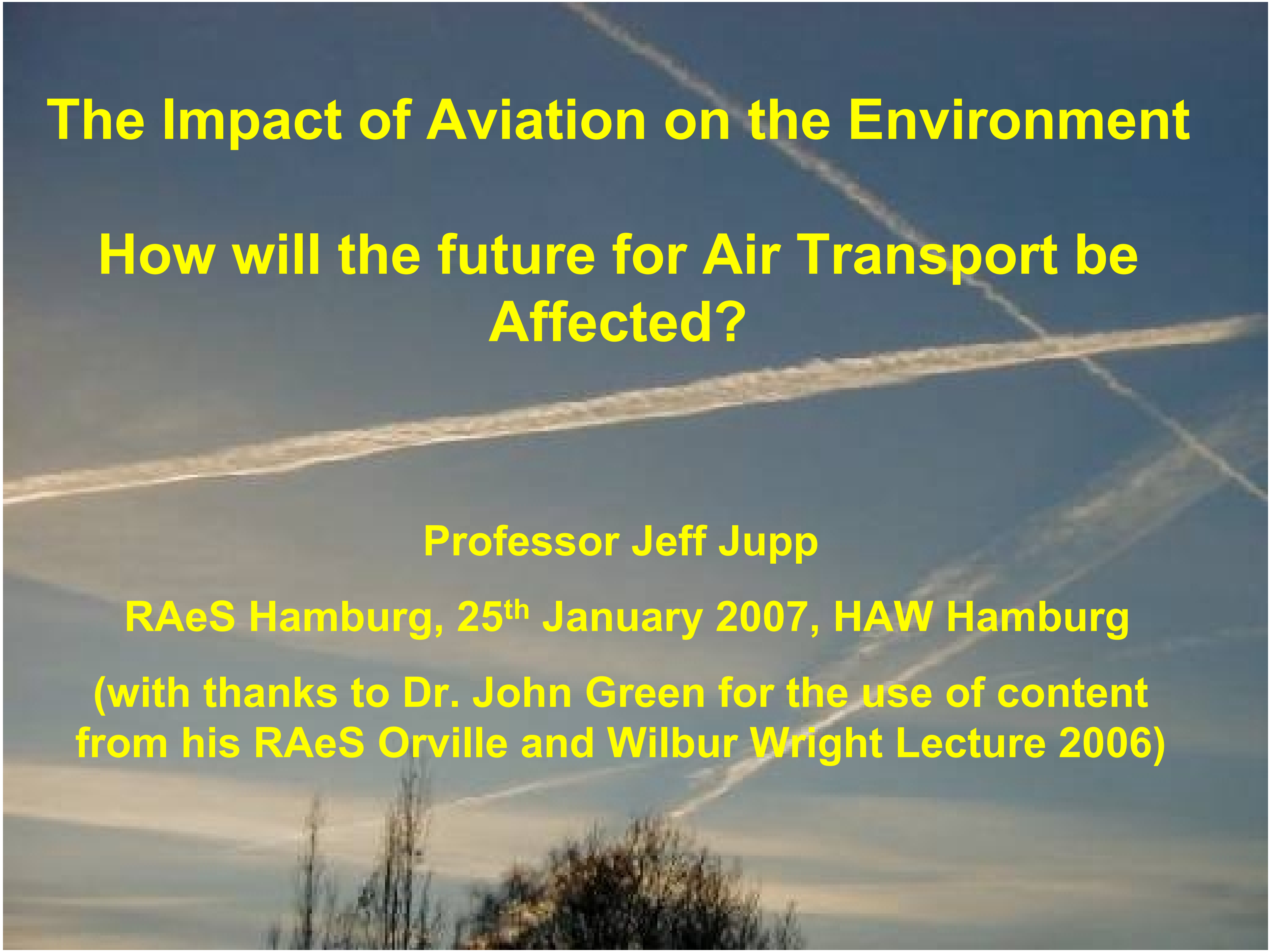


The Impact of Aviation on the Environment

How will the future for Air Transport be Affected?

Professor Jeff Jupp

RAeS Hamburg, 25th January 2007, HAW Hamburg

(with thanks to Dr. John Green for the use of content from his RAeS Orville and Wilbur Wright Lecture 2006)

The Challenge

- **Predicted growth rates for air travel are approx 5% per annum; double year 2000 by 2020 and triple by 2030**

- **“The (UK) Government recognises the benefits that the expansion of air travel has brought ……..” “But we must do more to reduce the environmental effects of aviation”
(“The Future of Air Transport” UK DfT, December 2003)**

- **Impact of aviation on climate change is predicted to increase from around 3% of Man’s total in 2000 to 6% to 10% before the middle of the Century, including significant improvements in technology. Some estimates are considerably higher.**

- **Even the year 2000 level of emissions may not be “Sustainable”**

Environmental objectives for aviation

- **Reduce noise around airports**
- **Improve local air quality near airports by reducing NO and NO_2 (NO_X) emissions in the LTO cycle**
- **Reduce contribution to climate change**
  - reduce fuel burn
  - reduce impact of NO_X emissions at altitude
  - reduce formation of contrails and cirrus cloud

ACARE environmental targets for 2020

(Advisory Council for Aeronautical Research in Europe)

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

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

(Targets for new aircraft and operations relative to 2000)

UK Initiatives

(1) Air Travel - Greener by Design (launched March 2000)

• Objectives:	To assess and progress options for mitigating the environmental impact of aviation
• Sub-Groups:	Technology Operations Market-Based Options
• Founders:	Royal Aeronautical Society Society of British Aerospace Companies British Air Transport Association Airport Operators Association Department for Transport Department of Trade and Industry

- Now incorporated as a Group within the Royal Aeronautical Society

Greener By Design

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

S &T Sub Group 2nd report
July 2005

Full review of the environmental issues and relevant UK and European Research Programmes

Recommendations for future research priorities:- Atmospheric Science, Trade off studies, Product Technologies and Operational Advances.

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

UK Initiatives

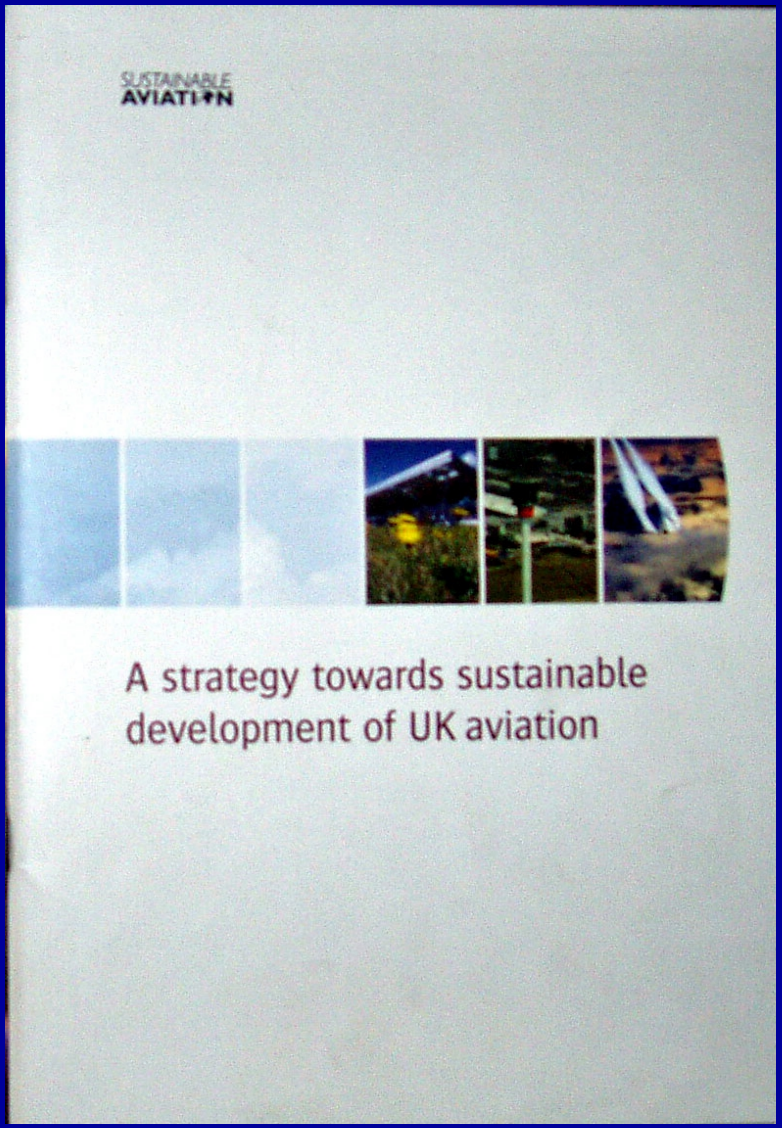
(2) Sustainable Aviation

- Objectives: To be a framework for action with goals and commitments in the following areas:- Implementation and Communication; Climate Change; Noise; Local Air Quality; Surface Access [to airports]; Natural Resources; Economics and Social matters.

