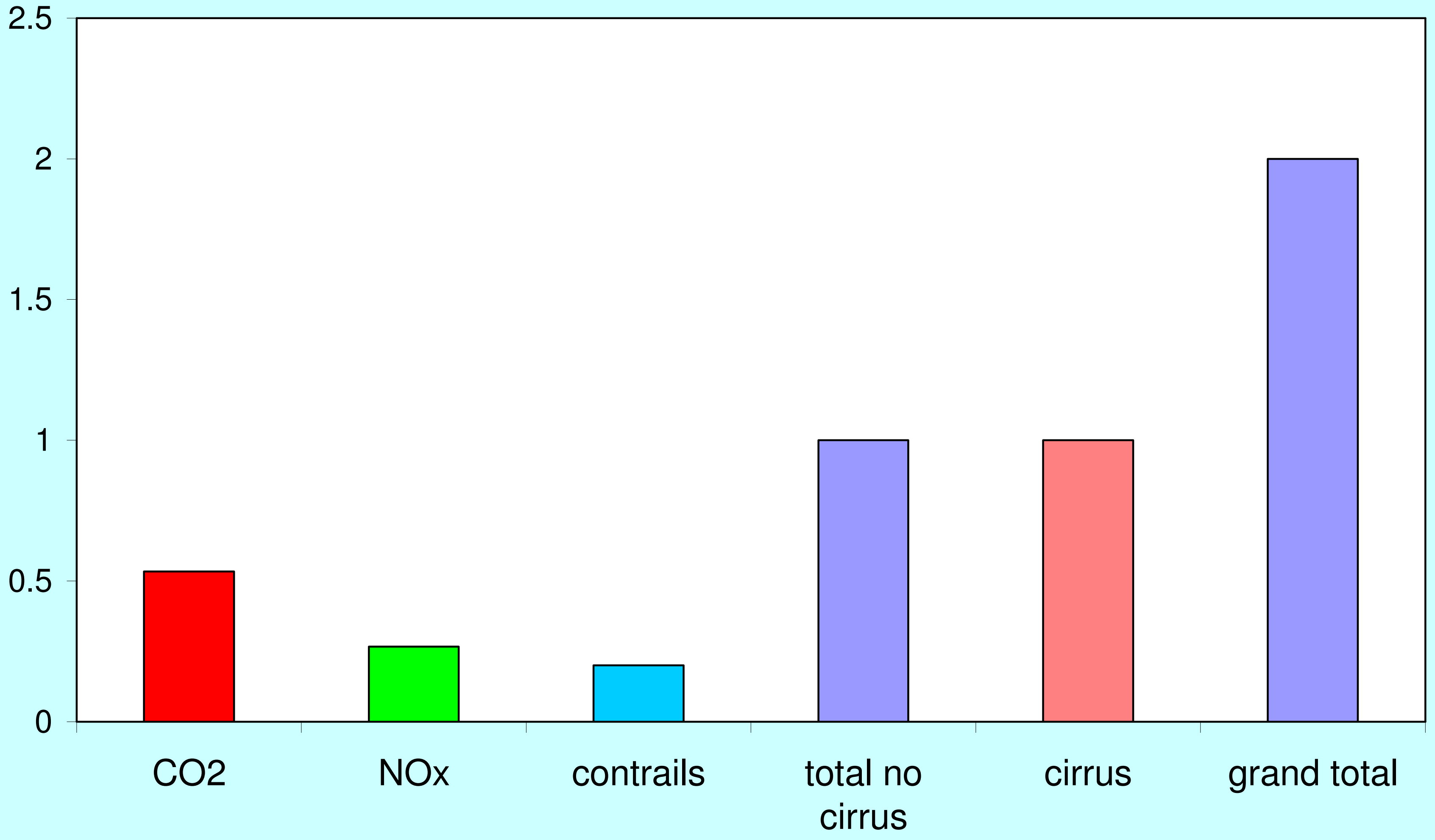
Technology	Fuel burn reduction %	Applicability (fleet fraction)	Overall % reduction	Phase in
Lightweight materials 1	12	all	12	2010 - 2040
Lightweight materials 2	12	all	12	2025 - 2055
Open rotor	12	1/3	4	2018 - 2048
HLFC	15	2/3	10	2020 - 2050
BWB	18	1/3	6	2025 - 2055
LFW	36	1/3	12	2035 - 2065
Cooled cooling air	1	all	1	2015 - 2045
Operations	10	all	10	2010 - 2030
Multi-stage long-distance travel	15	1/3	5	2015 - 2030
Formation flying	10	1/4	2.5	2030 - 2040

