CRYOPLANE

Flugzeuge mit Wasserstoffantrieb

Dr. Reinhard Faaß
Airbus Deutschland GmbH

Hamburg, 06. Dezember 2001

Overview

Why Work on Hydrogen Fuelled Aircraft?

Short History

Technology - Status and Challenges

Safety Aspects

Environmental Aspects

The Path to the Transition

The Need to Act Now - Decisions Requested

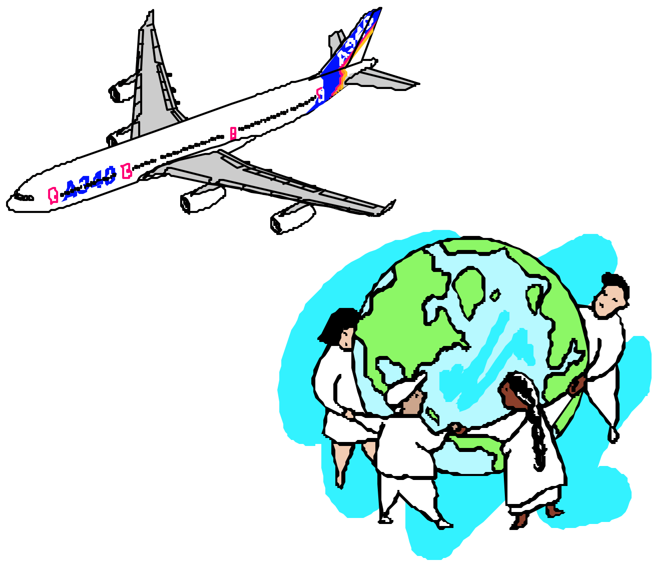
Why Work on Hydrogen Fuelled Aircraft?

Prepared HG Klug September 2001

The Vision

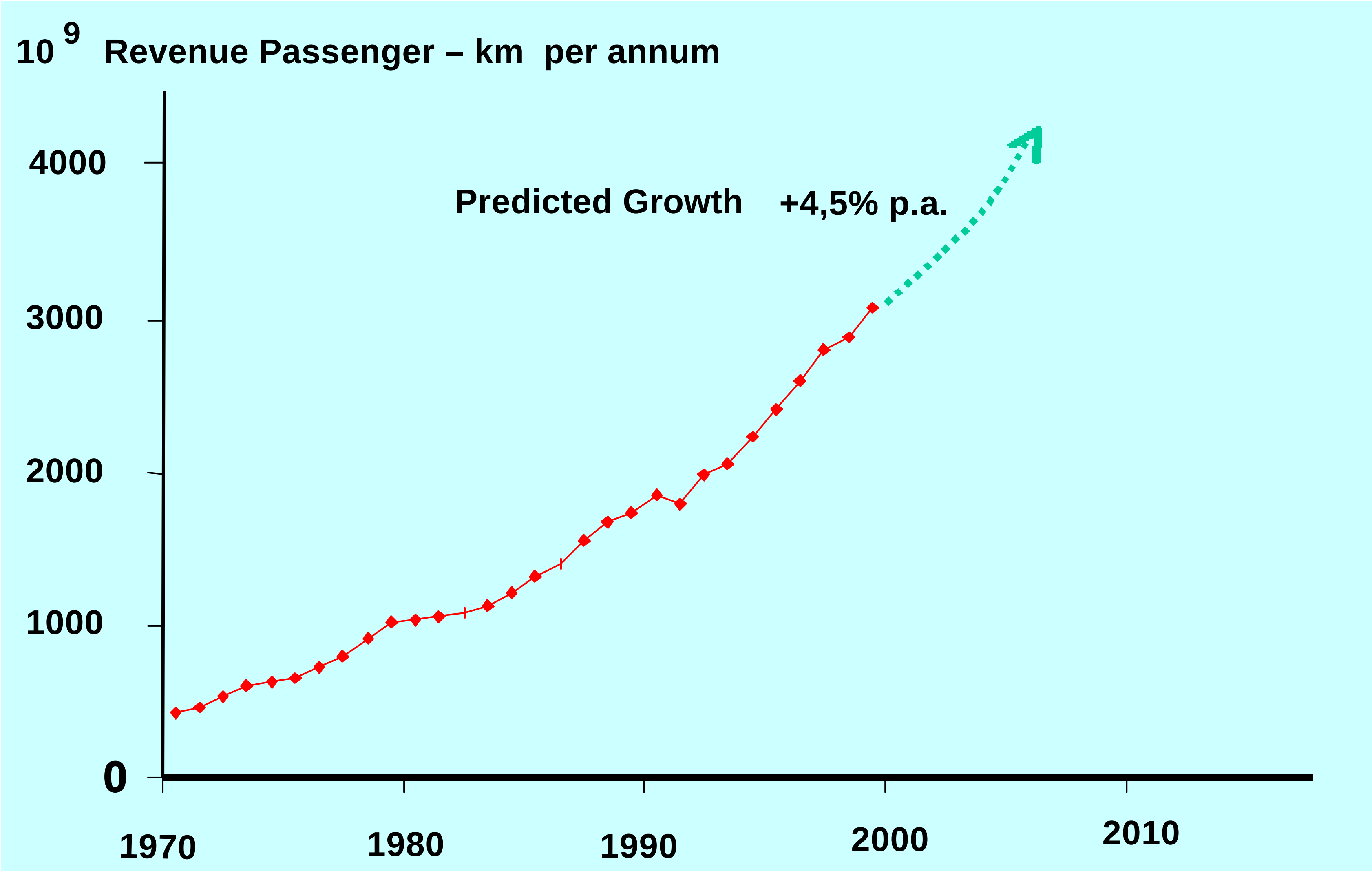
The vision is:

To achieve long term continuing growth of civil aviation until every man and woman on earth can fly as often and as far as they want, and when doing so, do no harm to other human beings , or to the environment.