- Sponsors: Society of British Aerospace Companies (SBAC)
  British Air Transport Association (BATA)
  Airport Operators Association (ATA)
  National Air Traffic Services (NATS)

- Signatories: Airbus UK, Rolls Royce, Smiths, Messier-Dowty…..
  British Airways, Virgin Atlantic, Monarch……..
  British Airports Authority, Manchester Airports……

Sustainable Aviation



SUSTAINABLE
AVIATION

A strategy towards sustainable development of UK aviation

Sustainable Aviation Strategy issued June 2005 with foreword by the UK Prime Minister.

First Progress Report issued December 2006.

Further Updates scheduled every 2 years

All reports etc available on the Web Site www.sustainableaviation.co.uk

UK Initiatives

(3) OMEGA "Opportunities for Meeting the Environmental challenge of the Growth in Aviation"

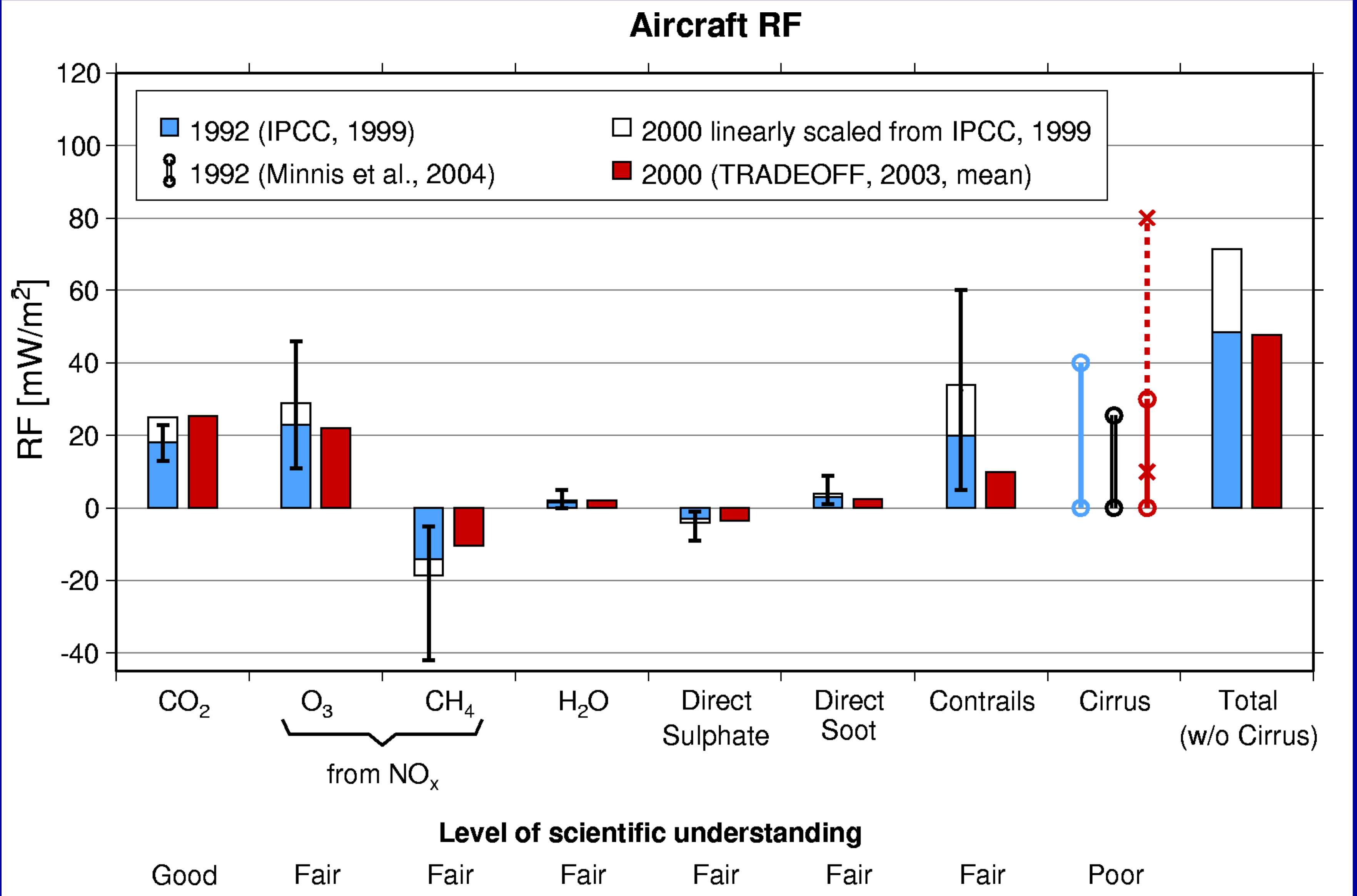
- Objectives: To establish a respected, enduring, academic centre in the field of aviation and the environment and a Knowledge Transfer Network with Government and Industrial Stakeholders

- Core Members: Manchester Metropolitan University
  Cambridge University
  Cranfield University

- Other Members: 6 other UK Universities. Links to be forged with European and USA Academic Centres.

- Funding: Higher Education Innovation Fund (£5m)

Updated Aviation Radiative Forcing for 2000



Sausen et al., 2005

Chief contributors to aviation RF in 2000 (after TRADEOFF, 2003)

• CO_2	25.3 mW/m^2	(100%)
• NO_X (net effect of O_3 – CH_4)	11.5 mW/m^2	(45%)
• contrails plus contrail cirrus	20 – 90 mW/m^2	(79 – 355%)

Total compared with CO_2 alone:- 224% to 500%

Persistent contrails and contrail cirrus

Reducing contrail and contrail cirrus formation

- Fly under, over or around regions of air which are supersaturated with respect to ice

- 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

- Today the effect on Climate Change is not sufficiently quantifiable to take decisions – but we should start to think about ATM procedures etc.?

Reducing the climate impact of NO_X

- reduce fuel burn (most measures to reduce fuel burn reduce CO_2 and NO_X proportionately)

- introduce low NO_X technology to reduce EI_{NOx}
  - lean burn combustor
  - Inter-cooled engine cycle
  - cooled cooling air

- reduce engine overall pressure ratio (future engine design optimisation)

- reduce cruise altitude (as an operational measure or as part of future aircraft design optimisation)

ANTLE lean-burn premixed combustor

Premixed flame does not pass through stochiometric mixture, avoiding peak NOx production.

