CRYOPLANE
Flugzeuge mit Wasserstoffantrieb

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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?
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.

Prepared HG Klug September 2001
Civil Aviation Growth

Without UdSSR/CIS

10^9 Revenue Passenger – km per annum

Predicted Growth +4.5% p.a.

Air Traffic - Relationship to Economic Wealth

Status 1994

Passenger-km per capita

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<th>Rank</th>
<th>Country</th>
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<td>1</td>
<td>India</td>
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<td>2</td>
<td>PR China</td>
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Prepared by DASA Airbus HK 23.12.1999
Air Traffic and Population

Status: 1994

USA

41% of Passenger-km

4,6% of World Population

PR China + India

37% of World Population

3.4% of Passenger-km

Prepared by DASA Airbus HK 26.11.199
Growth and Replacement

Market Volume - Seat Miles → Aircraft, Number of Seats

Growth Rate 4.5 % p.a.

200% for Growth

100% for Replacement

25 years Typical Life of Aircraft

Prepared by DASA Airbus HK 11.11.1999
Where we will go with “Business as Usual”

Total: + 2%/year
Air Traffic: +2,5%/year

Total CO2 appr. 6.8 GtC/year
Anthropogenic

Total Traffic
Air Traffic

Kyoto-Target: 1990 -5.2%
appr. 3.5 Gt C/year

appr. 1.2 GtC/year
long term

What we must do to avoid a global temperature increase greater than 2.5° by CO2 alone

Prepared by DASA Airbus HK 1.11.1999
CO₂ – Content of Atmosphere - Past and Future

Source: GEO
Progress in Fuel Efficiency

Liter per 100 seat-km

-2%pa expected
-2.6 to -3.5%pa theoretical potential

Various Types [DLR]
Airbus Family [DASA]
DLH Fleet [DLH] 70% SLF assumed
World Fleet [Momenty] per pax-km
Results of DASA Study

Prepared/Revised by DASA Airbus HK 7.2.2000
Specific Fuel Consumption liter/seat-mile: Improvement 2% per year

- Passenger-miles +4.5% per year
- seat-miles per liter +2% per year
- CO₂ Emission +2.5% per year
- Business as usual
- Transition to Hydrogen

Kyoto-Target: 95% of Emission in 1990

Prepared HG Klug September 2001
Short History
1937      Dr. v. Ohain rig-tests He-S-2 experimental turbojet engine on hydrogen
1957      US Air Force B 57 bomber flight tests
1950ies  Lockheed studies on Mach 2.5 reconnaissance 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 aircraft 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“

Prepared by Airbus Deutschland HK 28.8.2001
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

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

Prepared by Airbus Deutschland HK 28.8.2001
Technology - Status and Challenges
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 (LH₂, -253°C) for reasons of volume and weight of tanks.

LH₂ 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

Weight

Kerosene : LH₂

1 : 2.8

Volume

LH₂

Kerosene

4 : 1

Prepared by DASA Airbus HK 8.12.1999
“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 strengthening fuselage, fairings
- Fuselage stretch to accommodate increased payload
- Strengthening of wing structure

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

Prepared by DASA Airbus HK 3.1.2000
Aircraft Configuration

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
Safety - General Aspects

Danger Zones of Spilled Liquid Gases
Example: 3.3m³ Liquid Gas Spilled - 4m/sec Wind

- 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.

Source: BAM

Prepared by Airbus Deutschland HK 28.8.2001
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, University Miami. 2001
German Airship “Hindenburg” destroyed 06.5.1937 at Lakehurst, USA, during landing.

Airship contained about 200,000 m³ = 18,000 kg of gaseous hydrogen.

According to latest research, static electricity set fire to highly flammable impregnation of fabric cover.

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!
Environmental Aspects
Combustion Products - Kerosene vs. Hydrogen

* Fuel masses of identical energy content

1 kg Kerosene *

Air

3.16 kg CO₂, 1.24 kg Water CO, Soot, NOₓ, SO₂, UHC

0.36 kg Hydrogen *

Air

3.21 kg Water NOₓ

Prepared by DASA Airbus HK 8.12.1999
Combustion Process - Control Ranges

°K Theoretical Flame Temperature

Control Range
Hydrogen

Primary Combustion Zone Equivalence Ratio

Lean Rich Mixtue

Control Range Conventional Kerosene Combustor

1 = Idle (Taxi)
2 = Full Load (Take-off)

T(Inlet) = 800°K
p = 5 ATM

Prepared by DASA Airbus HK 8.12.1999
Low Nox Combustion - Results of EQHPP

- EQHPP = 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

Source: Pratt & Whitney Canada
Prepared by DASA Airbus  HK 9.2.2000
Micro-Mix Combustion Chamber, FH Aachen

160 120 80 40 ppm NOx (mol)

100 200 300 kW

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

Source: FH Aachen

Prepared HG Klug September 2000
Comparison of Greenhouse Effects - Gaseous Emissions

Simplified Parametric Analysis based on GWP Concept.

12 km
- CO2
- H2O
- NOx

11 km
- CO2
- H2O
- NOx

10 km
- CO2
- NOx

9 km
- CO2
- NOx

Kerosene Aircraft
Hydrogen Aircraft

Source: Bakan/Gayler/Klug, EGS 1996
Prepared by DASA Airbus HK 8.5.2000
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)

Potential for LH2 to be produced from waterpower reserves of Quebec

Prepared by DASA Airbus HK 1998
During tests, demonstration and early operation: LH₂ can be dispensed from conventional tank trailer (above).

Long term solution: Production and storing of LH₂ 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/recycling/re-circulation by ground vehicles/system.

LH₂ 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.