Potential of reducing the environmental impact of aviation by using hydrogen
Part I: Background, prospects and challenges

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ABSTRACT

The main objective of the paper is to evaluate the potential of reducing the environmental impact of civil subsonic aviation by using hydrogen fuel. The paper is divided into three parts of which this is Part I, where the background, prospects and challenges of introducing an alternative fuel in aviation are outlined. In Part II the aero engine design when using hydrogen is covered, and in Part III the subjects of optimum cruising altitude and airport implications of introducing liquid hydrogen-fuelled aircraft are raised.

Looking at the prospect of alternative fuels, synthetic kerosene produced from biomass turns out to be feasible and offers environmental benefits in the short run, whereas hydrogen seems to be the more attractive alternative in the long run.

Powering aero engines and aircraft with hydrogen has been done successfully on a number of occasions in the past. Realising this technology change for a fleet of aircraft poses formidable challenges regarding technical development, energy requirement for producing hydrogen, handling, aircraft design and making liquid hydrogen economically compatible with kerosene.

NOMENCLATURE

CFC	chlorofluorocarbons
CH_4	methane
CIAM	Central Institute of Aviation Motors
CO	carbon monoxide
CO_2	carbon dioxide
EC	European Commission
EQHHPP	Euro-Québec Hydro-Hydrogen Pilot Project
H_2O	water vapour
IPCC	Intergovernmental Panel on Cimate Change
KSPA	Kuibyshev Scientific-Production Association
LH_2	liquid hydrogen
LNG	liquid natural gas
NASA	National Aeronautics and Space Administration
N_2O	nitrous oxide
NO	nitric oxide
NO_x	nitrogen oxides ($NO + NO_2$)
NO_2	nitrogen dioxide
O_3	ozone
ODAC	oil depletion analysis centre
OH	hydroxyl radical
RF	radiative forcing
SO_x	Sulphur oxides
SO_2	Sulphur dioxide
UHC	unburned hydrocarbons

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1.0 INTRODUCTION

Since commercial aviation started in 1920 it has undergone spectacular growth, and today it has become a fundamental part of business and commerce. Mainly for business purposes, engine and aircraft manufacturers, and airlines compile forecasts for future traffic growth. Over the next 20 years global passenger aviation traffic is expected to grow, averaging around 5·3% annually (Rogers *et al*(1)), implying an almost threefold traffic volume at the end of this period. It is expected that capacity growth, i.e. number of seats offered, will expand at a slower rate, provided that passenger load factors maintain their improving trend over the long term.

In addition to the anticipated air traffic growth, the dwindling fossil oil resources raise concerns. In 2000 the United States Geological Survey estimated that the ultimate recoverable world oil resources would supply an expansion of 2% per annum through 2025, reaching around 125 million barrels per day (Schnieder and McKay(2)). Thereafter a plateau could occur for around two decades before depletion would lead to a permanent decline in production. Other specialists believe that the plateau will be reached earlier. The Oil Depletion Analysis Centre (ODAC)† believes that a plateau of conventional oil production will be reached before 2010, with significant price rises thereafter.

Moreover, the greenhouse effect generated by emissions produced by human activity, particularly carbon dioxide, has become an increased concern. The majority of scientists today are in agreement that discharging greenhouse gases (or their precursors) and particulates into the atmosphere has an impact on the global climate. It is, therefore, essential to find an alternative to kerosene for civil aviation. In the context of this paper, hydrogen, in the longer term produced from renewable energy sources, is addressed as a suitable future fuel in order to cope with these concerns. Because the introduction of hydrogen would influence the complex interactions among a number of different fields affected by this change and because hydrogen is not considered a practical alternative at present but a number of years ahead, this paper covers a number of selected fields. This broad study results in making it possible to define those fields of which more research and development are necessary in order to move towards liquid hydrogen-fuelled aircraft in civil aviation. Furthermore, a broad approach will provide knowledge on the technical feasibility of this fuel change, taking practical aspects into account.

The objective of the paper is to evaluate the potential of reducing the environmental impact of civil subsonic aviation by changing the source of energy from kerosene to the energy carrier hydrogen. In addition, the practical and technical feasibility of introducing hydrogen as fuel is investigated. The paper is divided into three parts of which this paper constitutes Part I. Here the environmental concerns of aviation are outlined in Section 2, including a brief overview of the greenhouse effect and its potential consequences. Also in Section 2 is provided a brief insight on which are the pollutant emissions of conventional aviation, how they are formed and their effects on the environment, with emphasis on global warming. The prospects and difficulties in general of introducing an alternative fuel in civil aviation are outlined in Section 3, and in Section 4 previous work on the concept of using hydrogen for aviation is summarised. The paper is concluded by a summary of the conclusions and a discussion of prospects and challenges of introducing an alternative fuel in civil aviation (Section 5).