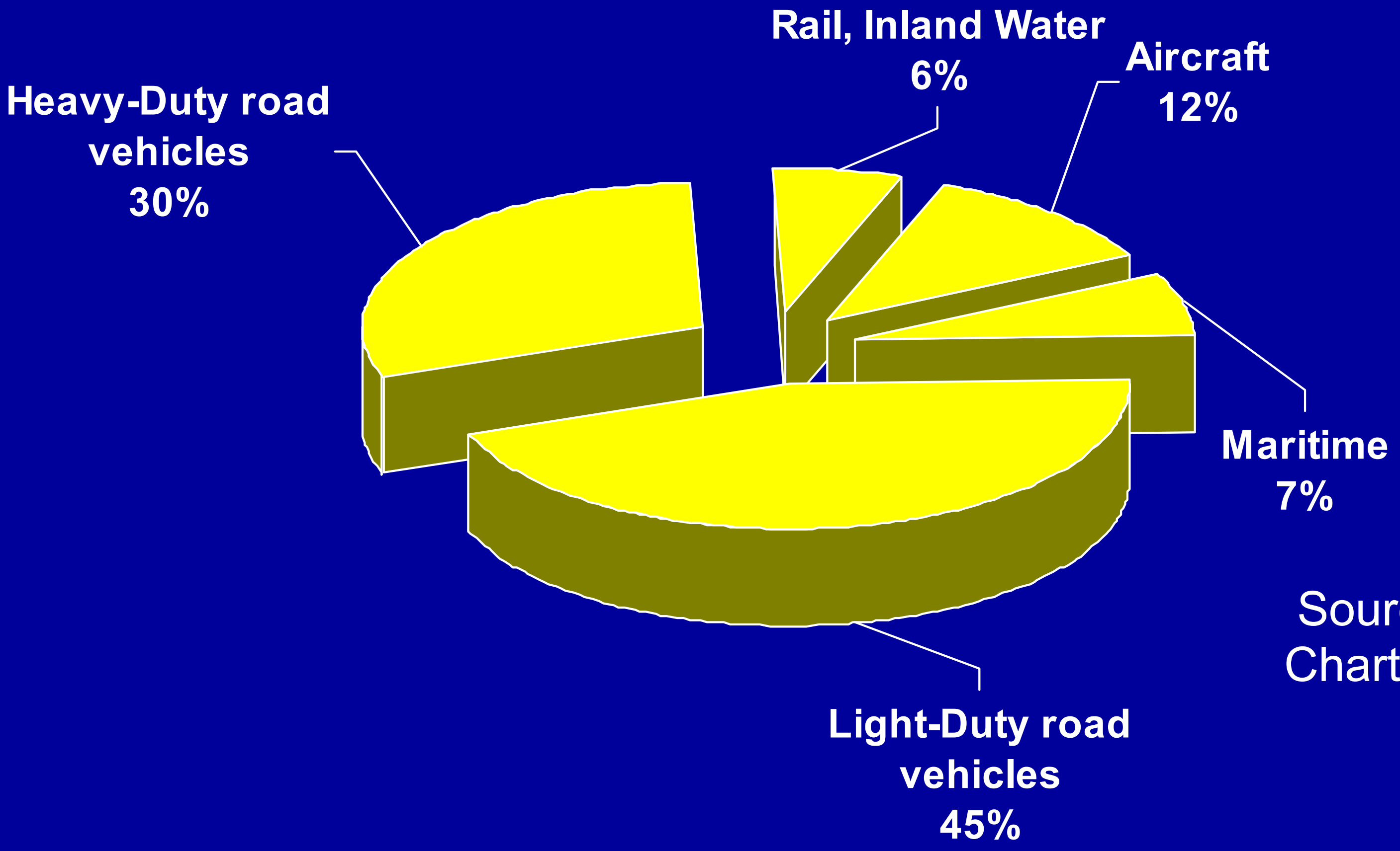
Direct injection, lean-burn single annular combustor