Engine thermal efficiency	1% per annum, 2000 – 2015 0.5% per annum, 2015 – 2050 Basis of assumed baseline thermal efficiency of new engines entering the fleet at a given date

Fuel burn reductions attributed to specific technologies



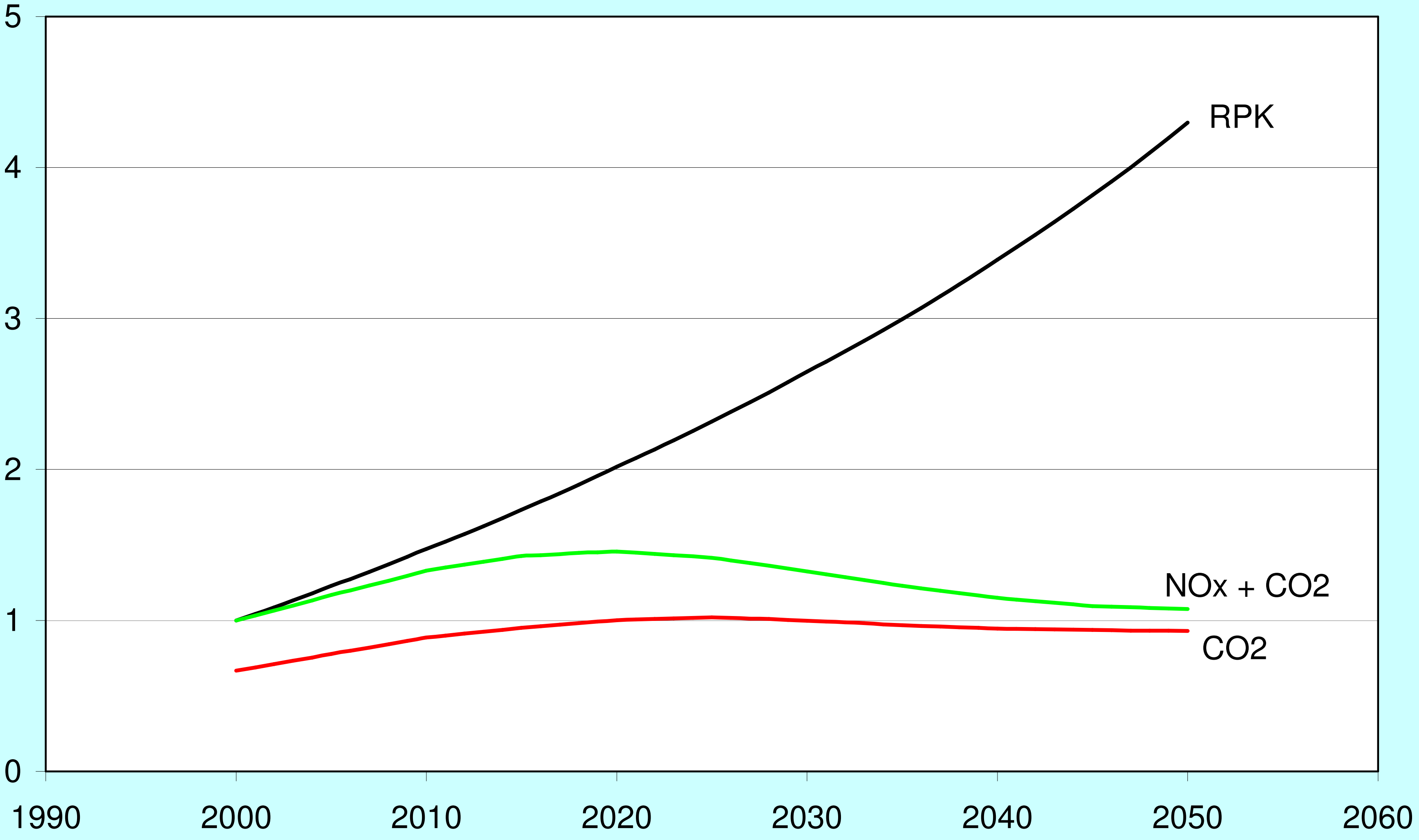
World fleet fuel burn projections, 2000 - 2050



