CRYOPLANE

Hydrogen Fuelled Aircraft

Submission for the Energy Globe Award 2001
Category “Transport”

Hamburg, 13.October 2000

List of Contents

1. Summary

Civil aviation has enjoyed fast growth for a long time; some 4% to 5% traffic increase per annum has been predicted for the nextfew decades. As 2/3 of aircraft produced will serve additional traffic and only 1/3 will replace old aircraft, manufacturers (both of airframes and engines) have a very strong interest in such continuing growth. However, technology improvements are not sufficient to balance traffic growth: fuel consumption and hence CO_2 emissions increase by some 2% per annum, in contradiction to the accepted requirements of protecting the atmosphere (Kyoto Protocol).

Liquid Hydrogen is the only known fuel suitable for aircraft to be produced from renewable energy and offering extremely low emissions (zero CO_2, CO, SO_2, UHC, soot; very low NOx). Use of Liquid Hydrogen can eliminate the dependency of aviation upon dwindling crude oil resources. It can eliminate, or at least reduce dramatically, the contribution of aviation to the anthropogenic greenhouse effect. Use of Liquid Hydrogen hence could allow long-term growth of aviation without penalizing the environment.

Using hydrogen as an aviation fuel offers obvious advantages but also poses great technical challenges. For reasons of system weight and volume, hydrogen must be stored by aircraft in its liquid state at –253°C (20°K). Even so, fuel volume is 4 times greater than for kerosene, leading to changes of aircraft configuration. The fuel system will be completely new, both with regard to its architecture and to its components. The engine will see significant changes. A specific challenge is to ensure low NOx emissions; tests have proved that this is, in fact, achievable. Safety level will be at least as good as for kerosene fuelled aircraft.

Thirty-five partners from Austria, Belgium, France, Germany, Greece, Italy, Netherlands, Norway, Spain, Sweden and Great Britain, representing Industry, Research Establishments and Universities, have come together for a comprehensive „System Analysis“ of Liquid Hydrogen Fuelled Aircraft (dubbed „CRYOPLANE“). The 2-year project will be supported by the European Commission within the 5th Framework Program.

The “System Analysis” will cover all aspects relevant for assessing the technical feasibility, safety, environmental compatibility and economic viability of using Liquid Hydrogen as an aviation fuel. It is expected that the project will help to lay the foundation for a consistent European long term strategy for the transition to the new fuel in aviation. Both political commitment and public support are necessary.

2. Contact Person

EADS Airbus GmbH
Dept. EZX 4
Dr. Heinz G. Klug
P.B. 95 01 09
21111 HamburgGermany
Phone: ++49 40 7437-2580
Fax: ++49 40 7437-4751
E-mail: heinz-guenter.klug@airbus.dasa.de

EADS Airbus GmbH is coordinating the current project "CRYOPLANE – Hydrogen Fuelled Aircraft - System Analysis" within the 5th Framework Program of the EC.

For the complete list of partners in the consortium, see next page.

3. List of Partners

EADS Airbus GmbH	Germany
Advanced Products NV	Belgium
AEROSPATIALE MATRA AIRBUS ?????????????????????	France
Motoren- und Turbinen-Union München GmbH	Germany
FINMECCANICA S.p.A. ALENIA	Italy
Aristotle University of Thessaloniki, Lab. of Heat Transfer and Environmental Engineering	Greece
Aristotle University of Thessaloniki, Dep. of Physics, Laboratory of Atmospheric Physics	Greece
Bodenseewerk Gerätetechnik GmbH	Germany
BAE Systems	UK
Bundesanstalt für Materialforschung und Prüfung	Germany
Centro Italiano Ricerche Aerospaziali	Italy
Construcciones Aeronauticas S.A. ??????????????????	Spain
Cranfield University, College of Aeronautics	UK
Cranfield University, School of Mechanical Engineering	UK
Deutsches Zentrum für Luft- und Raumfahrt e.V., Institut für Physik der Atmosphäre	Germany
Dornier Luftfahrt GmbH	Germany
ET GmbH Hydrogen Technology and Test Center	Germany
Universidad Politecnica Madrid	Spain
European Commission - Joint Research Ispra	Italy
Fachhochschule Aachen	Germany
Flygtekniska Försökanstalten, Environment Group	Sweden
Fraunhofer Gesellschaft e.V., Institut für Atmosphärische Umweltforschung	Germany
Grimm Aerosol Technik GmbH & Co KG	Germany
Air Liquide	France
Linde AG	Germany
Universitetet i Oslo	Norway
Secondo Mona S.p.A.	Italy
SNECMA, SEP Division	France
SEXTANT Avionique, Sensor Unit France	France
Shell Hydrogen B.V.	Netherlands
Steyr MID Space Technology	Austria
Technische Universität Berlin	Germany
Technische Universität Hamburg-Harburg	Germany
Technische Universität München	Germany
Delft University of Technology	Netherlands