Civil Aviation Growth

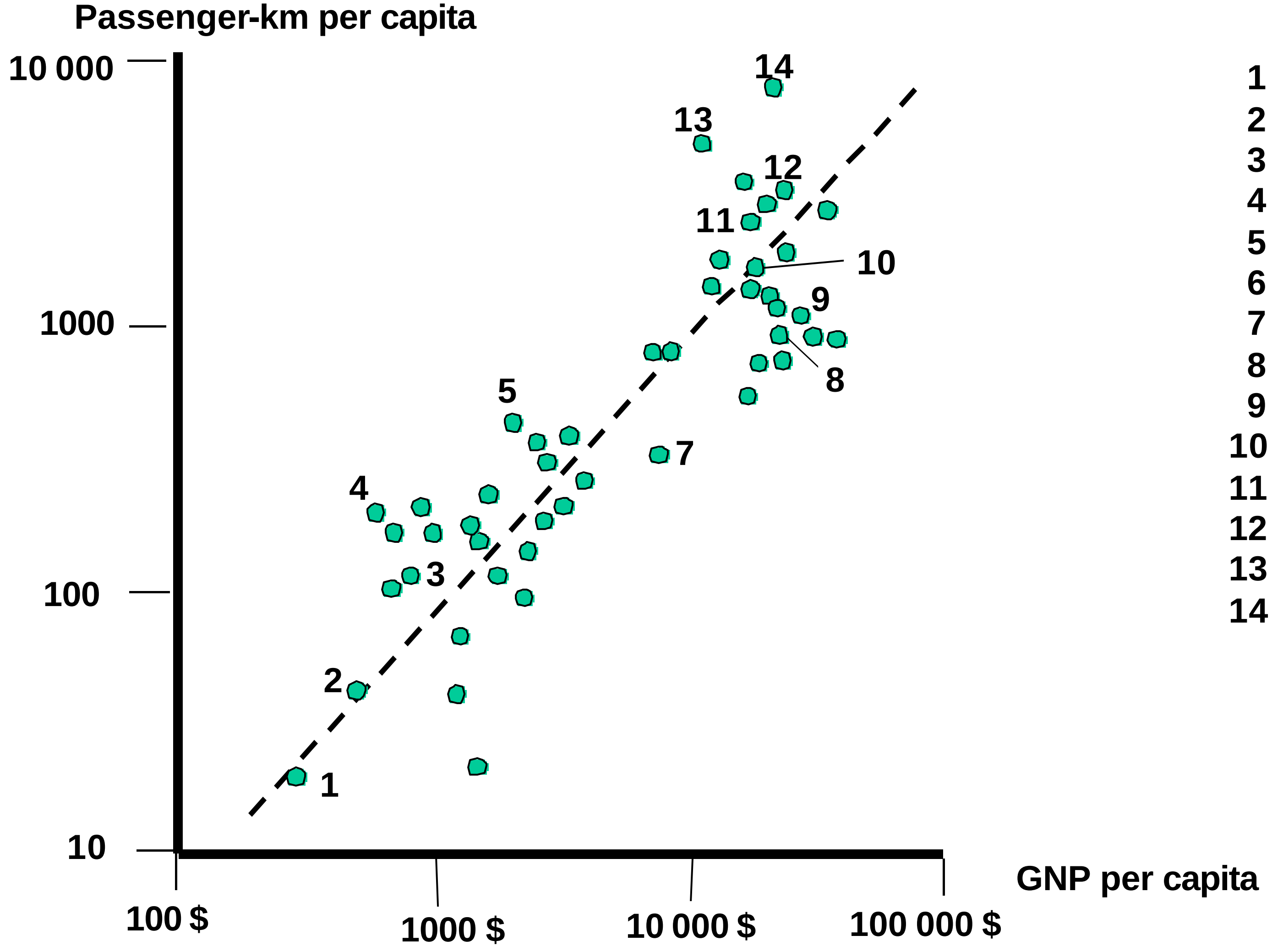
Without UdSSR/CIS



Source: EADS Airbus Dep. LSM Prepared HG Klug 2000

Air Traffic - Relationship to Economic Wealth

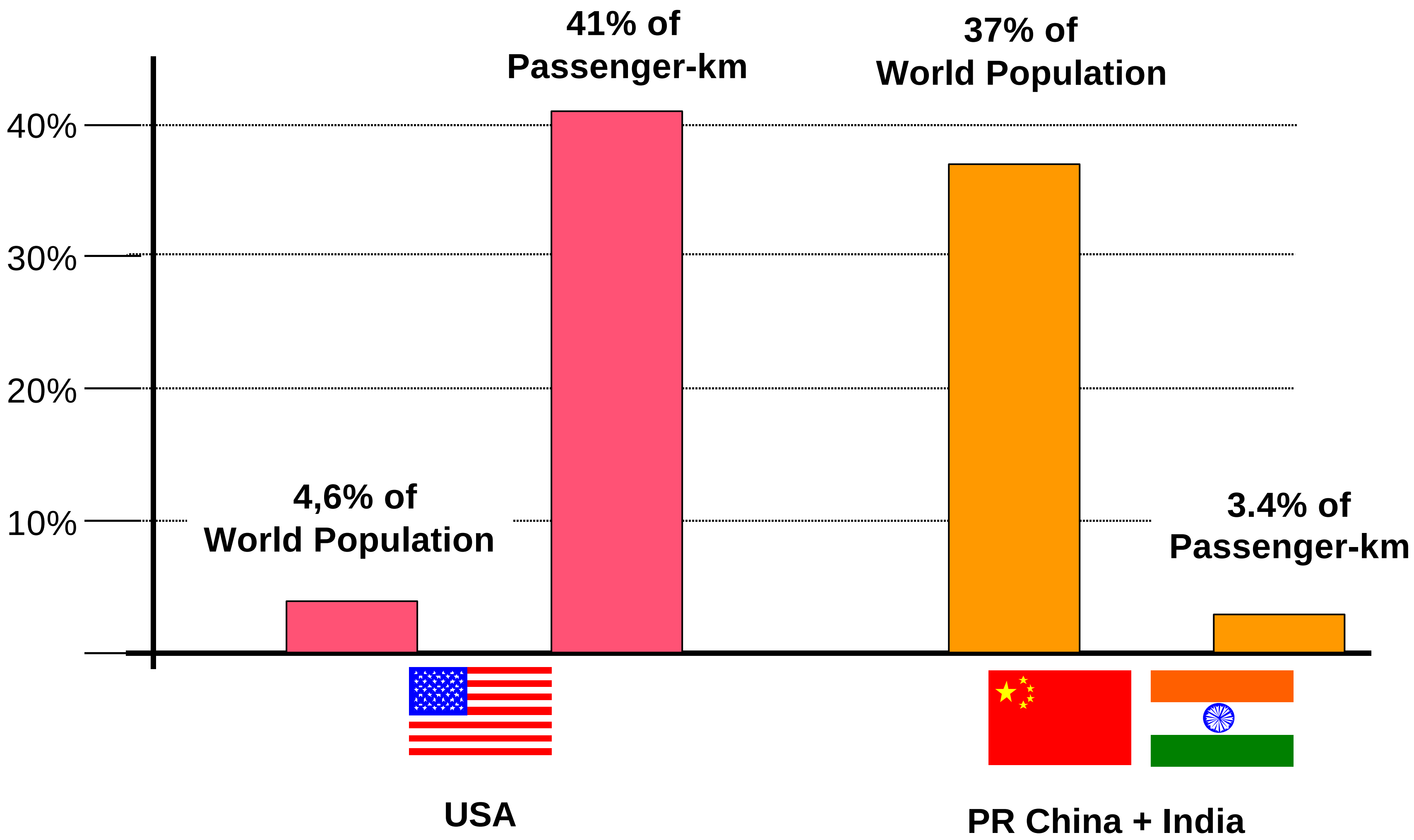
Status 1994



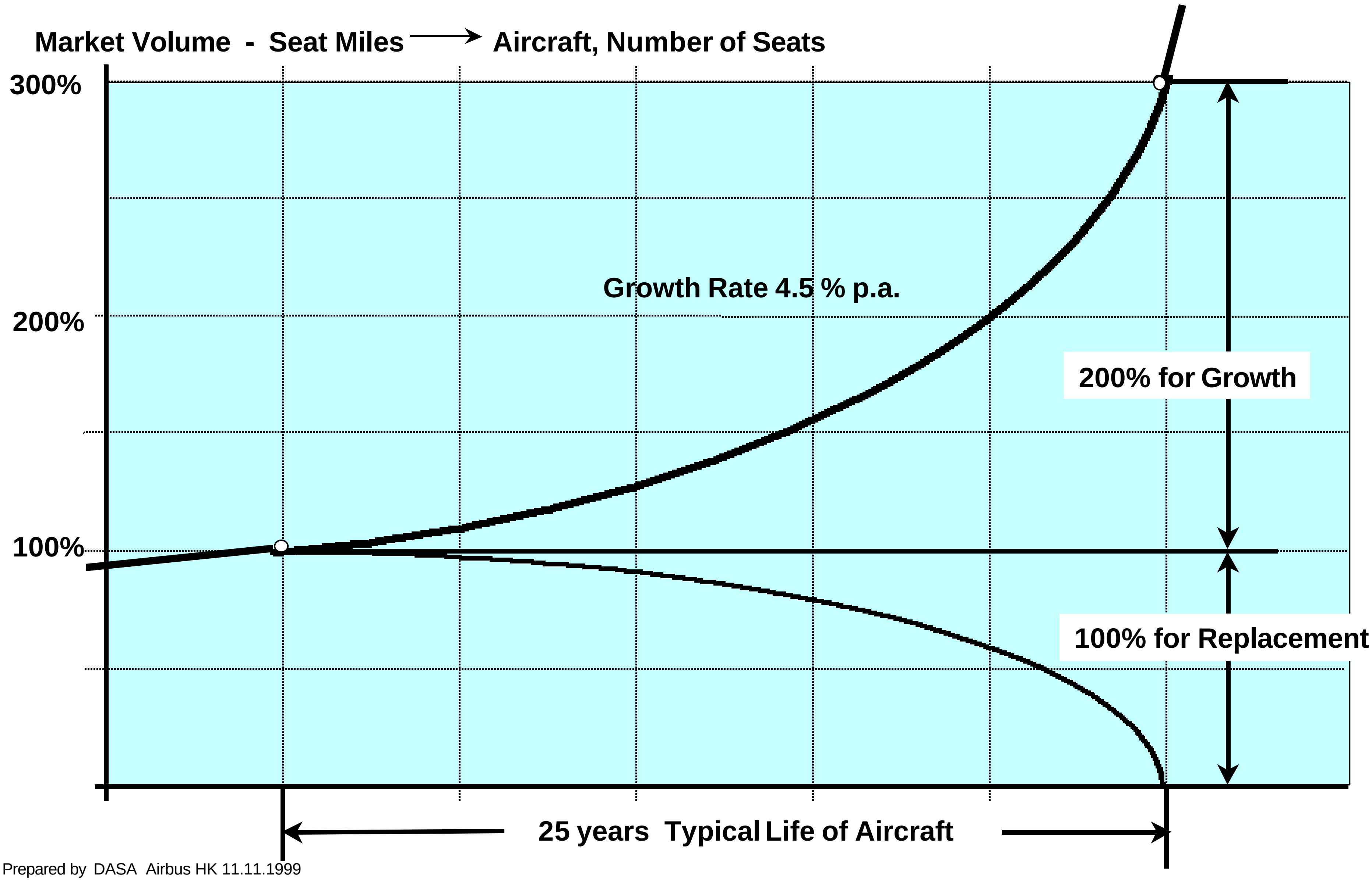
1 India
2 PR China
3 Indonesia
4 Sri Lanka
5 Thailand
6 Brazil
7 Argentina
8 Germany
9 Denmark
10 Canada
11 Great Britain
12 USA
13 New Zealand
14 Iceland