Estimated breakdown of RF due to aviation in 2000 (after EC TRADEOFF study, 2003)

Technology	Cruise EI_{NOx} reduction %	Phase in
Lean-burn combustion	50	2015 - 2045
Cooled cooling air	10	2015 - 2045
Inter-cooling	30	2020 - 2050

Reductions in EI_{NOx} in cruise attributed to specific technologies

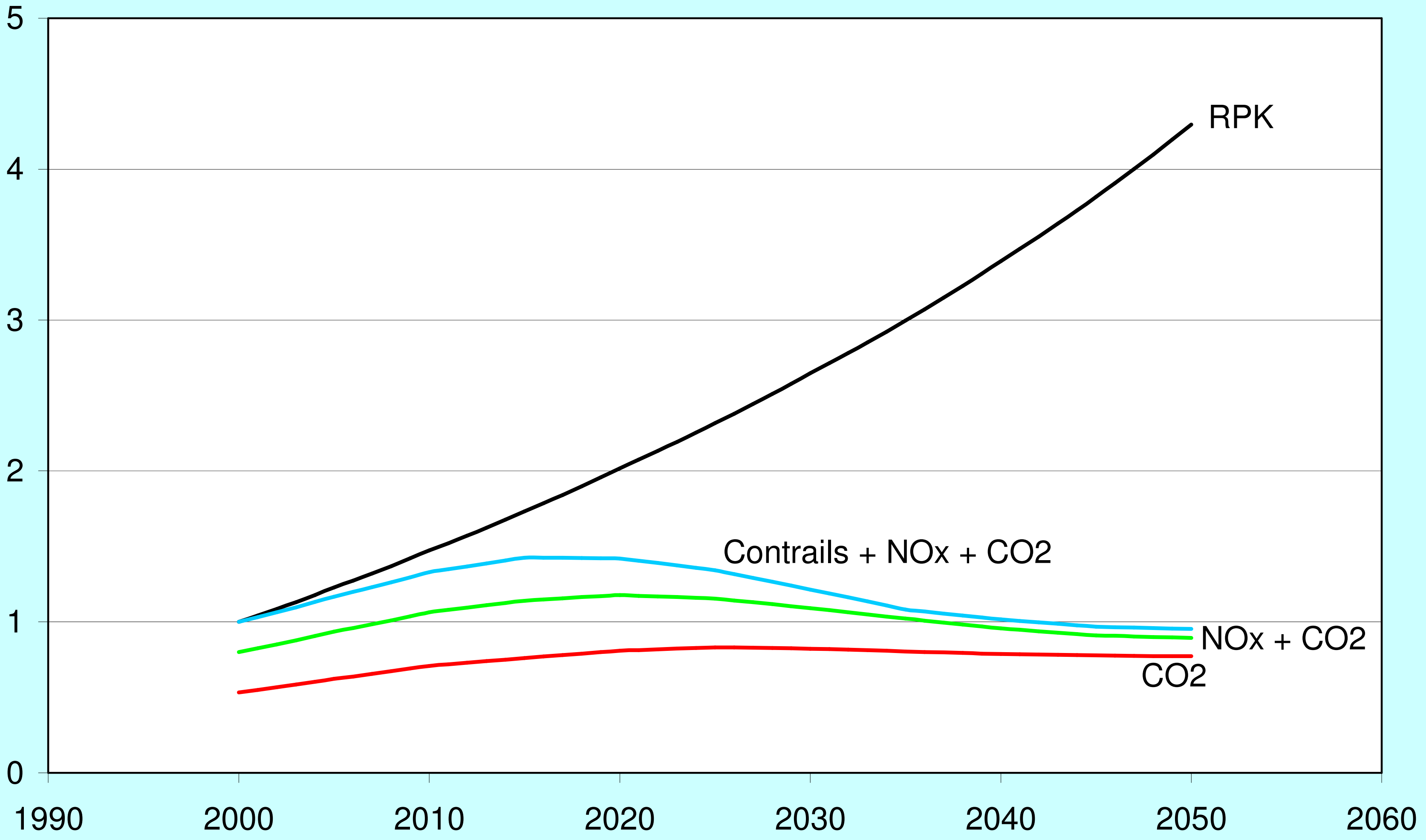


Projected fleet emissions of CO_2 and NO_X

(scaled in proportion to estimated contributions to RF)

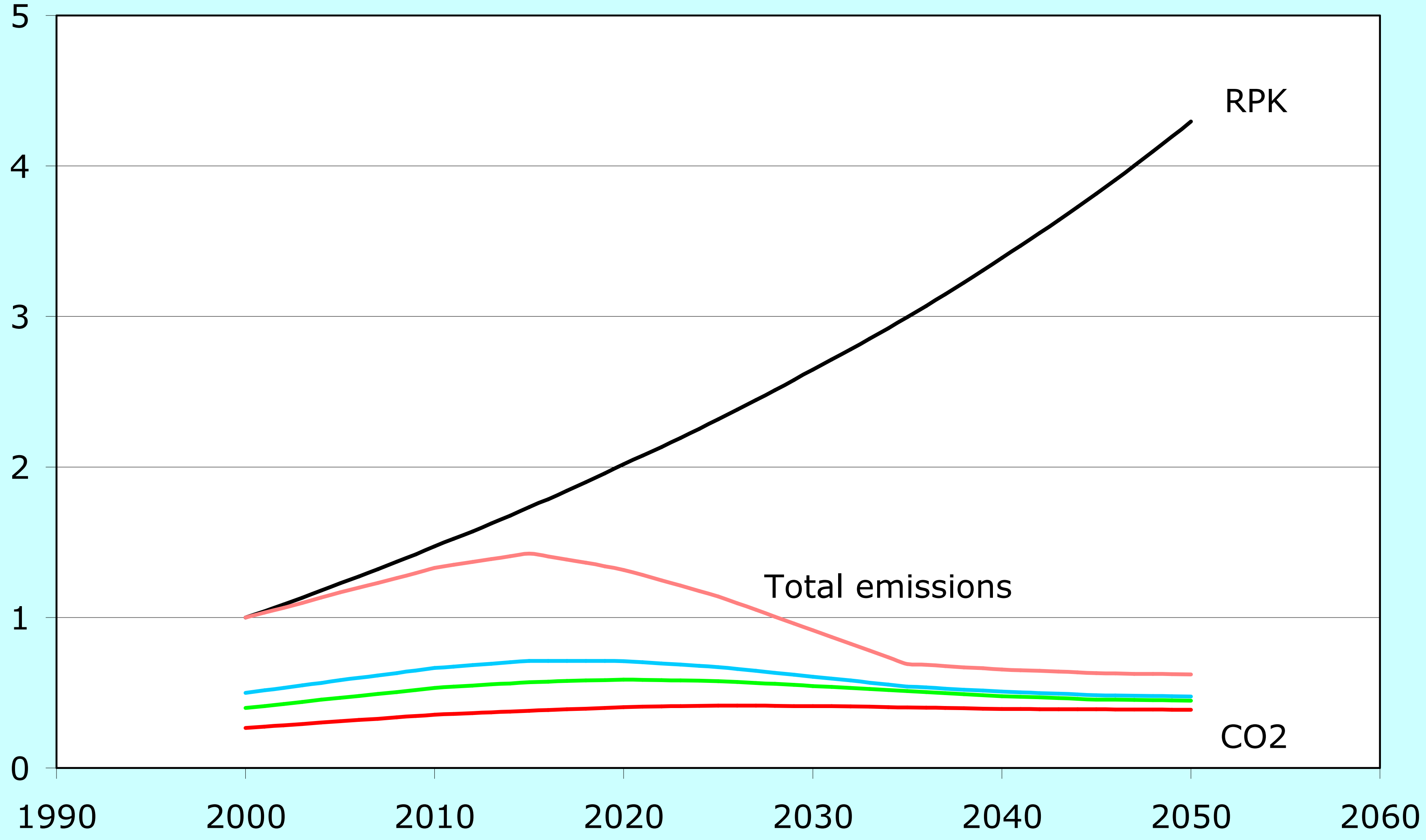
Conjectured reduction in contrail formation