4. Description of Project

4.1 The Challenge – Objective of the Project

Without the free and cost effective movement of products and people, the economic system of our world will not work. World-wide tourism has become an important source of income for many countries. To give up the degree of mobility achieved by now neither is desirable nor feasible. To the contrary: Expectations with regard to available mobility will continue to grow both in respect to volume and to quality, specifically with the economic growth in areas like China, India, or South America.

World-wide mobility is offered by air traffic. On average, air traffic demand grows by some 4-5% per year. Saturation of world wide air traffic is still far away; even in areas with the most advanced air traffic systems, like the USA or Europe, there is still strong growth. **Long term growth of air traffic by more than a magnitude of order appears possible from market demand point of view**.

However, unlimited growth of traffic can and must not happen under today's technical conditions. Burning gasoline, diesel, and kerosene consumes resources which are limited. These fuels are produced on the basis of fossil crude oil which will be virtually exhausted within a few decades.

Even more important: **Burning such fossil fuels causes release of emissions which affect local air quality and contribute globally to the anthropogenic greenhouse effect**. Since the Environment Summit at Rio de Janeiro in 1992, it is generally accepted that specifically the emission of carbon dioxide, product of burning fossil hydrocarbon fuels, must be reduced – while energy consumption wants to grow! At the Kyoto Summit of 1997, industrial countries agreed to reduce their emissions in the 2010/2012 time frame by 5.2% relative to 1990.

In view of such targets, the limits of growth to all sorts of traffic relying upon conventional vehicle technology become obvious: **No refinement and perfection of conventional technologies can balance the expected traffic growth for a longer period of time.** This is specifically true for aircraft, which are definitely close to the limits of conventional technology: Saving fuel to minimize cost and maximize payload has always been a prime target for the manufacturers – industry has no improvements ready "in the drawer". Further progress is costly and slow.

The CRYOPLANE project takes a completely new approach:

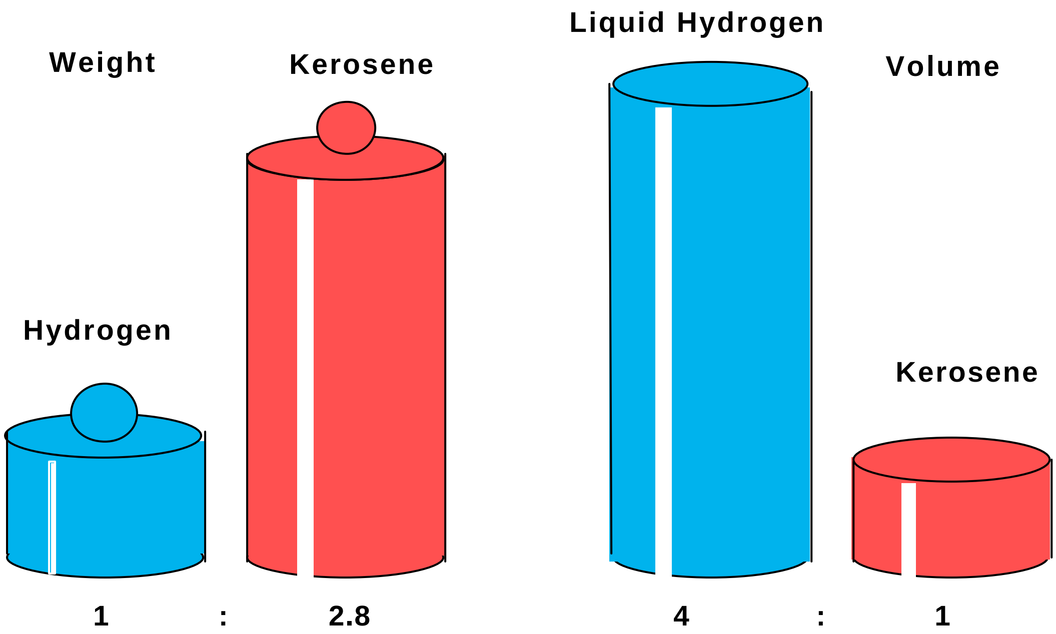
to produce hydrogen from renewable energy sources; to use such hydrogen as an aviation fuel; making the aircraft compatible with the environment and thus ensuring sustainable long term growth of air traffic.