Air Traffic and Population

Status: 1994

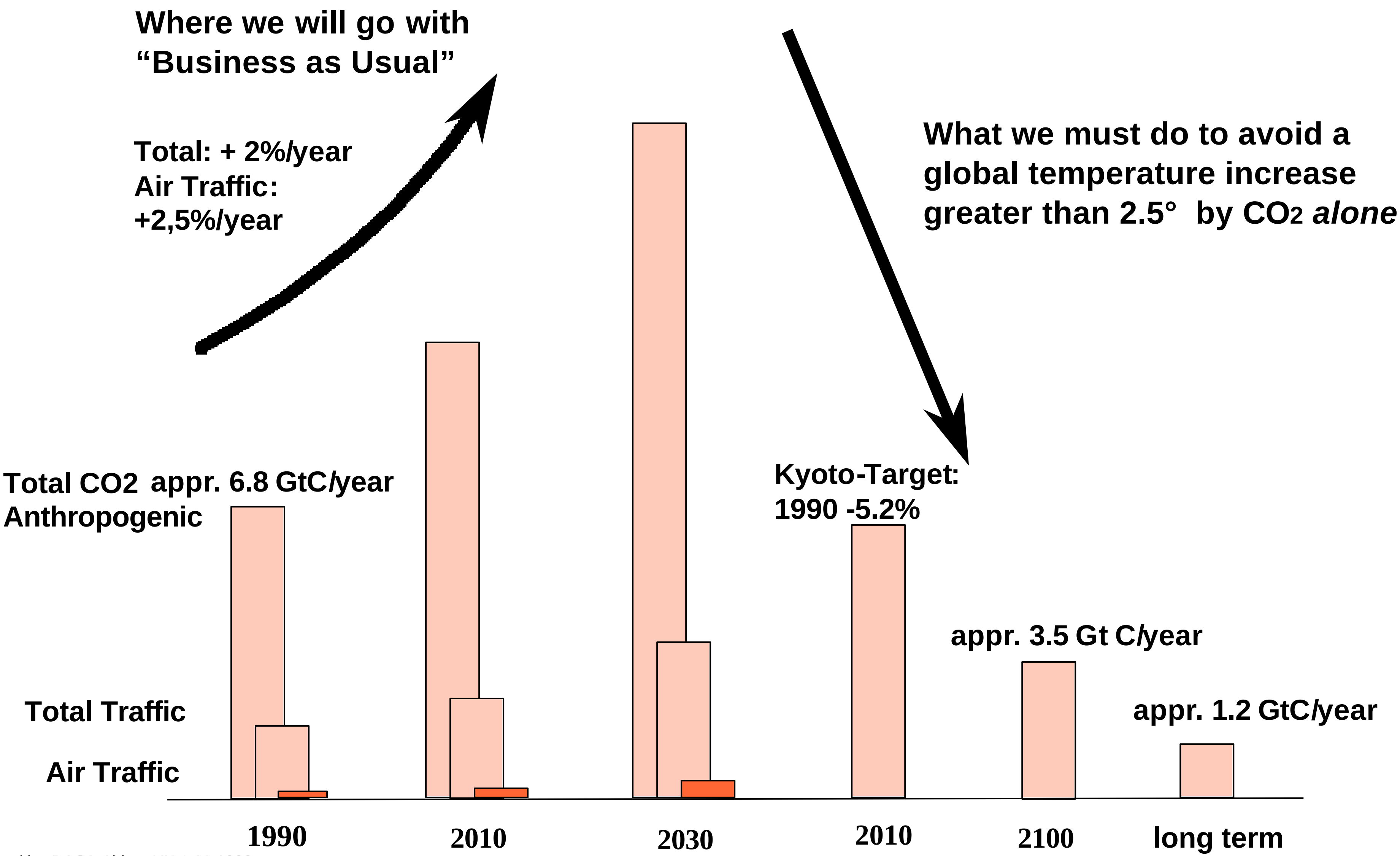


Growth and Replacement



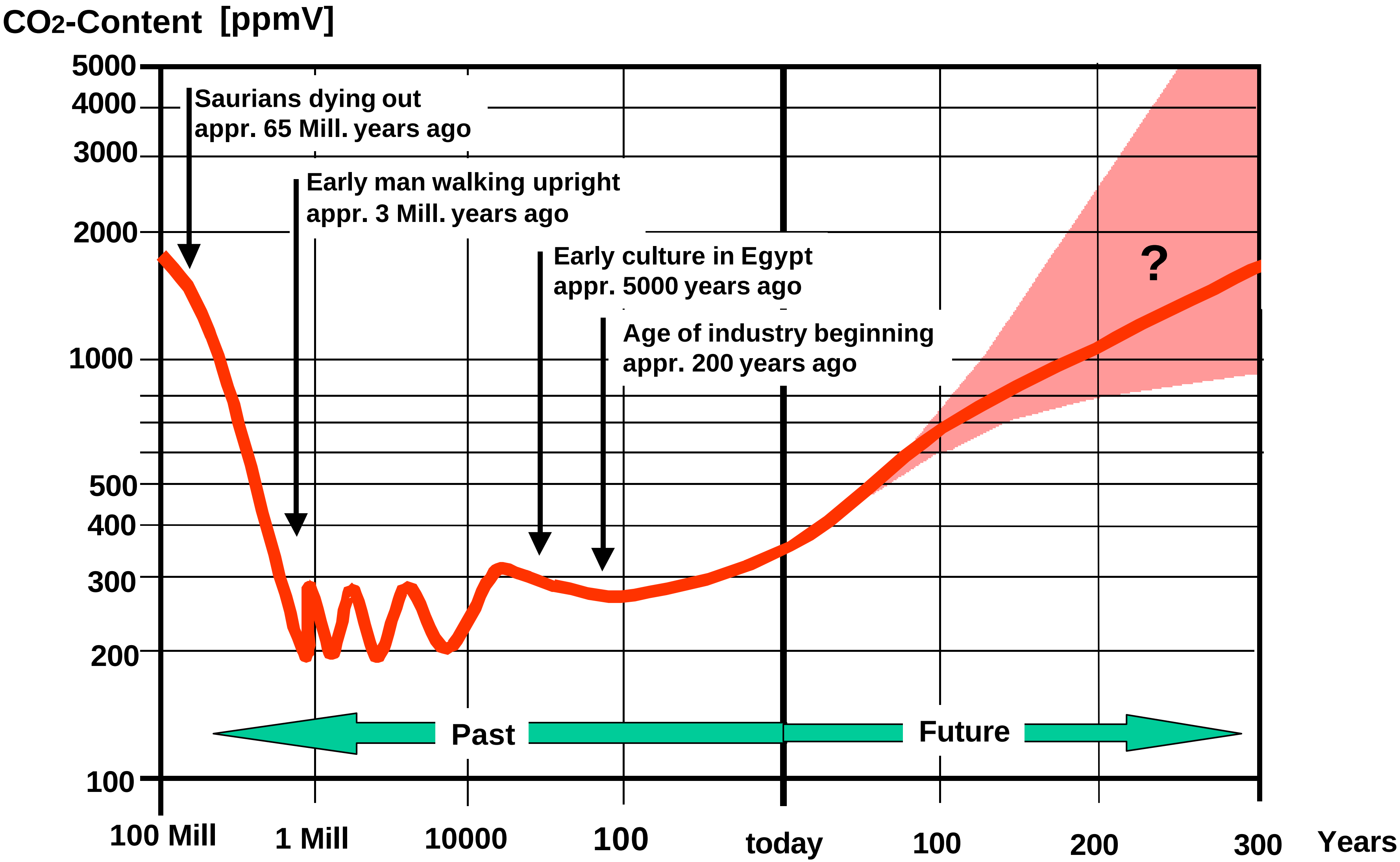
Prepared by DASA Airbus HK 11.11.1999

CO_2 Emissions - Trends and Targets



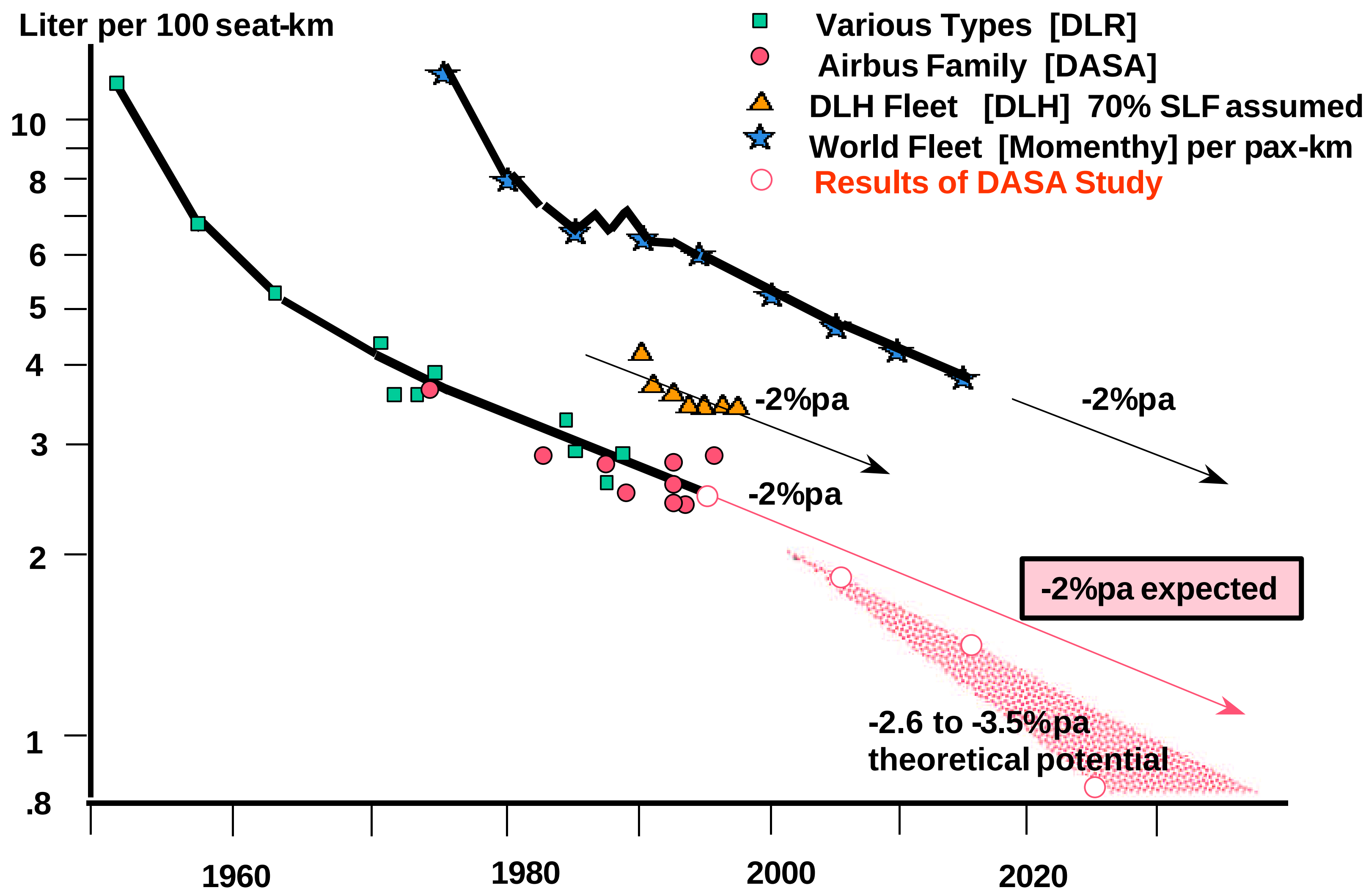
Prepared by DASA Airbus HK 1.11.1999

CO_2 – Content of Atmosphere - Past and Future



Source: GEO Prepared H.Klug 20.6.2000

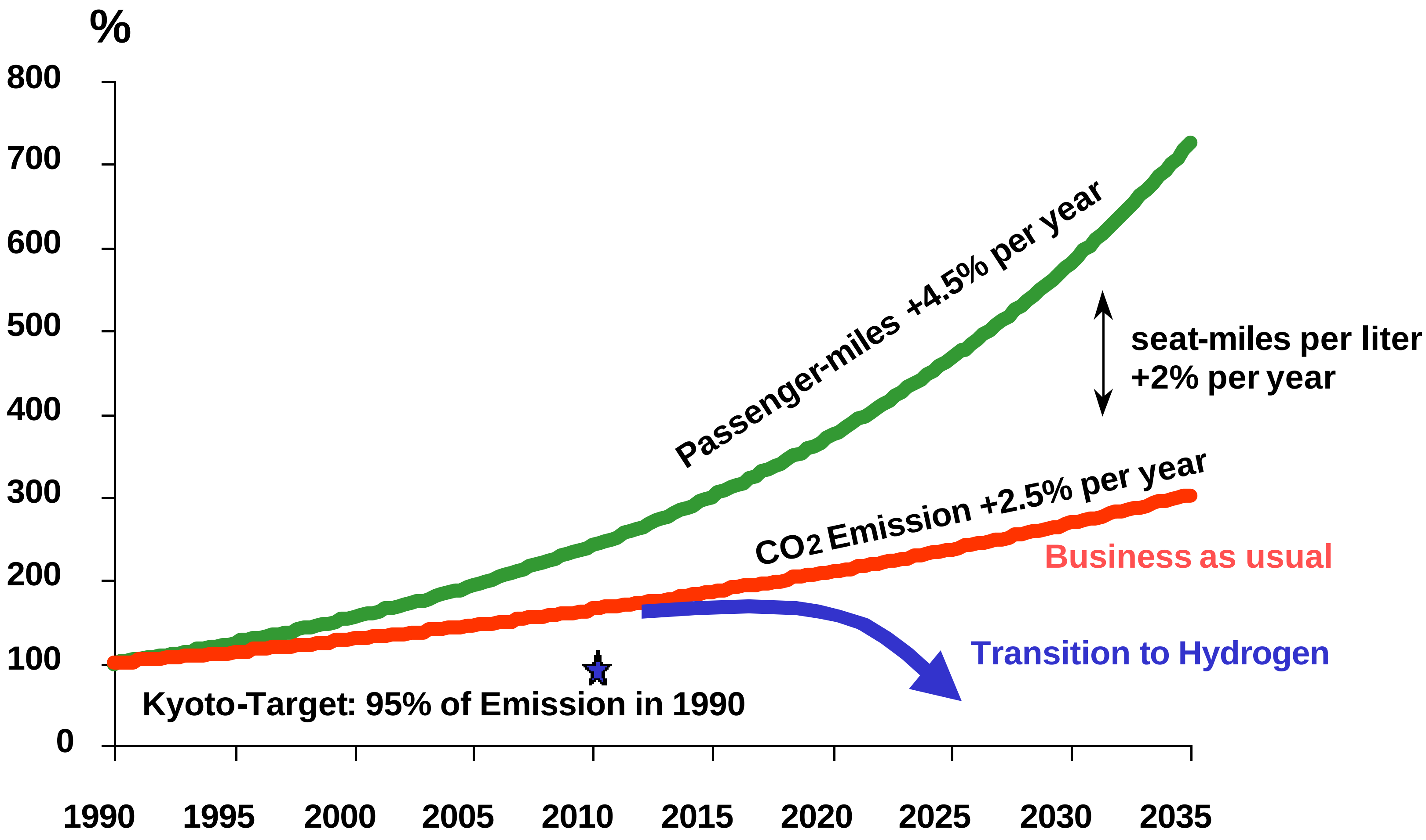
Progress in Fuel Efficiency



Prepared/Revised by DASA Airbus HK 7.2.2000

Air Traffic; CO_2 Trend and Target

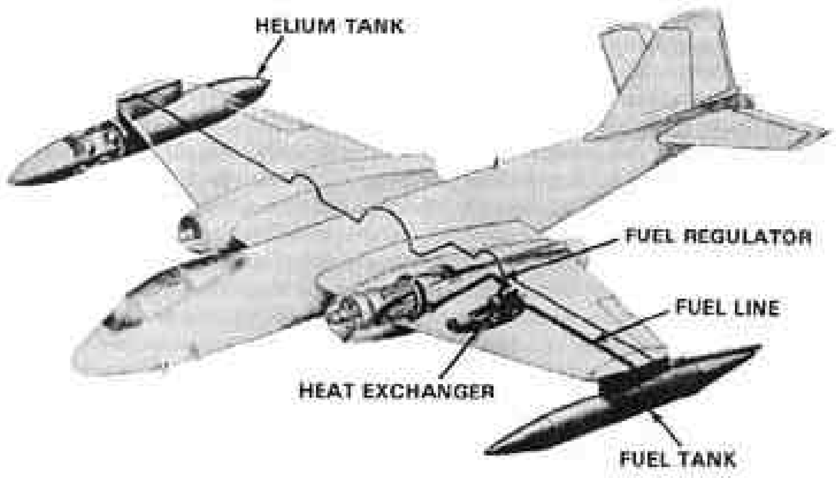
Specific Fuel Consumption liter/seat-mile: Improvement 2% per year



Prepared HG Klug September 2001

Short History

Hydrogen in Aviation - History



1937 Dr. v. Ohain rig-tests He-S-2 experimental turbojet engine on hydrogen

1955 Report of NACA -Lewis Flight Propulsion Laboratory on the potential of hydrogen

1957 US Air Force B 57 bomber flight tests

1950ies Lockheed studies on Mach 2.5 recon-naisance airplane

1970ies Studies by NASA Ames; Institute of Gas Technology; Linde/Union Carbide Corporation, Lockheed, and others; civil transport aircraft, safety aspects

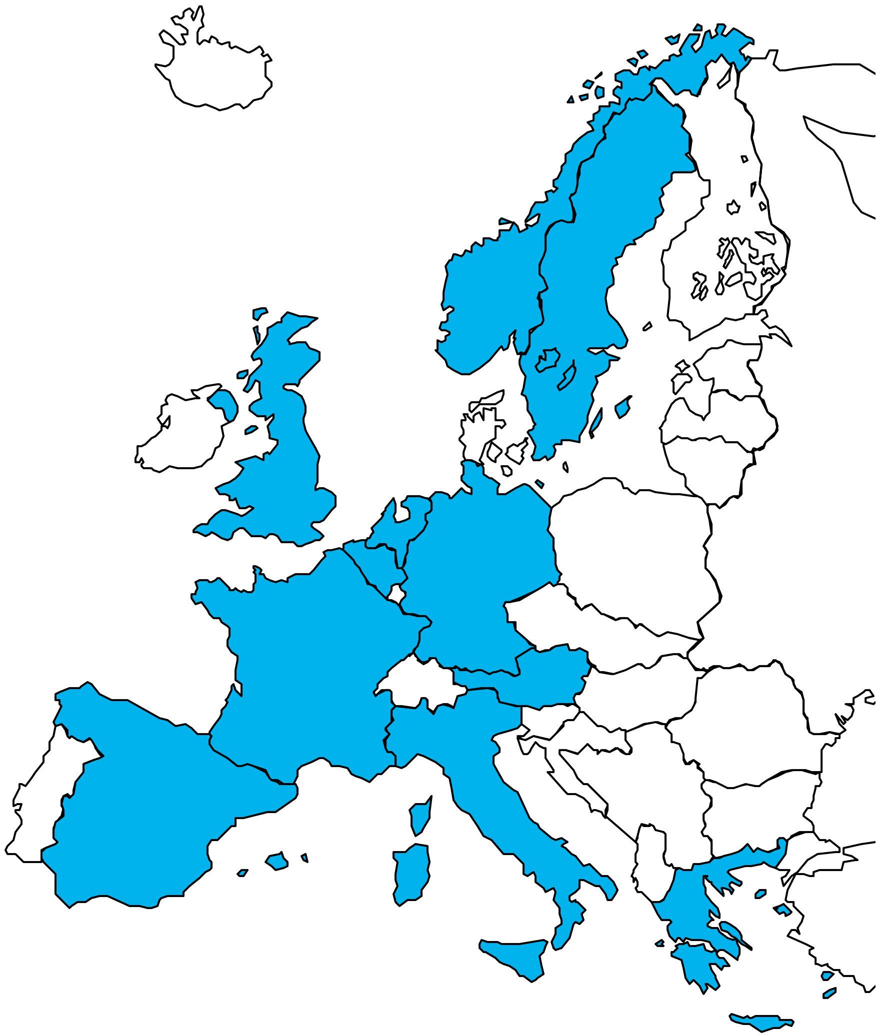