- Persistent contrail formation can be reduced by ATM action to deny flight at critical cruise altitudes
- Studies at Imperial College suggest achievable reductions in the European ATM area in the range 65%-90% for fuel burn penalties in the range 2%-7%
- For this study, a reduction of 80% is assumed at a fuel burn penalty of 4%
- It is conjectured that ATM avoidance measures will first appear in 2015 and will become universal by 2035
- It is assumed that cirrus will be reduced in proportion to contrails
- There is still considerable scientific uncertainty about aviation-induced cirrus and its radiative impact



Projected emissions of CO_2 and NO_X and formation of contrails

(scaled in proportion to estimated contributions to RF)



Projected emissions of CO_2 and NO_X and formation of contrails and cirrus cloud

(scaled in proportion to estimated contributions to RF)

Postscript: BIOFUELS

- Not considered in depth by GBD S&T Sub Group in 2005 report, but a rapidly developing topic
- Consensus is that, to be accepted, fuel needs to be a ‘drop-in’ replacement for kerosene – ie ‘biokerosene’
- Net effect of biokerosene production (by Fischer-Tropsch or comparable process) needs to be significant capture of CO_2
- Suitable biomass feedstocks key issue. Algae and halophytes may be good candidates

Where do we go from here – contrails, contrail-cirrus and NO_X?

- In the medium term, contrails and contrail-cirrus can be reduced substantially by ATM action
- In a similar or shorter timescale, EI*NOX* of new production engines can be reduced substantially
- Neither is likely to happen without regulatory action
- Regulatory action is unlikely without a better scientific understanding of climate impacts of contrails, cirrus and NO_X
- Possibly between 2010 and 2020 in both cases?

Where do we go from here - CO_2?

- The A320/B737 replacement – environmentally the most important aircraft design decision in the next 20 years
  - Laminar flow control?
  - Open rotors?
  - Between 2010 and 2020
- When to expect a civil BWB?
- When to expect hybrid laminar flow control?
- When to expect full laminar flow control?
- When to expect truly sustainable bio-kerosene to be available in quantity?
- Rising fuel price should speed progress on all these

Potential by 2050?

- World fleet fuel burn and CO_2 emission per passenger kilometre down by a factor of 3
- NO_X emission at altitude down by a factor of 10
- Contrail and contrail-cirrus formation down by a factor of 5-15
- If bio-kerosene becomes available, net CO_2 emissions could be reduced still further – perhaps substantially

2008 priorities?

- Atmospheric science
- More efficient ATM and other operational practices
- Contrail reduction strategy
- Accelerated fleet renewal
- Open rotors
- Reduced NOx at cruise
- Design range – business model for 3,000nm as baseline design?
- Laminar flow control
- Design methodology for minimum climate impact