Staged injector

40% CAEP/2 NOx

Source Rolls-Royce

CO2 emissions from transport

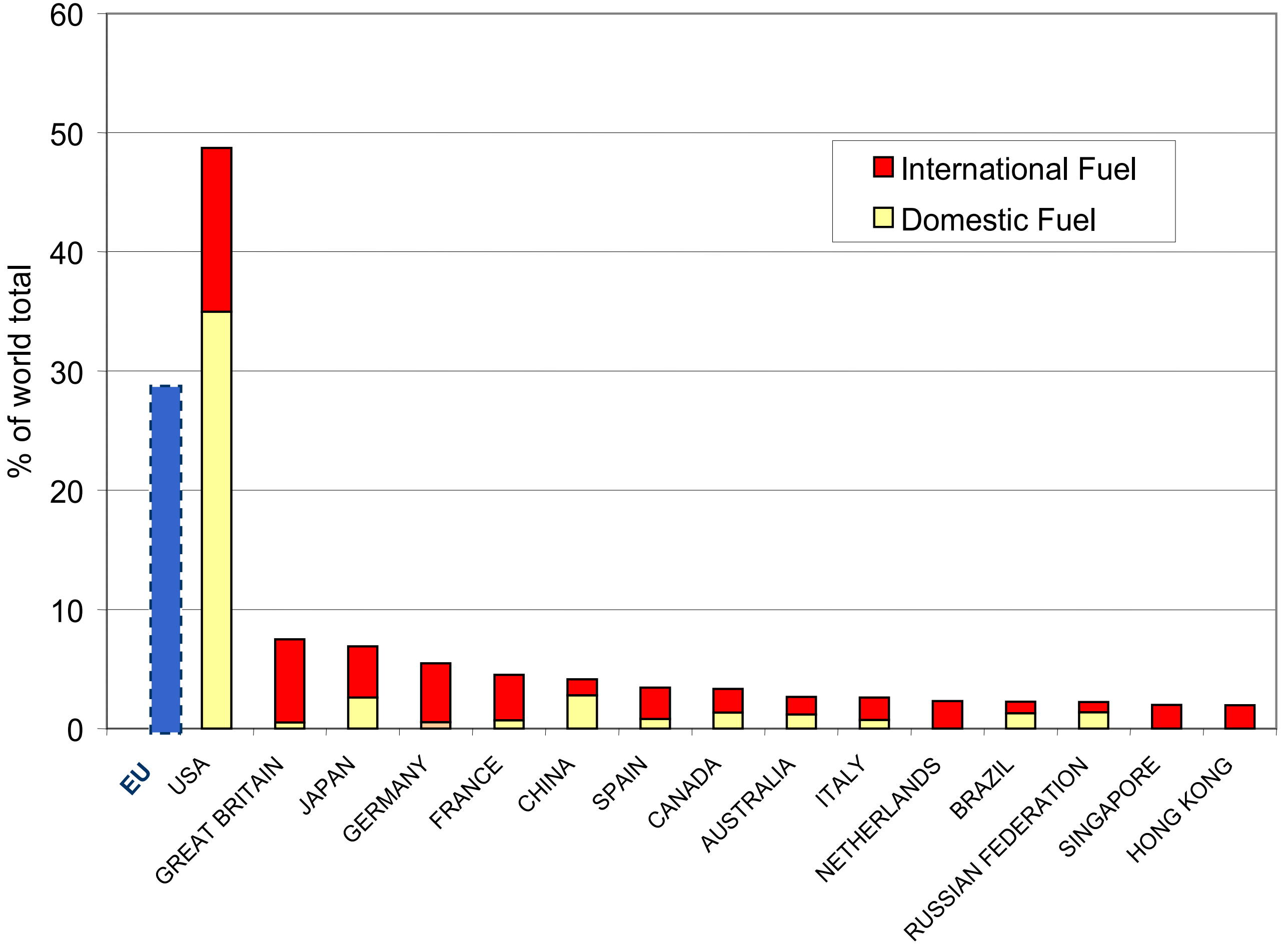


Source:IPCC
Chart for 1990

1990 Transport CO2 14% - 16% world total CO2e (IPCC 1999)

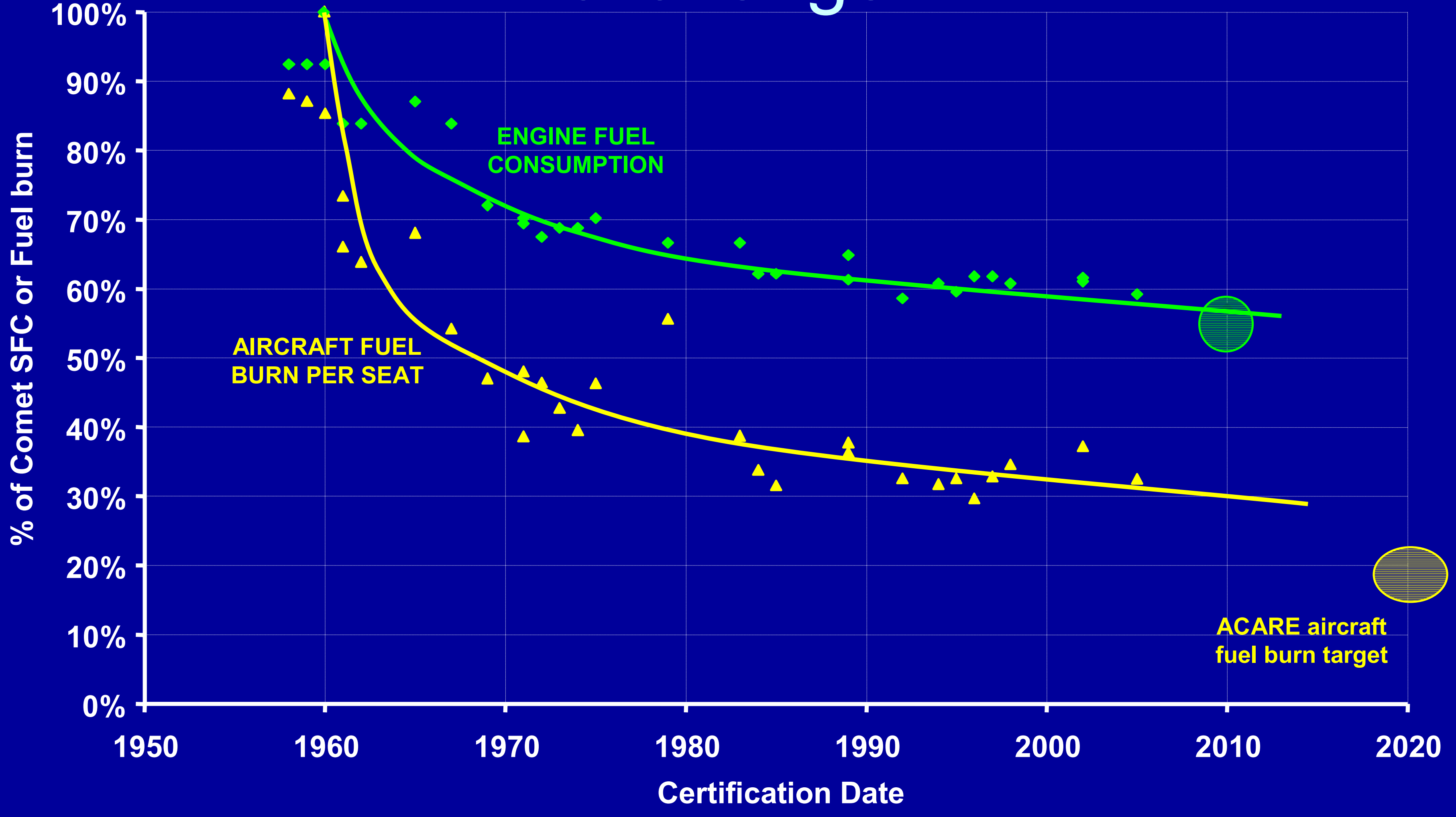
2000 Transport CO2 14% world total CO2e (Stern Review 2006)