1988 First flight of Tupolev Tu 155 Laboratory aircraft; proves principal feasibility of transport aircaft flying on Liquid Hydrogen and Liquid Natural Gas, respectively (LNG is main interest of Russia)

1990 Daniel Brewer publishes "Hydrogen Aircraft Technology"

European Efforts in the 1990ies

1990	German-Russian Cooperation (DASA, Tupolev, Kuznetsov and others) initiated
1990/93	German-Russian “Feasibility Study” - CRYOPLANE based on A310 defined
1992/96	EQHHPP Combustion Chamber Tests
1994/99	EU/INTAS Tank Tests(Tupolev, with DA and Air Liquide)
1994/99	APU Tests (FH Aachen, with DA and Allied Signal)
1995/98	German/Russian studies for Demonstrator Aircraft based on Do 328
1996/99	ISO/TC 197 WG4 “Airport Hydrogen Refueling Facility”
1998	Daimler Benz DASA Top Management orders Project Manager to initiate a European R&D Program ⟶ „System Analysis“

CRYOPLANE - System Analysis



Project within 5th Framework Program of European Commission, targeted at "Sustainable Growth".

Comprehensive Systems Analysis to provide decision basis for future technology development..

Covers Configuration, Systems & Components, Propulsion, Safety, Environmental Compatibility, Fuel Sources & Infrastructure, Transition

35 Partners from Industry, Research and Academia, from 11 European Countries.

Total volume 4.5 Million EURO, total effort planned 550 Person-months.

Total project time 24 months.