4.2 The Energy Carrier Hydrogen

Protecting fossil fuel resources and reducing the emission of carbon dioxide requires transition to renewable energy sources. Such transition is feasible only step by step over a longer period. Water power and (with some limitations) wind power are competitive energy sources already today; solar thermal power and use of biomass will follow, and photovoltaics in the long run.

Normally, electrical power will be produced on the basis of such energy sources. But electrical power is only of limited use for ground vehicles not running on tracks, and can not be used in aircraft at all. However, electrical power can be used to produce the energy carrier (i.e. fuel) hydrogen by electrolysis of water. Hydrogen can be carried in ground vehicles stored in metal hydrides or nanofibres, as a pressurized gas, or liquefied at –253°C. **But for aircraft, only the storage in liquefied form is practical for reasons of tank weight and volume**. Fuel Cells which are now seen as a favorite way to power cars will be far too heavy for the very high power requirements of aircraft, which must go on to burn the fuel in turbofan powerplants (fuel cells might be used for serving electrical power needs of aircraft systems). **The only primary product of the combustion process in the engine is water again – the cycle is closed**.

Characteristics of Hydrogen
(Masses of equal energy content)



4.3 Technical Challenges

4.3.1 Configuration

With respect to weight, hydrogen contains 2,8 times more energy than the aviation fuel kerosene. A significant part of this advantage will be eaten up by the weight of the complex fuel system, specifically by the large tanks. However, **it is expected that hydrogen will allow to increase the payload at a given Take-off Weight.**

On the other hand, **to store the same amount of energy, Liquid Hydrogen needs a volume 4 times bigger than kerosene**. In addition, the tanks must have a spherical or cylindrical shape to allow for insulation requirements and a (small) differential pressure.

This results in **unusual configurations**. Tanks on top of the fuselage are an attractive solution for big passenger aircraft. Large external tanks under the wing appear feasible for small aircraft with stiff wings and short design ranges. Wings bigger than required to support the aircraft ‘s weight could take a major part of the fuel; In the extreme, unconventional configurations like a “All-Wing-Aircraft” may turn out to become attractive.

4.3.2 Systems and Components

The **Fuel system will be more complex** than for a conventional kerosene aircraft, as the Liquid Hydrogen virtually is a boiling liquid which can evaporate; so the system will contain fuel both in the liquid and in the gaseous phase. Components can not simply be taken from space technology, as aviation requires much longer component life (10000 hours compared to a few minutes). **Structural materials**, specifically for the large tanks, should be light, but must work at the very low temperatures and must stand large temperature changes; Aluminum-Lithium alloys are promising candidates. Composites could be lighter, but the technology needs to be developed. **Insulation** must be light and effective, but also reliable; it must not break down due to some small damage.

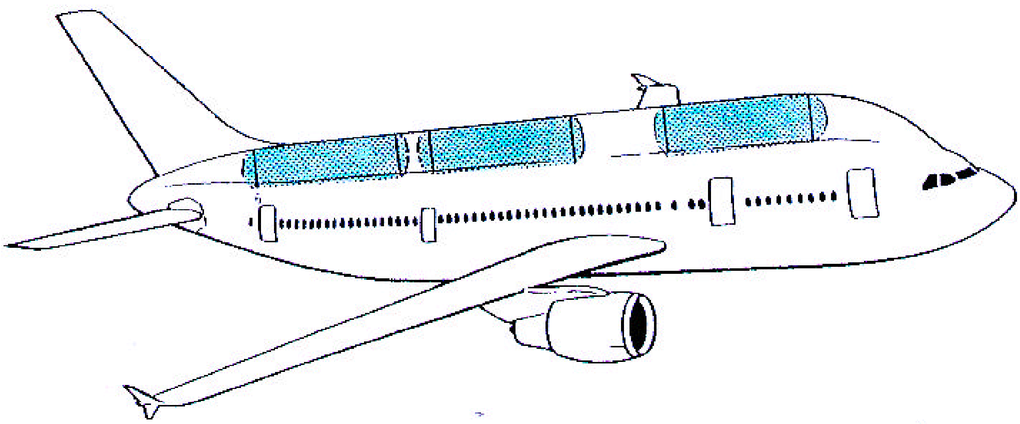
4.3.3 Propulsion

Engines will see some new components. A specific challenge is the development of combustion chambers that ensure very low NOx emissions. Before the hydrogen is injected into the combustion chamber, it must be warmed up in a heat exchanger which is a novel feature. . Components like the HP fuel pump or the flow control valve need much technology development work to reach operational readiness. Use of the cooling capacity of the Liquid Hydrogen may lead to novel engine configurations.