World aviation fuel burn in 2000
by country of departure



Source:
AERO2K

The ACARE fuel target is a real challenge



Options for reducing fuel burn per passenger-km

The Bréguet range equation

Fuel burn per tonne-kilometre

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

where

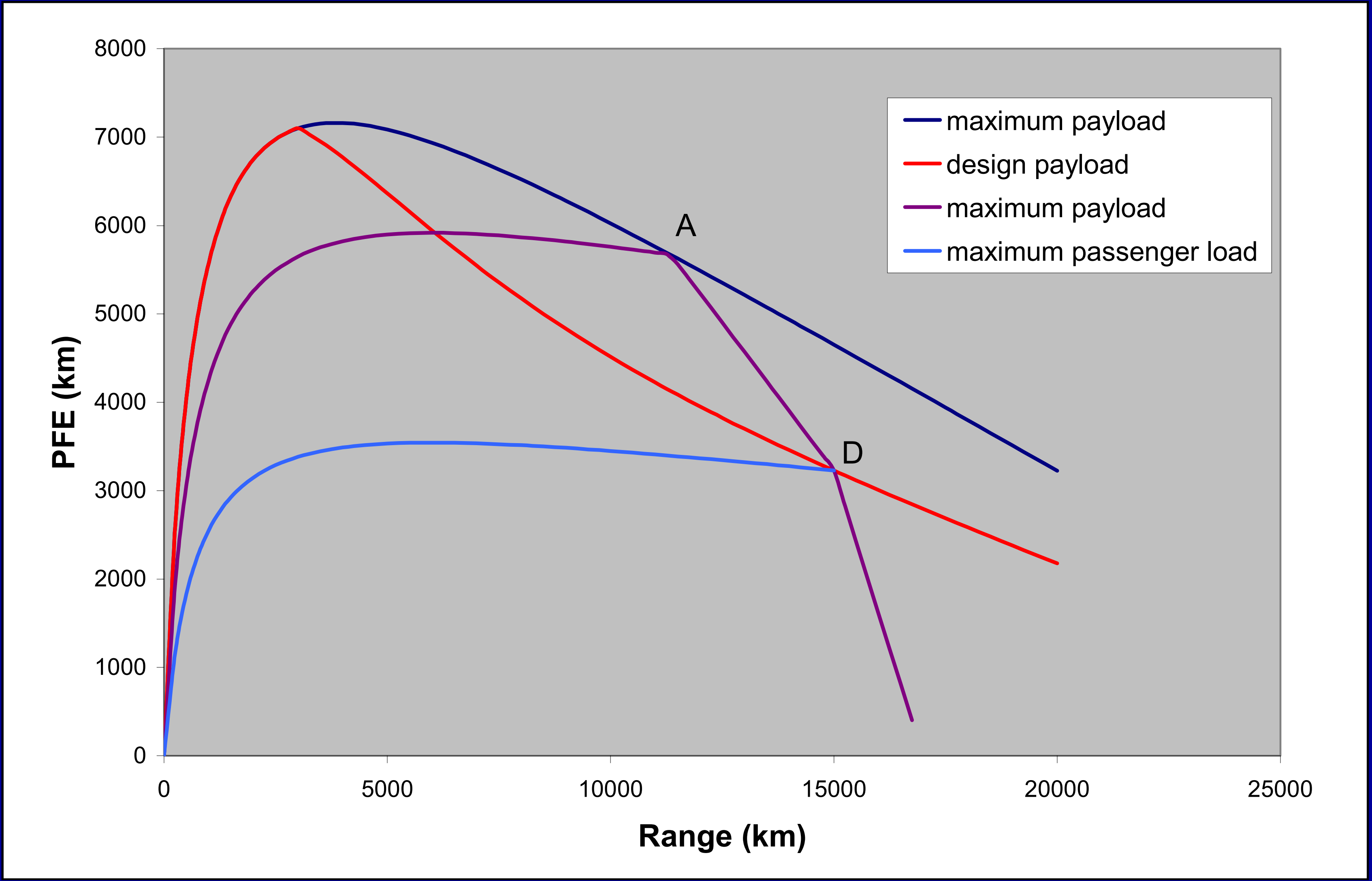
$X = H\eta L/D$

H = calorific value of fuel

η = overall propulsion efficiency

L/D = lift/drag ratio

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



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

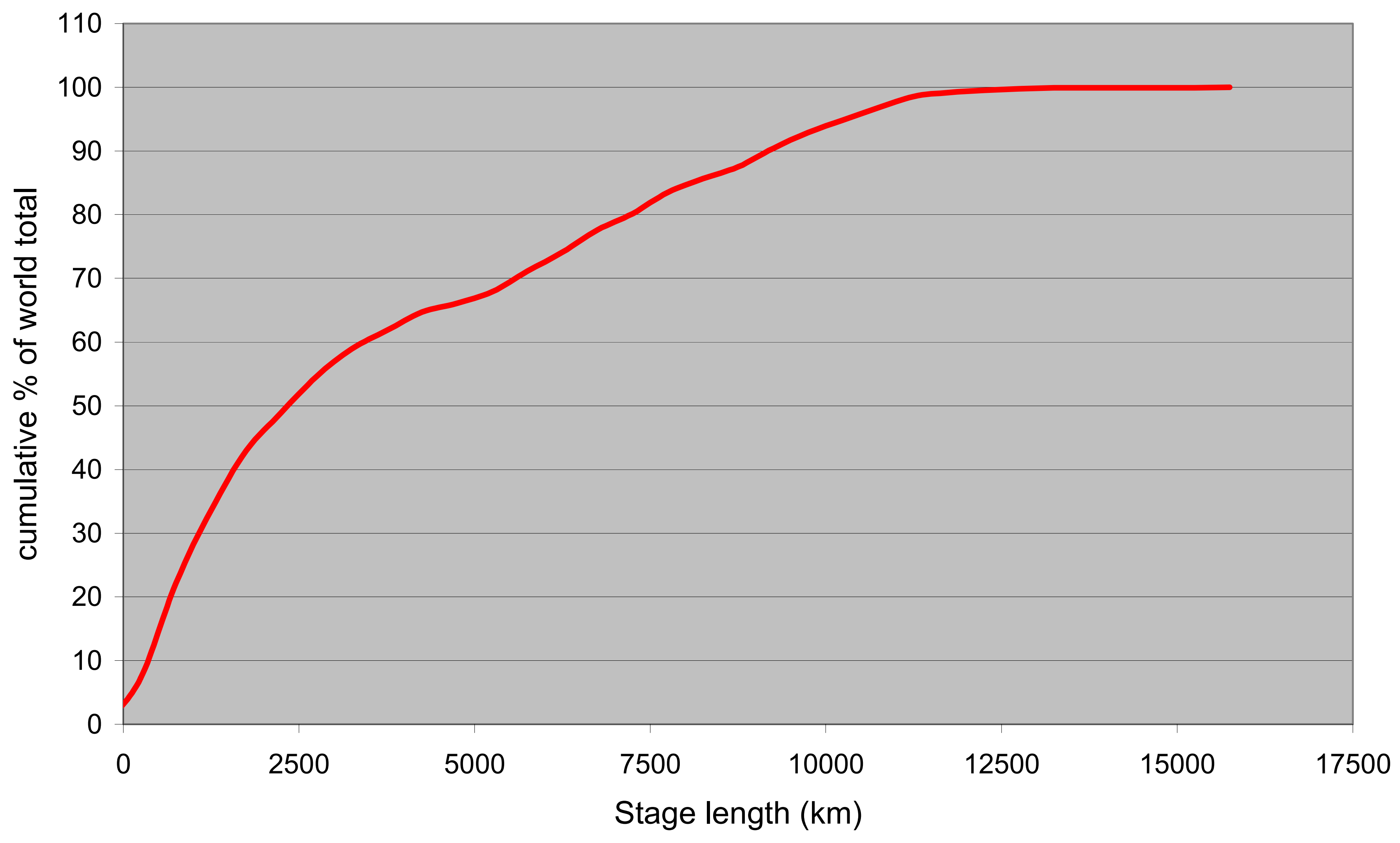
Design range km	Payload tonne	Mission fuel tonne	Reserve fuel tonne	Max TOW tonne	OEW tonne	Fuel for 15,000km tonne
15,000	25.9	120.3	13.5	300.0	140.3	120.3
5,000	25.9	20.4	5.4	120.0	68.4	61.1

Travelling 15,000km in one hop or three

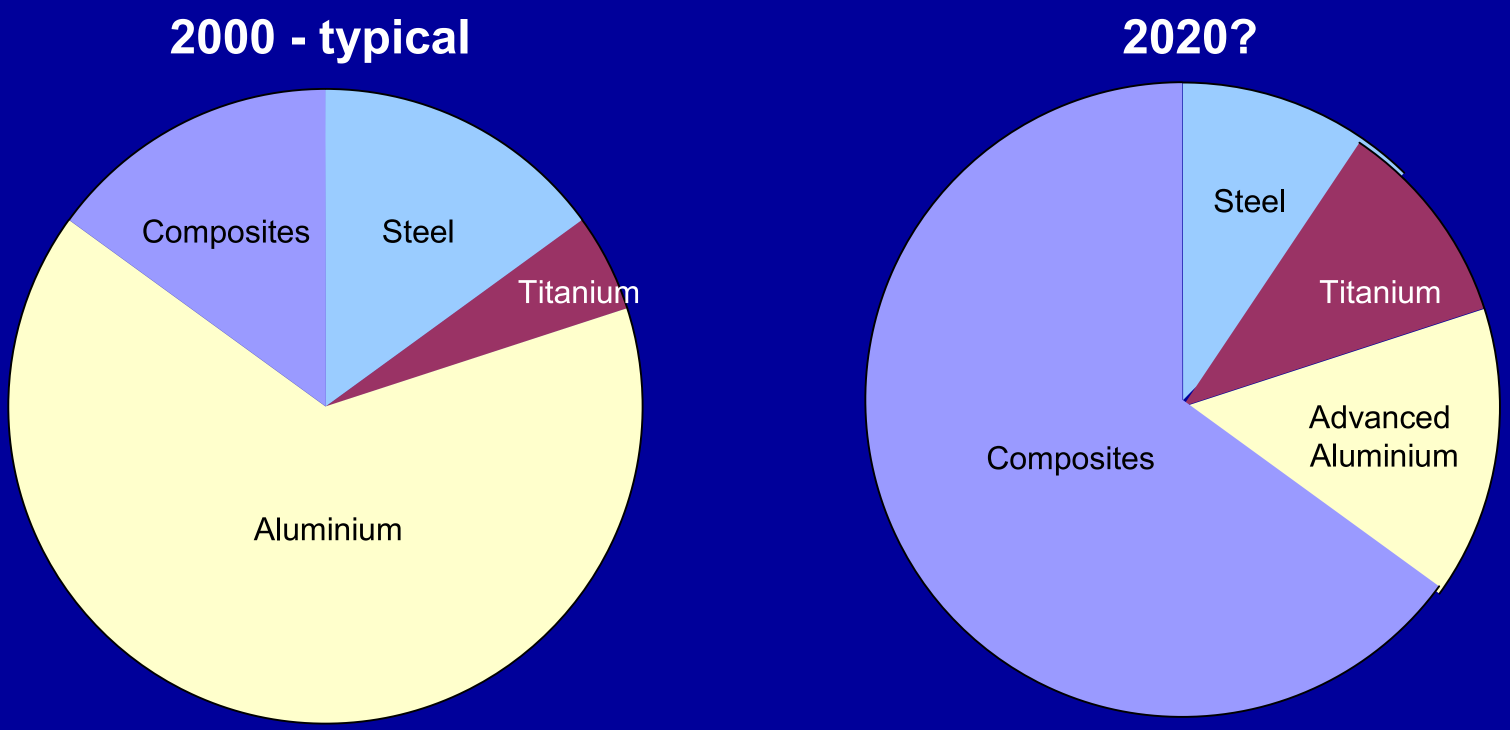
Revision of earlier GBD estimates:

Correction published in August 2006 issue of the Aeronautical Journal

Cumulative world fuel burn versus stage length



Reducing fuel burn – reducing weight by use of advanced structural materials



potential to reduce structure weight by ~ 15% plus

Trend well established with Boeing 787 and Airbus A350 projects

Reducing fuel burn by reducing ratio of empty weight to payload

- Increased use of CFRP and other light structural materials
- More efficient structural design – advances in design methods, flying wing for larger aircraft
- Design parameters –cruise Mach number, design range, regulatory margins
- Design and operational measures to increase passenger payload (cabin dimensions, seating layout, load factors, etc)