Start of project: 1.April 2000
Successful Midterm Review: 28./29.June 2001

See also: http://www.cryoplane.com

Technology - Status and Challenges

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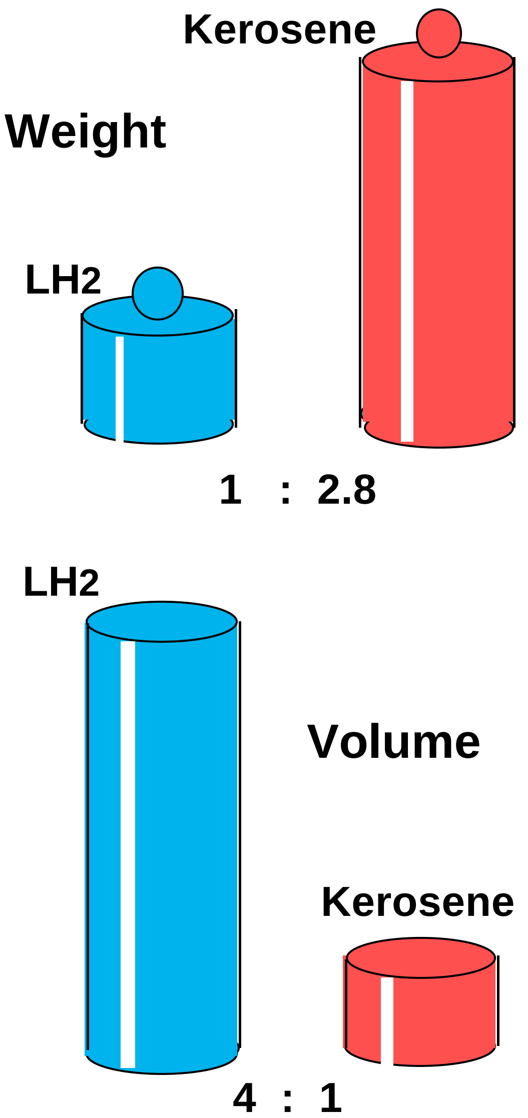
What is so Special about Hydrogen?

H2 CRYOPLANE

Fuel masses of same energy content



- Hydrogen production can be based upon every renewable energy used to produce electricity.
- Hydrogen can be produced by electrolysis of water - basically everywhere.
- Burning hydrogen produces water - the cycle is closed.
- Hydrogen offers a high energy content per mass, hence promises payload or range increase for aircraft.

But

- For aviation, hydrogen must be cooled down to the liquid state (LH_2, -253°C) for reasons of volume and weight of tanks.
- LH_2 needs
  - 4 times greater volume than kerosene
  - Very good insulation of tanks, pipes ....
  - Tanks under some differential pressure
  - Spherical or cylindrical tanks
  - New aircraft configuration

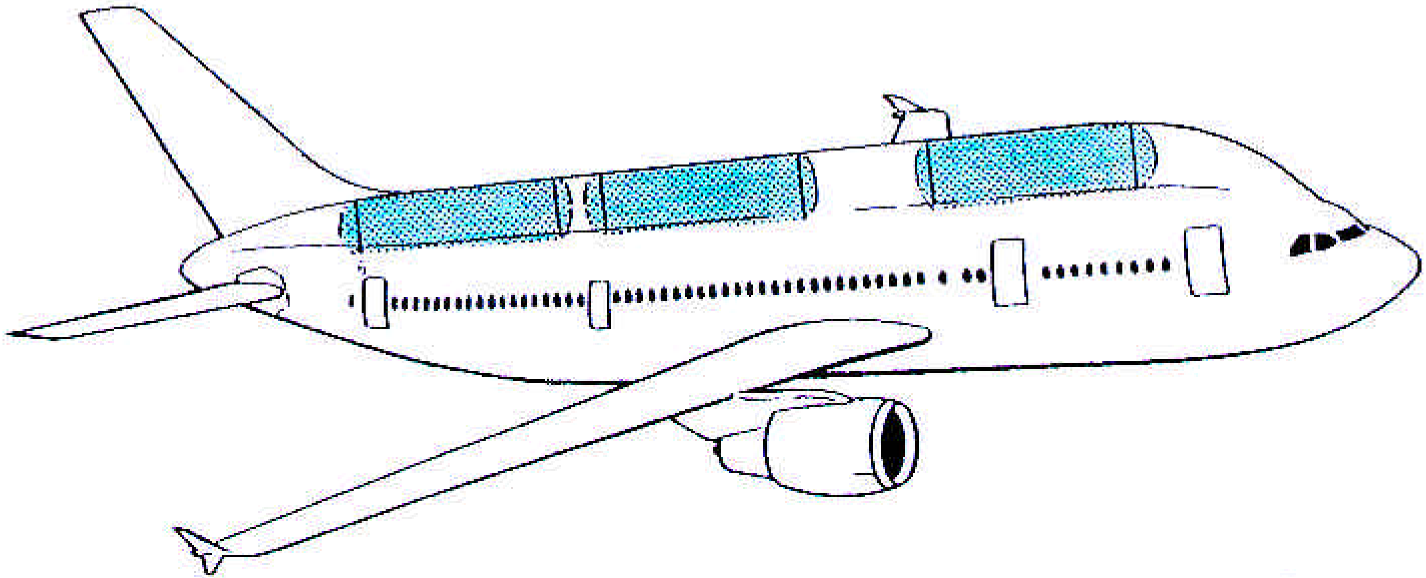
“Minimum Change” of Existing Aircraft

Systems

Fuel System: Tanks, Pipes, Valves, Pumps, Vents....
Fuel Control System : Sensors, Control Box....
Fire Protection :Sensors, Ventilation, Control Box...

Airframe

Tank support, local strenghtening fuselage, fairings
Fuselage stretch to accomodate increased payload
Strenghtening of wing structure



Powerplant

High Pressure Pump, Heat Exchanger,
Fuel Flow Control Valve, Combustion Chamber
Control Box, Oil Cooler

First conclusions from "System Analysis":

Practical configuration available for all categories of airliners

No "standard configuration" for all categories of airliners

Max TO Weight of long range aircraft some 15% smaller than for kerosene

Operating Weight Empty increased by some 20-25%

Specific energy consumption increased by 8-15%
(more wetted area, higher mean flight weight)

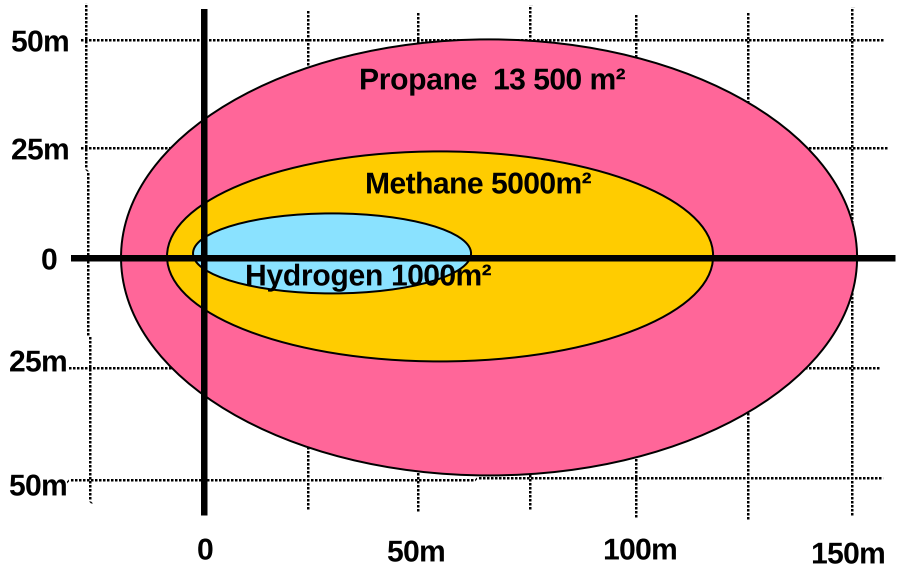
Advantages of unconventional configurations not obvious

Source: TU Delft et. al. - "System Analysis"

Safety Aspects

Danger Zones of Spilled Liquid Gases

Example: 3.3m³ Liquid Gas Spilled - 4m/sec Wind



Source: BAM

- **Psychological problem primarily.**
- **In free atmosphere, hydrogen rises quickly, hence small danger zone if hydrogen leaks out/ is spilled.**
- **Hydrogen will burn at concentrations significantly below the limit for detonation.**
- **No detonation in free atmosphere.**
- **Will not form a fire carpet.**
- **Fast burning, very low heat radiation.**
- **Not toxic. Combustion products not toxic.**

Practical Experience:

- **Large scale test over decades, involving millions of laymen: *Town Gas* contained appr. 50% hydrogen.**
- **"Worst case tests" for car tanks successful (BAM Berlin/ BMW)**
- **Side-by-side tests at University of Miami prove clear safety advantage of hydrogen vs. gasoline.**
- **Excellent safety record for LH2 related tanks/ tank trailers/test installations.**

Comparative Safety Tests

Photo 1 - Time: 0 min, 0 sec - Hydrogen powered vehicle on the left. Gasoline powered vehicle on the right.

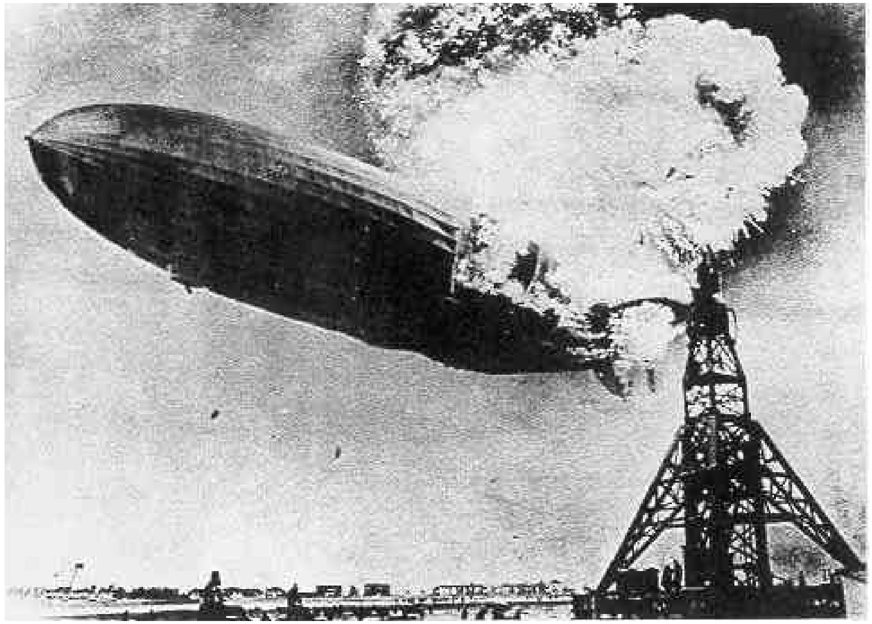
Photo 2 - Time 0 min, 3 seconds - Ignition of both fuels occur. Hydrogen flow rate 2100 SCFM. Gasoline flow rate 680 cc/min.