Engineering Challenges

Configuration
Integrate large cylindrical or spherical tanks, preferrably above or at a distance from the passenger cabin.

Structure
Provide tank support and fairing
Local strengthening,
Fuselage stretch for more payload.



Systems
New Fuel System and Fuel Contro System
New well insulated Cryo-tanks New Pipes, Valves, Pumps, Vents, Sensors, Control box.
Fire protection features – Sensors,Ventilation.

Powerplant
New High Pressure Pump, Heat exchanger, Fuel flow control valve, Combustion chamber, Control box, Oil cooler.

4.4 Operational Aspects

4.4.1 Economics

Airlines will be ready to change over to hydrogen only if this gives them an economic advantage. Higher payload fraction on the one hand and the operating cost of a more complex fuel system can be expected to balance each other. In this case, the economic comparison between a kerosene aircraft and a hydrogen aircraft depends primarily upon the fuel price (of course in relation to its energy content – four liter of Liquid Hydrogen are equivalent to one liter of kerosene)

Today, Liquid Hydrogen if mass-produced on a renewable energy basis and free of tax, would cost in the order of taxed gasoline or diesel. Hence, **liquid hydrogen today is not economically competitive to tax-free kerosene. However, the economic equation will change when political measures to force reduction of CO2 emissions will become effective.** What these measures will be, is still open: ICAO has been charged at the Kyoto Conference to come up with a proposal how to deal with the "bunker fuel" problem of civil aviation; the mechanism to be applied will have to be in keeping with the general mechanisms still to be agreed between the states concerned.

4.4.2 Safety

Principal Aspects
Every efficient energy carrier – i.e. every useful fuel – will have *a* danger potential.
Hydrogen offers advantages when compared to other widely used fuels:

- In the free atmosphere, hydrogen rises much faster than other gases such as Natural Gas or Propane, hence the danger zone is small if hydrogen leaks out/ is spilled.

- Hydrogen will burn at concentrations significantly below the limit for detonation. It can not detonate in free atmosphere.

- Hydrogen when spilled and ignited will not form a fire carpet as kerosene does. It burns very fast, but with very low heat radiation. It is expected that passengers can survive a post-crash fire by staying in the cabin.

- Hydrogen is not toxic, and its combustion products are not toxic.

Practical Experience
The safety record for Hydrogen in general, and Liquid Hydrogen specifically, is quite good, e.g. for Liquid Hydrogen tanks, tank trailers, test installations.

German "Worst case tests" for car tanks have been extremely satisfactory.

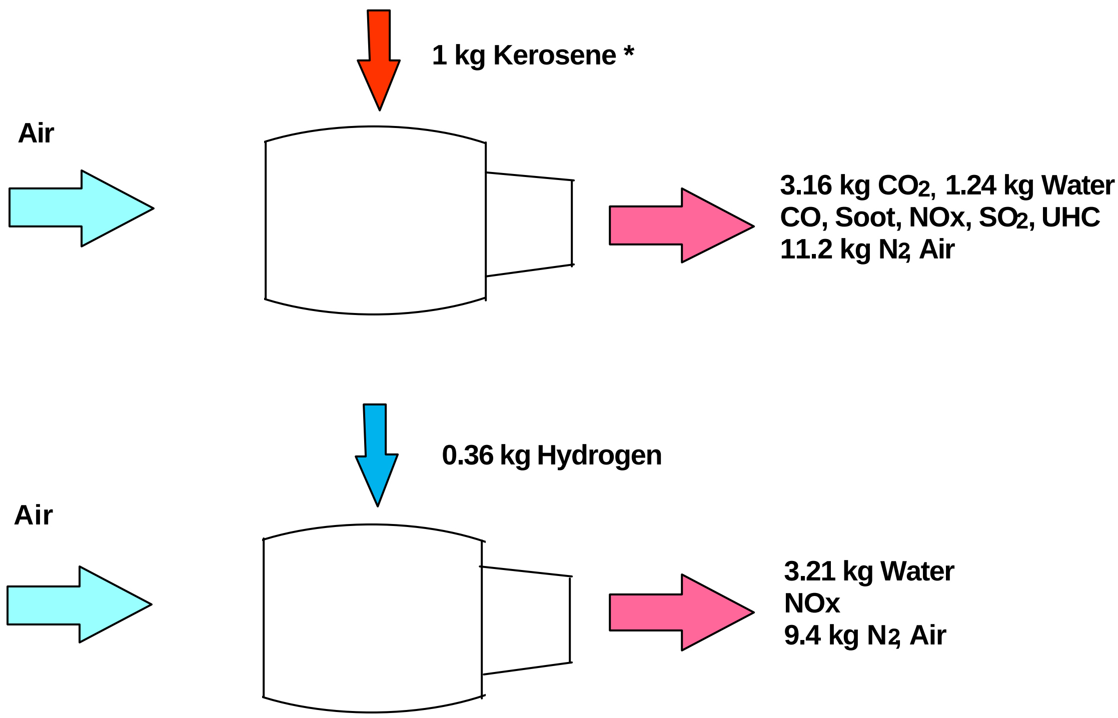
There has been la successful large scale „ test" over decades, involving millions of laymen: *Town Gas* contained appr. 50% hydrogen by volume!