Options for reducing fuel burn per passenger-km

The Bréguet range equation

Fuel burn per tonne-kilometre

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

where

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

Reducing fuel burn by increasing propulsion efficiency

Overall propulsion efficiency

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

where η_{therm} = thermal efficiency

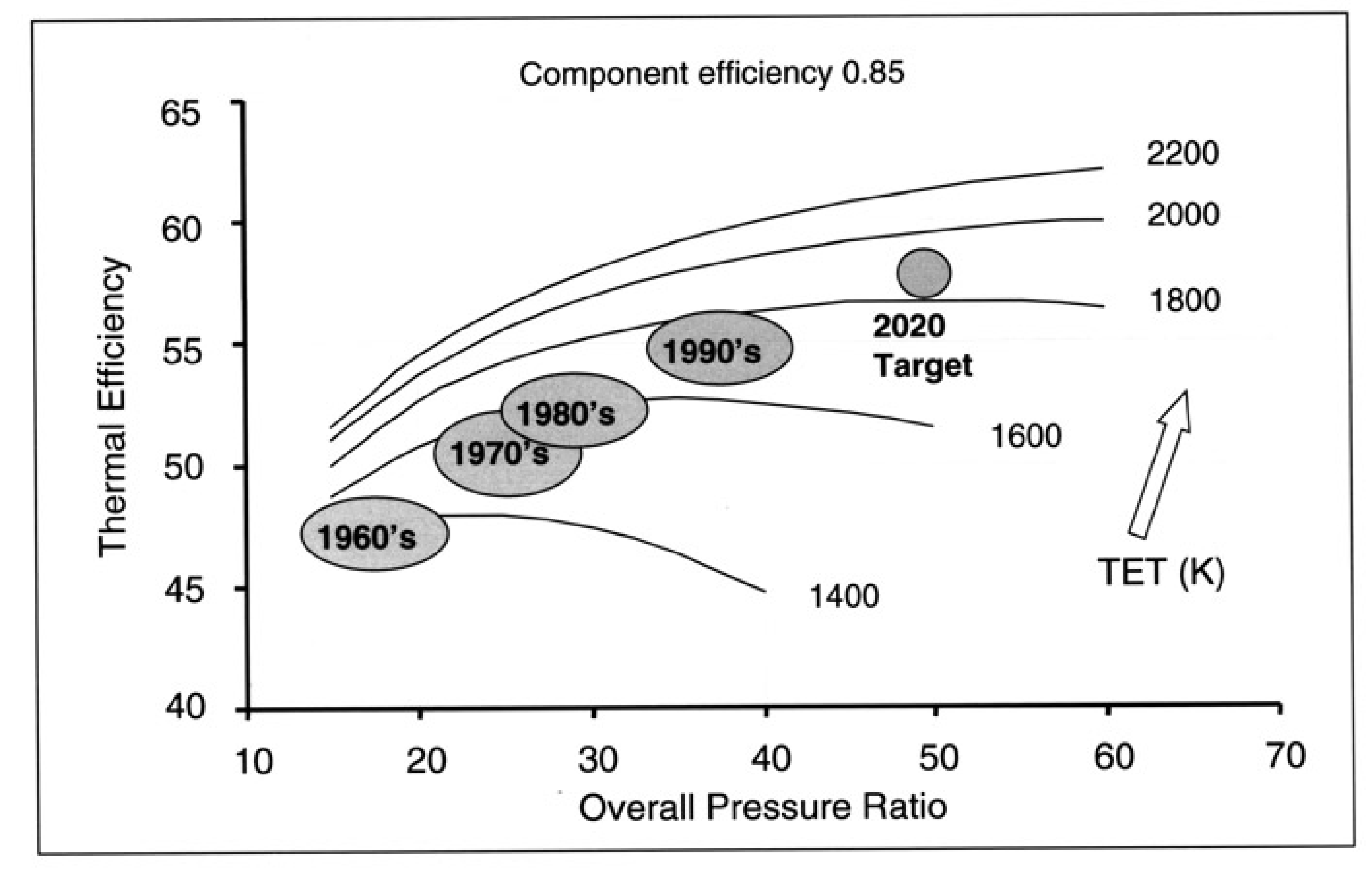
η_{trans} = transfer efficiency

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

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

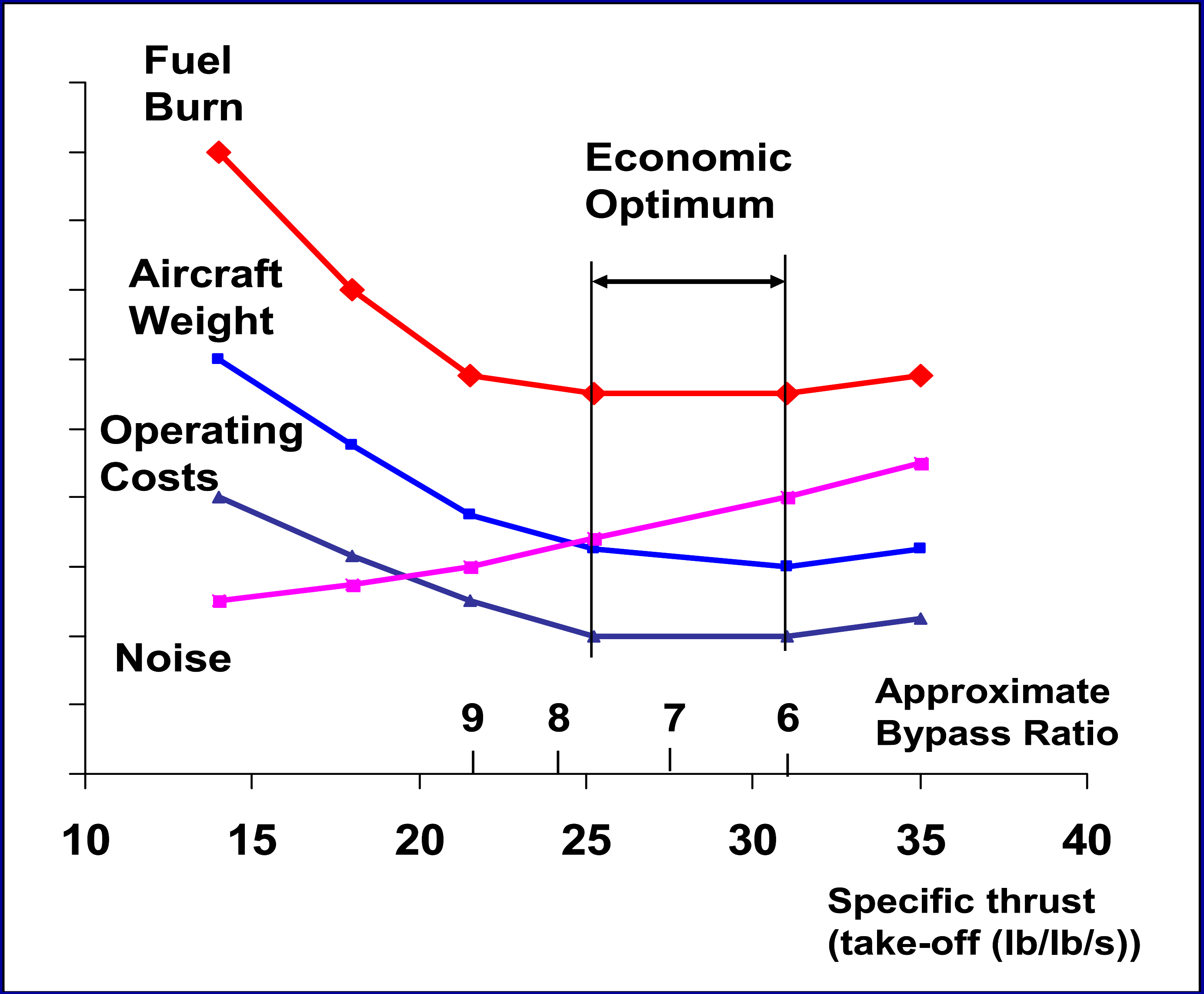
where V is flight velocity and Th_S is specific thrust