Photo 3 - Time: 1 min, 0 sec - Hydrogen flow is subsiding, view of gasoline vehicle begins to enlarge

Photo 6 - Time: 2 min, 20 sec - Deflagration in the interior, following frame shows flames exiting around edges of trunk lid.

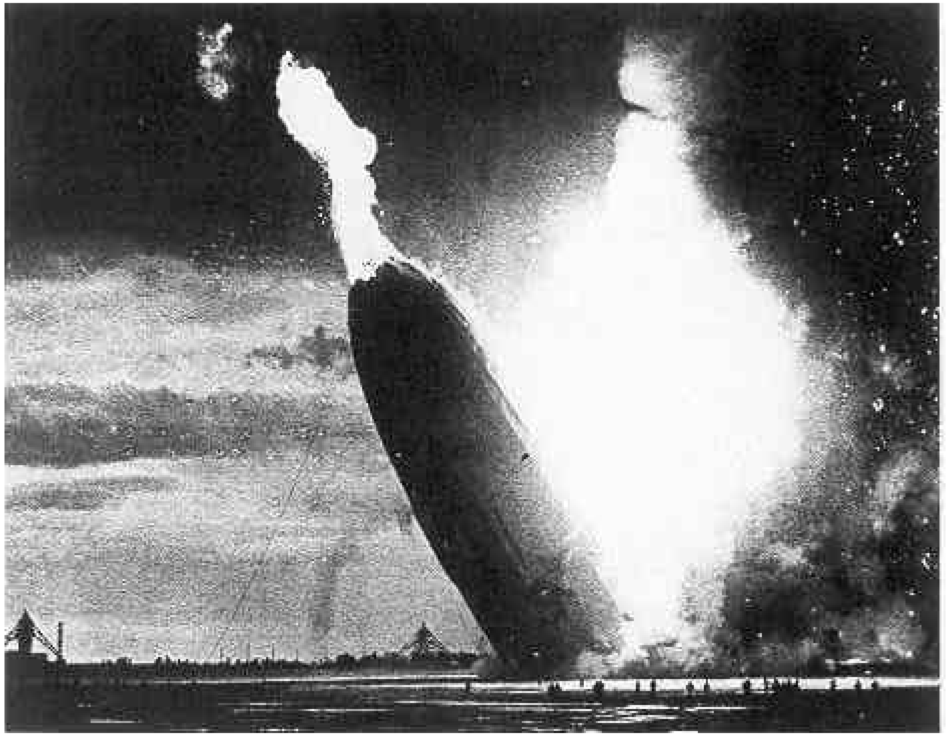
Source: M.R. Swain. Universitv Miami. 2001

Safety - A Historical "Demonstration"



- Airship floating at 60 m over ground when fire started.
- No explosion, but 1 minute of fire until airship settled on ground.
- 97 persons on board (crew plus passengers)
- 62 persons surviving!

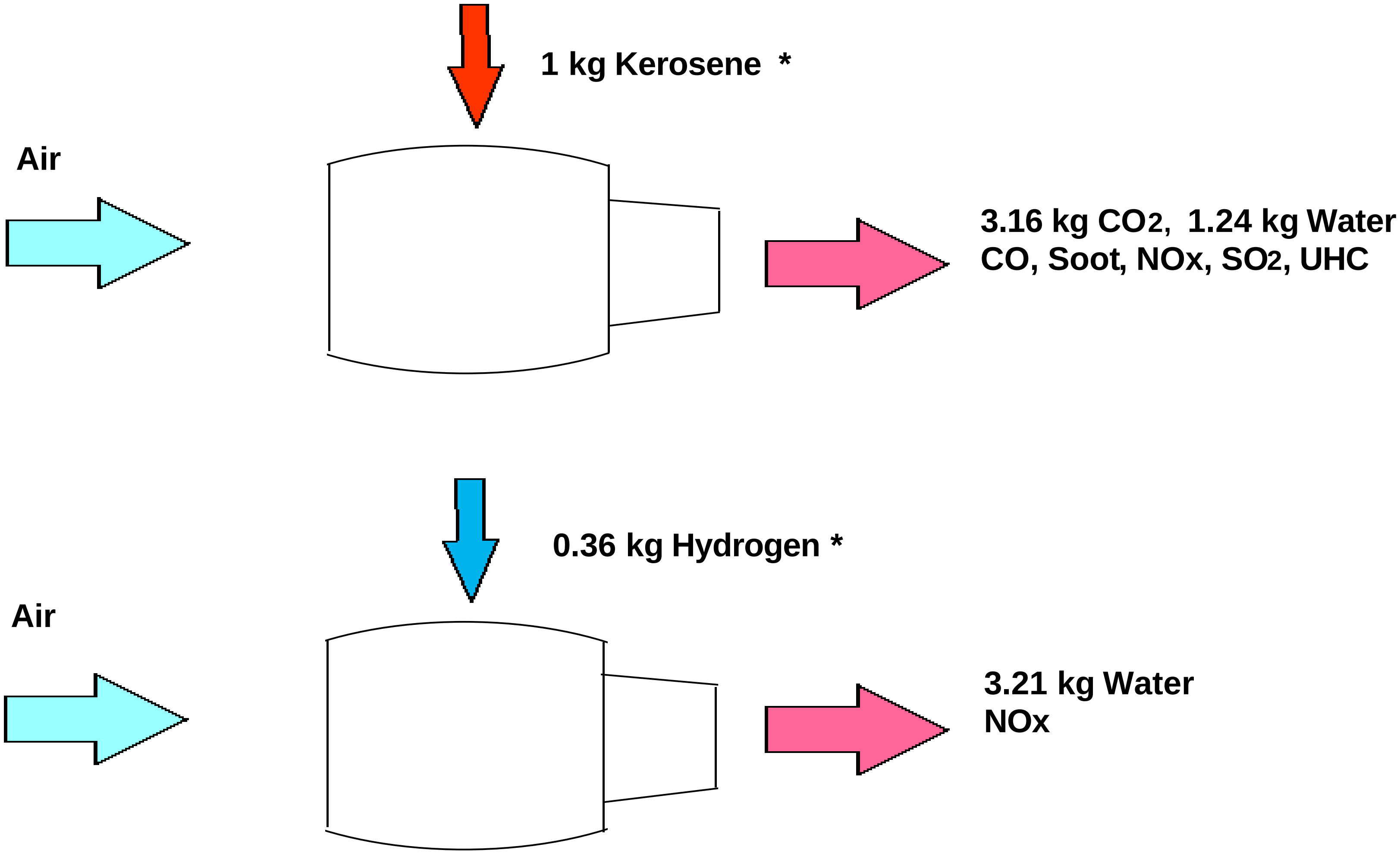
- German Airship *"Hindenburg"* destroyed 06.5.1937 at Lakehurst, USA, during landing.
- Airship contained about 200.000 m^3= 18.000 kg of gaseous hydrogen.
- According to latest research, static electricity set fire to highly flammable impregnation of fabric cover .