Even the much-cited „Hindenburg Desaster“ in 1937 must be seen as a successful demonstration. The hull went up in flames when the airship was still up at 50m, and then the 200 000m³ of gaseous hydrogen burnt. There was no explosion, and 62 persons out of the 97 on board survived.

4.4.3 Environmental Compatibility

When burning hydrogen, the only primary combustion product is water, and the only secondary emissions of potential significance are Nitrogen Oxides (NOx). Hydrogen eliminates the emission of Carbon Dioxide, Carbon Monoxide, soot, sulphuric acid, Un-burnt hydrocarbons. **The formation of NOx can be controlled by “lean combustion”, with resulting NOx emissions significantly lower than for kerosene** (proved by various tests within the „Euro Quebec Hydro Hydrogen Pilot Project“, and by Fachhochschule Aachen running complete „Auxiliary Power Units“).

Emissions (*Fuel masses of equal energy content)



Burning hydrogen produces 2.6 times the amount of water compared to a mass of kerosene of same energy content. Water vapour is an effective greenhouse gas in the otherwise dry and stable stratosphere. However, residence time even up there is relatively short (say 1/2 year) compared to Carbon Dioxide (100 years). **Various studies and global climate simulations have shown that the effect of water vapour is negligible at typical subsonic cruise levels.**

Contrails (condensation trails = ice crystals) in general will contribute to the anthropogenic greenhouse effect. Their formation depends upon thermodynamic criteria and upon the availability of condensation nuclei (e.g. soot, sulphuric acids, dust). There are only those few nuclei in the exhaust gases of a hydrogen engine, which come from the ambient air. Simulations indicate that such **contrails behind hydrogen engines, despite the larger amount of water emitted, probably will be optically thin and of little climatic effect** (to be confirmed by more further simulations within the current project, and finally by flight tests).

Anyway, contrail characteristics can not be “killer argument” against hydrogen in aviation. Supersaturation over ice, which is the precondition for persistent contrails, is found only in limited regions of the atmosphere, depending upon weather situation. So, it will often be possible to fly around such regions; if not, there is always the possibility to fly below the critical levels. Flying higher above the critical atmospheric layer may be more efficient, but will influence aircraft wing and engine sizing.

4.4.4 Infrastructure

Use of Liquid Hydrogen as a fuel will help to protect the environment only if release of CO_2 into the atmosphere during production is avoided. Steam Reforming of Natural Gas, the cheapest process today, is hence not acceptable. However, if CO_2 is sequestered and deposited e.g. in deep submarine layers, or if the carbon becomes available as carbon black (“Kvaerner Process”), this could be accepted for a transition phase. Anyway, **in the long run, hydrogen must be produced by gasification of biomass, or by electrolysis of water using electrical power generated from renewable energy sources.**

Processes to liquefy hydrogen are well known, but need to be translated into large-scale production. As they use about 1/3 of the original energy available, improvements would be very helpful to reduce the price of the fuel.