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



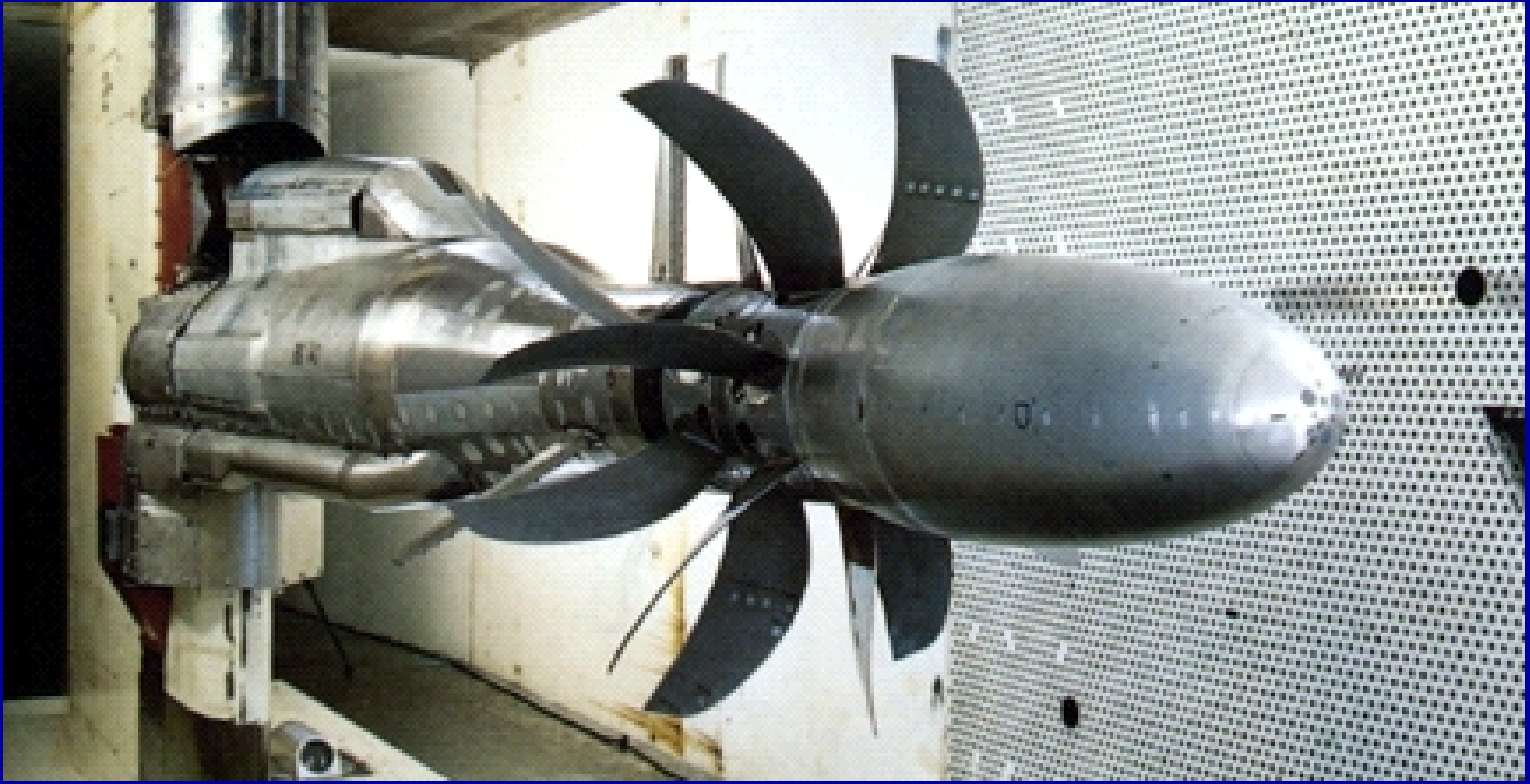
Source Rolls-Royce

Variation of turbofan-powered aircraft characteristics with engine specific thrust



Source Rolls-Royce

Eliminating nacelle weight and drag – an advanced open rotor



Source Aircraft Research Association

Turboprop Turnabout

Regional airlines rediscover the good economics of operating fuel-efficient propjets

Turboprop-powered aircraft, the most fuel-efficient and low-cost tool in regional manufacturers' arsenal, are making a comeback.

Bombardier, ATR, Saab Leasing, Raytheon and BAE Systems each confirm a surge of acquisitions and a scarcity of available used turboprop aircraft. The aircraft are being selected for operations in short-haul markets where their economics cannot be beat.

Fuel at $1.50 and more per gallon is the catalyst reviving demand for these aircraft. In the tight-squeeze cost zone of the 200/300/400-mi. flight segment, the high price of fuel is making the small jet the hands-down first choice of executives and perhaps even cost-conscious passengers.

"Turboprops are a hedge against the high fuel costs," says Steven A. Ridolfi, president of Bombardier Regional Aircraft. Adds Michael Magnusson, president/CEO of Saab Aircraft Leasing, "It's very hard to disregard the economics of turboprops when you are paying $1.50 a gallon." Comair President Fred Buttrell observes turboprops should not be counted out. In the short-haul segment, they use "30-40% less gas."

The turboprop revival served as a sideshow at last week's

BOMBARDIER AEROSPACE

Austrian arrows Bombardier Q400 (shown here) is one of 40 Q series aircraft ordered by the former Tyrolean Airways.

Maximising lift-to-drag ratio in cruise

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

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

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

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

Reducing fuel burn by increasing L/D

- Increase span
  - Increasing span increases wing weight. Stronger lightweight materials and/or reduced Flight Mach No. could allow re-optimisation.
- Reduce vortex drag factor κ
  - Very limited scope for improvement.
- Reduce zero lift drag area S_{DO}
  - Limited possibilities for today’s configurations with fully turbulent boundary layers. (eg riblets and artificial stability)
  - Radical solutions have high potential

Reducing zero-lift drag area S_{DO}

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

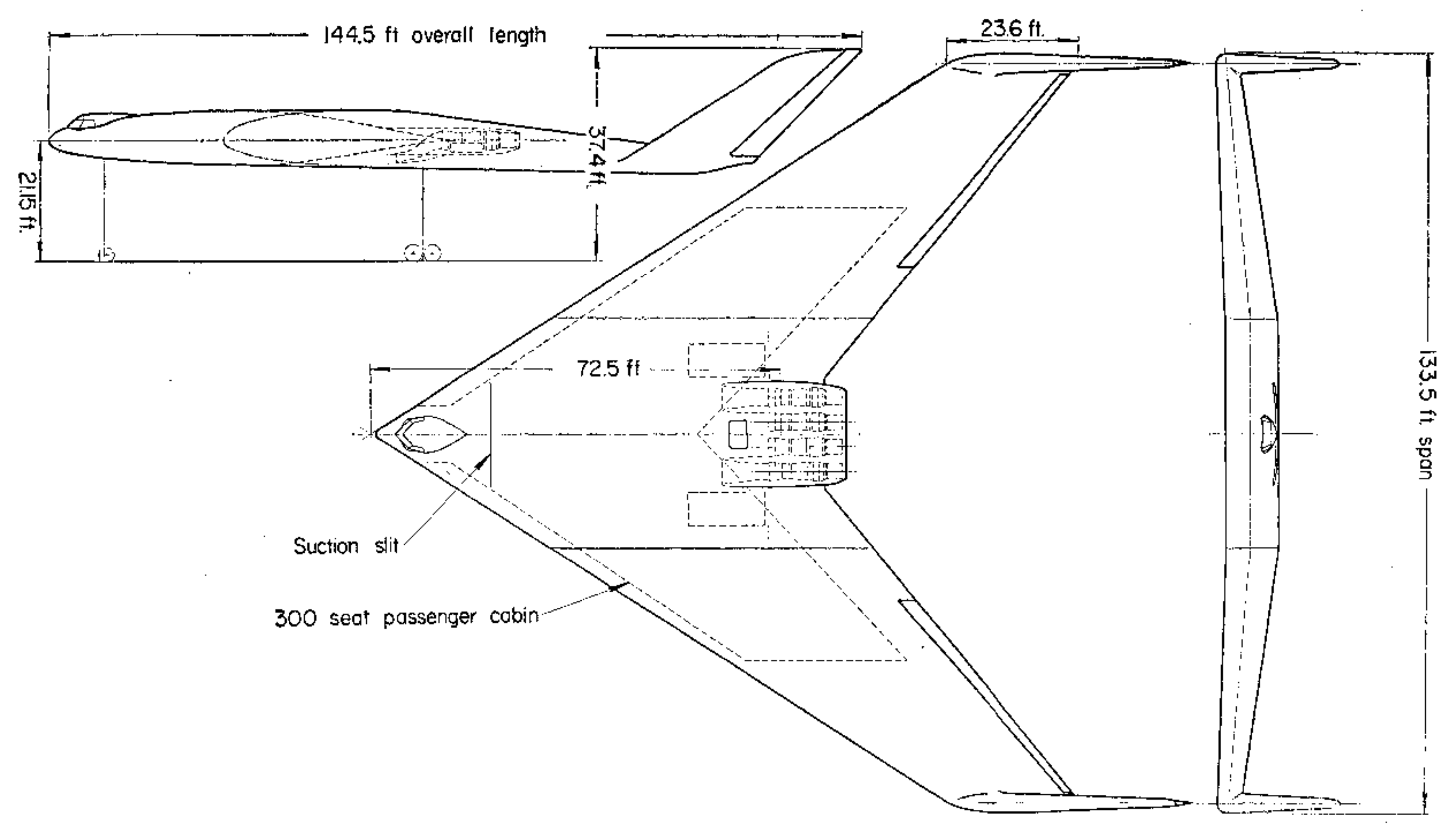
(See discussion of the physics of laminar flow control in the August 2006 issue of The (RAeS) Aeronautical Journal)