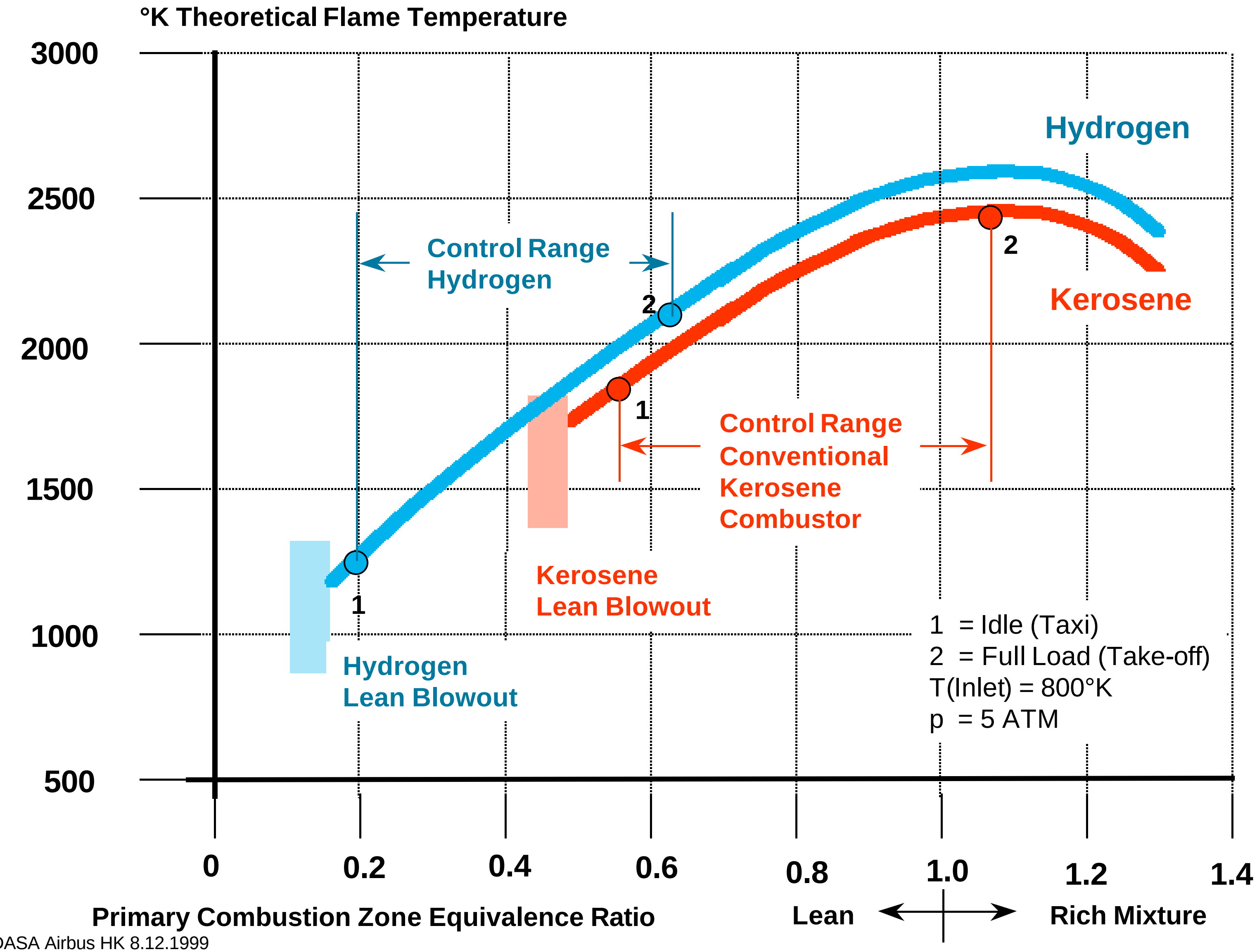
Environmental Aspects

Combustion Products - Kerosene vs. Hydrogen

* Fuel masses of identical energy content



Combustion Process - Control Ranges



Prepared by DASA Airbus HK 8.12.1999

Low Nox Combustion - Results of EQHHPP

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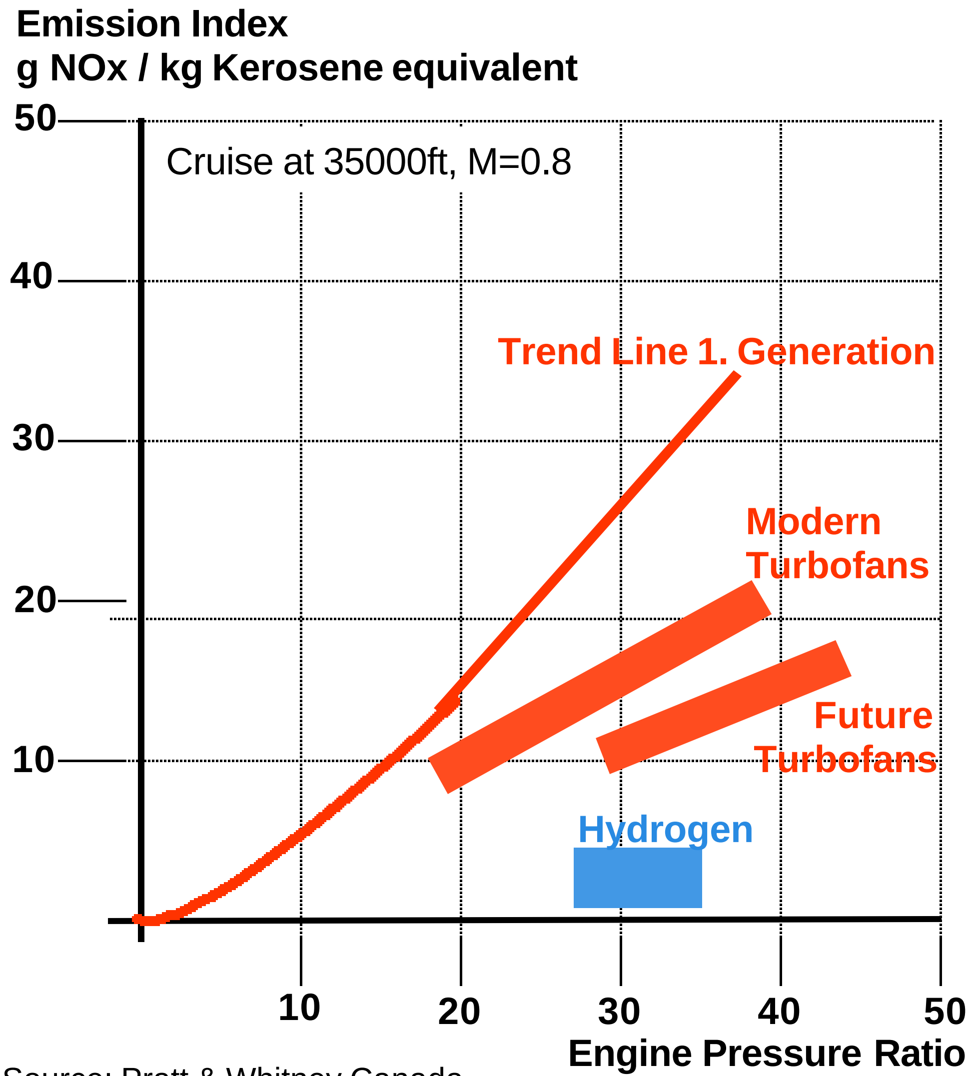


Source: Pratt & Whitney Canada
Preparedby DASA Airbus HK 9.2.2000

- **EQHHPP =Euro Quebec Hydro Hydrogen Pilot Project, sponsored by EC and the province of Quebec, Canada**
- **Low Nox combustion technology 1992 - 1996**
- **Participants: Pratt&Whitney Canada, United Technology Research Center, DLR, Allied Signal, Daimler Benz Aerospace, FH Aachen**

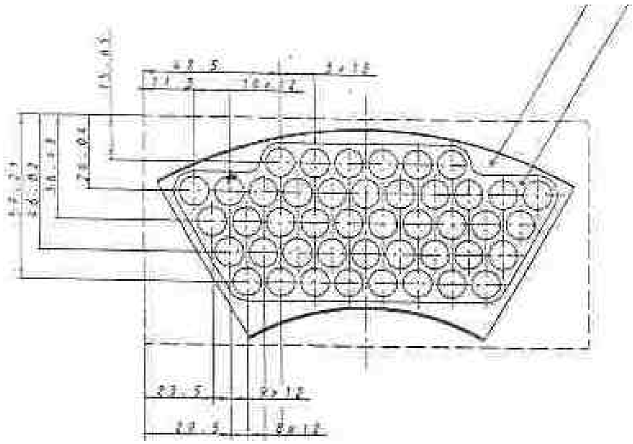
Tests:

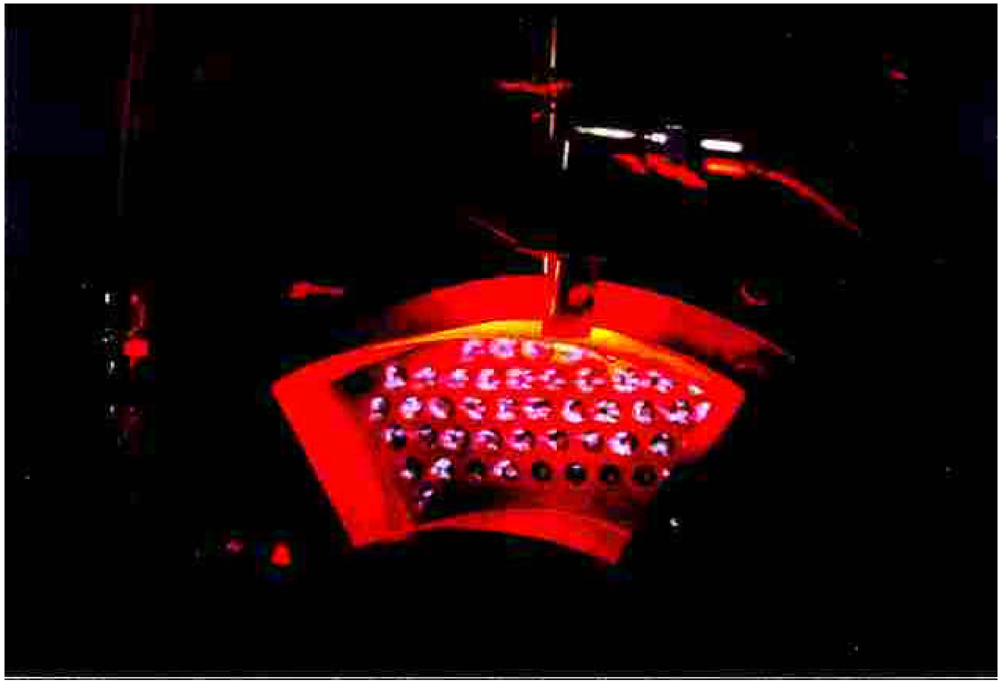
- **Generic nozzle tests (steady state combustion)**
- **Nozzle array tests (steady state combustion)**
- **Transient combustor tests**

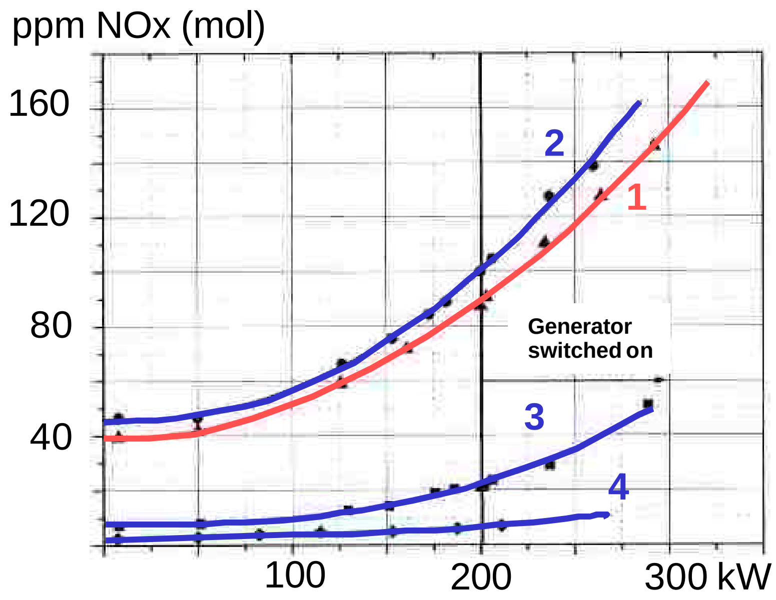
Conclusions:

- **Optimized High Swirl Nozzles offer very significant reduction in NOx compared to kerosene engines**
- **Premixing offers extremely low NOx emissions**
- **Safe operation feasible also for premix system**

Micro-Mix Combustion Chamber, FH Aachen







APU AlliedSignal GTCP 36-300

1 Kerosene, Original Combustion Chamber
2 Hydrogene, Nozzles exchanged
3 Hydrogen, Micro-Mix Chamber
4 Hydrogen, improved Micro-Mix Chamber

Source: FH Aachen

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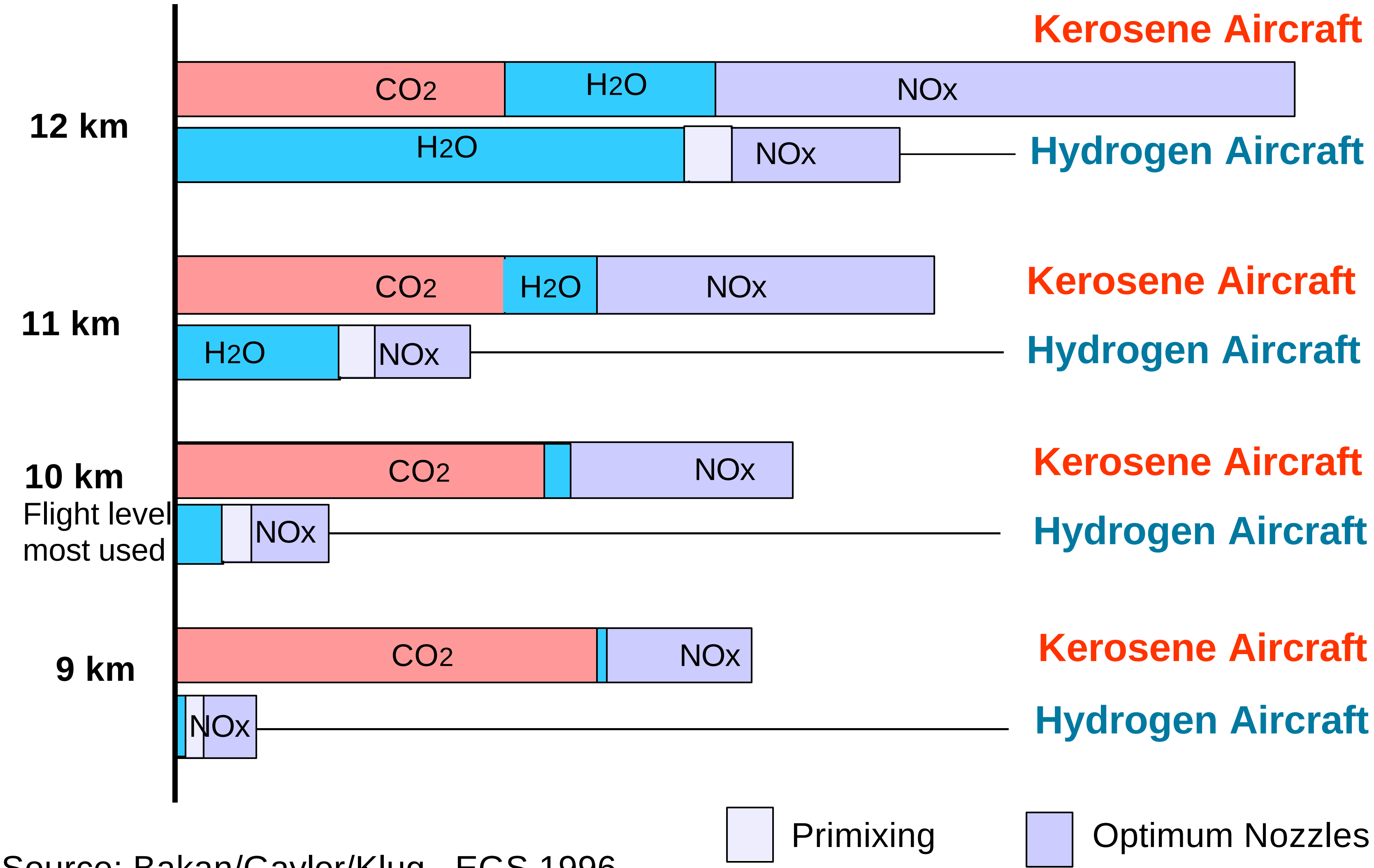
Comparison of Greenhouse Effects - Gaseous Emisions

CRYOPLANE

Simplified Parametric Analysis based on GWP Concept.



Source: Bakan/Gayler/Klug, EGS 1996

Prepared by DASA Airbus HK 8.5.2000

Contrail Characteristics

Contrails contribute to the anthropogenic greenhouse effect.

Due to higher water content of exhaust gases from hydrogen engine, contrails will form and persist under more atmospheric conditions, compared to kerosene. Cloud cover due to contrails may be up to 50% higher for hydrogen.

Optical density is predicted to be lower due to lack of condensation nuclei from engine (bigger but much fewer ice crystals), balancing higher rate of appearance. Confirmation by flight tests required!

Formation of contrails can be avoided by

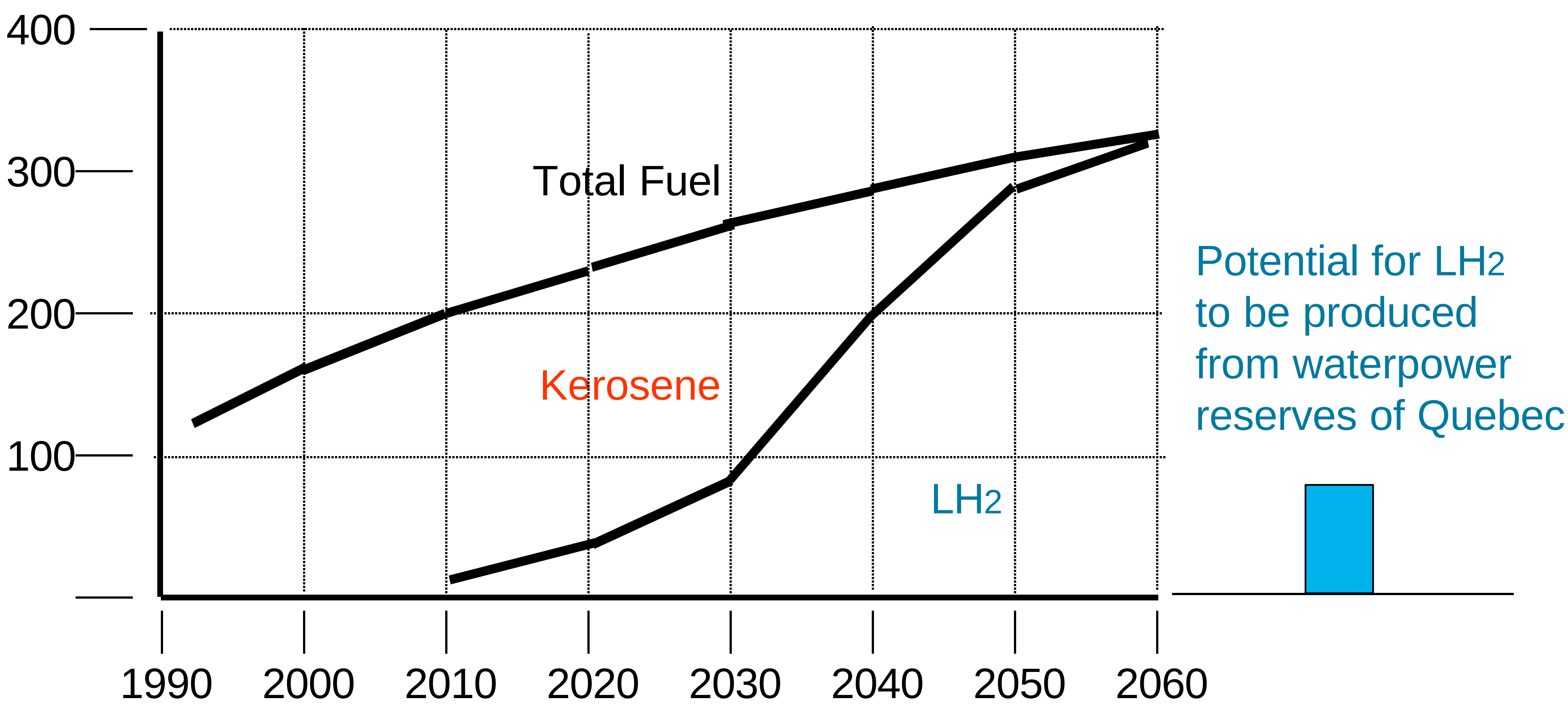
- „meteorological navigation", i.e. by flying around critical air masses where atmosphere is supersaturated over ice
- flying below critical air masses (applicable in summer/tropics?) or above such air masses (applicable in winter/arctics?)

The Path to the Transition

World Fuel Requirements - “Soft Transition to Hydrogen”

Data based upon DASA 1996 Market Analysis

World Aviation Fuel per Year
(Mill t Kerosene Equivalent)



Prepared by DASA Airbus HK 1998

Infrastructure

- During tests, demonstration and early operation: LH_2 can be dispensed from conventional tank trailer (above).
- Long term solution: Production and storing of LH_2 at airport, distribution by pipeline system (below).
- Servicing/refuelling of aircraft at terminal. Refuelling within normal turn-around time (see experience with refuelling of cars!)
- Current view: Aircraft designed for 12 hrs on ground before spilling hydrogen. Thereafter: catalytic combustion or collection/recooling/recirculation by ground vehicles/system.
- LH_2 production capacity in Europe today: 19 t per day; USA: 170 t per day. Full intra-European air traffic would require some 30.000 t per day!
- Long transition time to build up infrastructure.