In the beginning of the transition process from kerosene to Liquid Hydrogen, when only relatively small amounts of Liquid Hydrogen are required at an airport, fuel production and liquefaction can be centralised; the fuel can be carried to the airport by means of a conventional tank trailer; it can be dispensed to the aircraft via a mobile refuelling station. The necessary technology has been developed in Germany for refuelling road vehicles (Linde, Messer), but needs further development for aviation with its much higher refuelling rates.

In the fully developed system, hydrogen can be delivered in gaseous form via pipelines to the airport, or it can be produced there by electrolysis. It will be liquefied at the airport, will be stored in large tanks, will be distributed by a local system of well insulated pipes, and **will be dispensed to the aircraft while docked at the passenger bridge.**

5. History – Status – Outlook

5.1 Past

In 1957, a B57 bomber aircraft, modified to fly on Liquid Hydrogen, was successfully tested in the USA under military auspices. As a near term fuel shortage was expected at the time ("Fuel Crisis"), the 197ies saw many studies and safety related experiments, carried out *NASA Ames*, *Institute of Gas Technology*, *Linde/Union Carbide Corporation*, *Lockheed* and others. These activities were summarized in 1990 by Daniel Brewer publishing the standard reference book "*Hydrogen Aircraft Technology*".

In Russia, the Design Bureau *ANTK Tupolev* modified a trijet Tu 154 to become the Laboratory Aircraft Tu 155. Engine No.3 was modified by *Kuznetsov* to run on hydrogen or Natural Gas; these fuels were stored in the liquid phase in a tank which had been installed in the rear part of the cabin. First flight was in 1988. The aircraft made many successful flights, most of them on Natural Gas which was and still is of main interest in Russia because of the large reserves available.

During the 199ies, the European-Canadian "*Euro-Quebec Hydro-Hydrogen Pilot Project*" covered many aspects of hydrogen use. An extensive test series proved that very low NOx emissions can indeed be achieved in practical aircraft engines. Later, at the *Fachhochschule Aachen*, very low NOx were demonstrated by running "Auxiliary Power Units" on hydrogen. "Worst Case Tests" on Liquid Hydrogen tanks, carried out by the German Bundesanstalt für Materialforschung in co-operation with car manufacturer *BMW*, proved the high safety level achievable with hydrogen.

Many aspects of using Liquid Hydrogen as an aircraft fuel were studied in co-operation between *EADS Airbus*, the Russian design bureau *ANTK Tupolev*, and numerous German partners. However, efforts to initiate the realisation of a demonstrator aircraft to be based upon the Do 328 Regional Jet failed.

5.2 Present

Since mid of 2000, a consortium of 35 partners from 11 European countries is working on a comprehensive "System Analysis", supported by the European

Commission within the 5th Framework Program. The study covers all relevant technical, environmental and strategic aspects to provide a sound basis for initiating larger scale Research and Development activities. Specifically, it includes work on aircraft configuration, systems and components, propulsion, safety, environmental compatibility, fuel sources and infrastructure, and last not least on transition processes, both from a global and a regional point of view. Total volume of the study is 4.5 Million Euro, duration is 2 years.

It is expected that the study will confirm the principal feasibility and the environmental advantages of the CRYOPLANE concept, but also will identify in detail the need for future research and development activities.

5.3 Future

In a follow up phase to the current project, time critical development of key components and technologies should be initiated, and tests to settle finally questions of great importance for the practicality of the concept should be carried out.

The next steps will have to be the realisation of complete fuel system on the ground ("Iron Bird") and then in a "Validator" Test Aircraft to definitely prove the whole concept and gain operational experience. Only after that, the first aircraft type(s) could be developed for routine airline operation. If all runs well, first series aircraft could be delivered within 10-15 years from now.

The transition process should be "soft", i.e. avoiding unnecessary economic burdens for airlines and airports. Due to the long (appr. 25 year) life of individual aircraft, it may take several decades before kerosene has been replaced by Liquid Hydrogen world-wide. To initiate and control such a soft process will be a big challenge to the political authorities; it will need wide public support.

Changing to Liquid Hydrogen is a promising way to long term sustainable growth of civil aviation at high growth rates, as it will bring the emission of the long-living greenhouse gas CO_2 by aircraft down to zero, and will minimize other emissions.

It will be a very long process leading up to worldwide transition. But how to begin is clear: the process must start with clarifying key operational questions and developing the enabling technologies. To safeguard the long term prospects of civil aviation, the process must be started soon. Wherever it is started, it must become a worldwide process in the not too distant future.

It will be a long way to go, and the challenges are great, but we do not know any better technical approach to protect the long term growth of civil aviation.