Laminar Flow Wing

A320 - Hybrid Laminar Flow Fin

- Flight trials successfully completed
- Up to 50% chord laminarised
- Better than anticipated tolerance to external environment

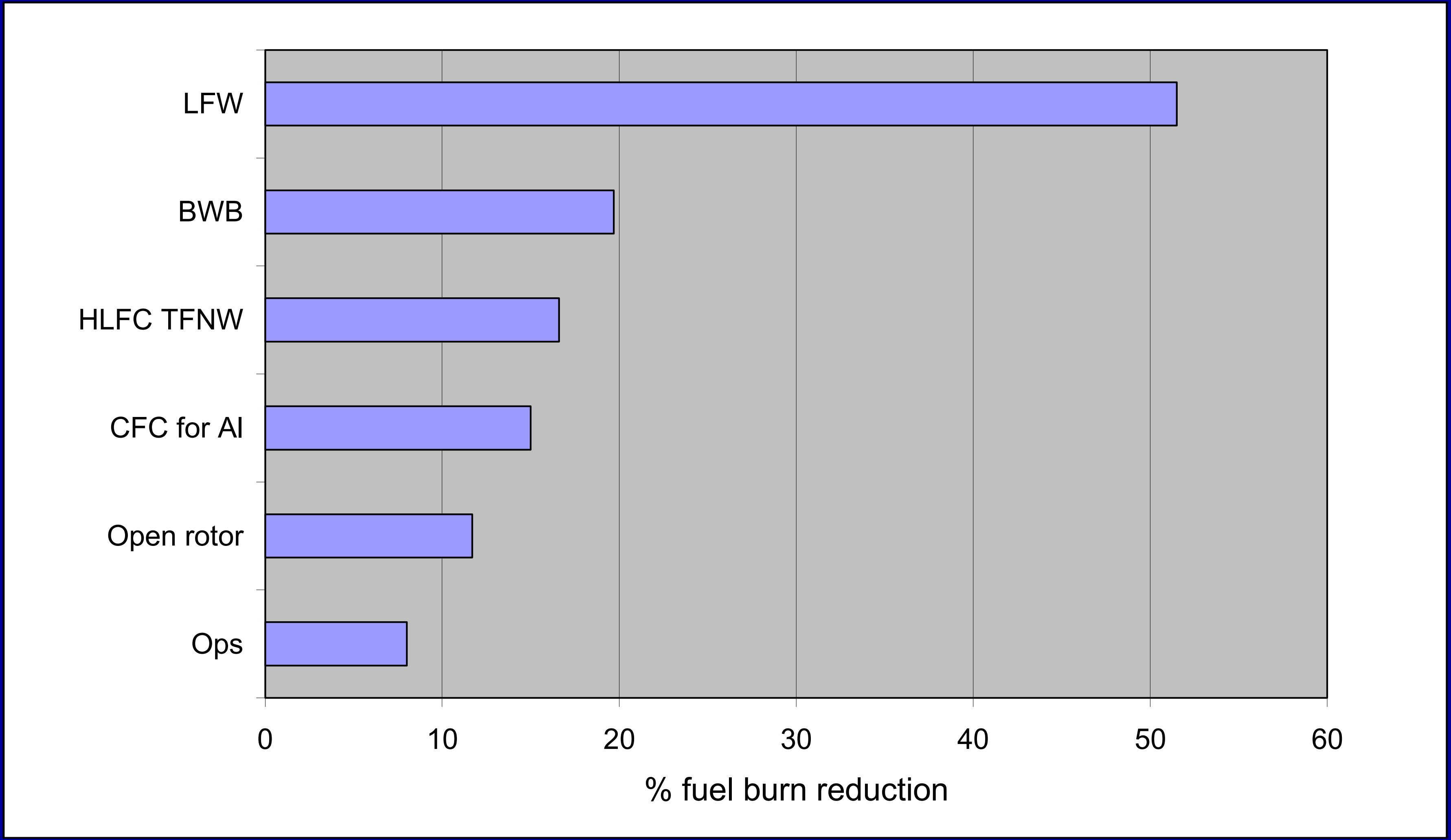
Handley-Page projected 300-seat laminar flow airliner (1961)



Reducing fuel burn by operational changes

- More direct no-delay optimum routings (improvements in ATM)
- Ground Taxiing Management
- Multi-stage long-distance travel?
- Air-to-air refuelling??
- Formation flying??

Potential reductions in fuel burn: GBD 2005 report



Fuels for Aviation

- Kerosene is expected to dominate for several decades
- “Biomass” carbon-neutral kerosene could become cost effective at a sustained oil price above $60 per barrel. A NASA scientist has promoted “Saline Aquaculture” to use desert regions and preserve water resources.
- Cryogenic Hydrogen is a long term possibility, but is only an energy “Carrier”! (water vapour and NOx emissions remain)

Where do we go from here?

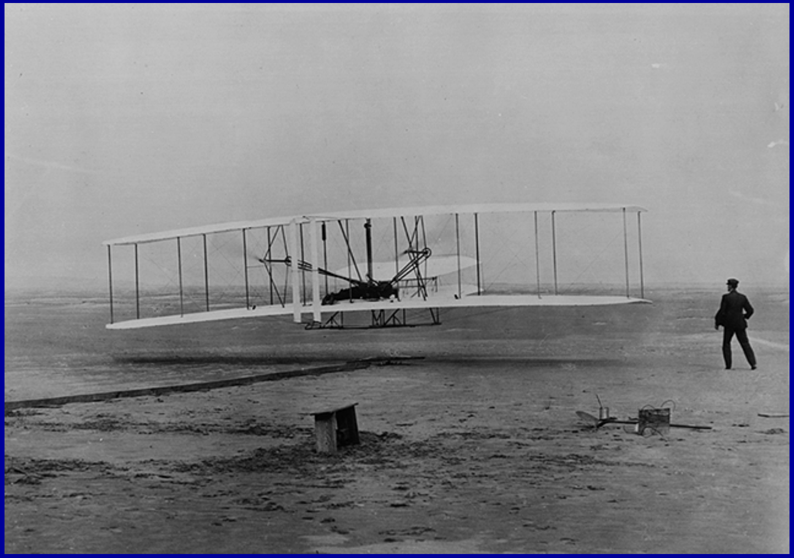
- Noise and local air quality

  ICAO regulations are in place and will continue to be tightened in line with technical progress, but only when the cost to the operators is acceptable. Local regulations at important destinations are likely to be the main drivers of change.

- Climate change

  ICAO is currently considering this but any internationally agreed regulation is likely to be some way off. Limits on EI_{NOx} at altitude and the introduction of worldwide emissions trading are under consideration. Local action at an important destination (such as Europe) may again be the main driver of change (as well as oil price).

An appropriate regulatory framework will be essential to make change happen.



1903

1947

2005

Supersonic Transport M = 2.2 – 2.4


AIRBUS
A350-800
A350

The Proactive Green Aircraft of the EC NACRE project

Source Airbus