In Part II the fundamental effects on aero engine pollutant emissions, performance and design of changing to hydrogen fuel are covered. Moreover, the subject of designing an aero gas turbine using hydrogen for low environmental impact is raised. In the last part, Part III, the optimum cruising altitudes for minimum global warming for a liquid hydrogen-fuelled aircraft and an equivalent conventional aircraft are investigated. Furthermore, the feasibility of introducing cryoplanes on a regional level is explored. The infrastructure changes and possible hydrogen production methods at Stockholm/Arlanda airport are discussed.

2.0 ENVIRONMENTAL CONCERNS OF AVIATION

In recent years the environmental effects of emission from civil aviation have been under discussion, and there is a growing body of evidence that future growth in air traffic might result in significant impacts on local air quality and the global climate (Rogers *et al*(1)). While the concerns of local air quality usually arise from the potential impact on human health of high concentrations of gaseous or particulate species over a relatively small area (tens of square kilometres), the global concerns relate to the potential impacts of the emissions on climate change.

This section is introduced with an overview of the physical mechanisms behind the greenhouse effect (Section 2.1). The influence of man-made emissions on the climate system, both up until the present point in time and projected influences for the future, are discussed. Section 2.2 provides a brief overview of the formation principles, mitigation strategies, and the effects on the environment and human health of the exhaust emissions of aircraft. Assessments of the climate impact of aviation today and in the future are given.

2.1 The greenhouse effect and Its potential consequences

In trying to understand the greenhouse effect one should be aware that the Earth's climate system is an extremely complex interactive system. Following the definition in IPCC†, the climate system consists of five major components: the atmosphere, the hydrosphere (all liquid surface and subterranean water), the cryosphere (sea ice, ice sheets and glaciers), the land surface and the biosphere, which are forced or influenced by various external forcing mechanisms, of which the sun is the most important one. Although the components of the climate system are very different, they are linked by fluxes of mass, heat and momentum. While some of these interactions are understood, some are poorly known or perhaps even unknown. Describing the interactions among all these components and attempting to provide a thorough description of the climate system is far beyond the ambitions of this paper. The interested reader is referred to IPCC(3).

Within the atmosphere a number of trace gases, so-called greenhouse gases are present. These gases have the features of being partly transparent for shortwave radiation from the sun, while absorbing and emitting a significant part of the longwave heat radiation from the Earth's surface. The most important greenhouse gases are carbon dioxide, methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). These gases have only a total volume mixing ratio of less than 0·1%, but play an essential role in the Earth's energy budget. Furthermore, the atmosphere contains the natural greenhouse gas water vapour (volume mixing ratio in the order of 1%).

About half of the radiation from the sun is absorbed by the Earth's surface; the rest is reflected immediately back into space or absorbed by the atmosphere (IPCC(3)). However, a substantial part of the infrared radiation from the Earth's surface is absorbed by the greenhouse gases in the atmosphere. In turn, these gases emit infrared radiation in all directions including downward to the Earth's surface. Hence, the greenhouse gases trap heat within the atmosphere, giving an average temperature on the surface of the Earth 33C higher than the temperature corresponding to the average radiation back into space. This mechanism is called the natural greenhouse effect IPCC(3).

Human beings, like other living organisms, have always influenced their environment. However, since the beginning of the Industrial Revolution in the mid-18th century, the impact of human activities has become significant and extends to a much

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† Oil Depletion Analysis Centre (ODAC) is a charitable organisation in London that is dedicated to researching the date and impact of the peak and decline of world oil production due to resource constraints, and raising awareness of the serious consequences of oil depletion. The assertion is made by Colin Campbell who is a Trustee of ODAC (see http://www.hubbertpeak.com/campbell/).

larger scale (continental or even global). In particular the combustion of fossil fuels that produce greenhouse gases has become a major concern. In addition, human activities have introduced strong greenhouse gases that are not naturally present in the atmosphere: chlorofluorocarbons (CFC) and other chlorine and bromine compounds. These gases not only contribute to the radiative forcing[†], but also lead to the depletion of the stratospheric ozone layer.

Mainly due to the combustion of fossil fuels (three-quarters) and the deforestation (one-quarter) (since the biosphere absorbs carbon dioxide), the concentration of carbon dioxide in the atmosphere has increased by more than 30% since pre-industrial times, and is still increasing at an unprecedented rate of on average 0·4% per year (IPCC(3)). It is the presence of an increased concentration of CO_2 and other greenhouse gases (such as methane, nitrous oxide and ozone) in the atmosphere due to anthropogenic sources that causes the enhanced greenhouse effect. An increased concentration of greenhouse gases in the atmosphere increases the absorption and emission of infrared radiation. The enhanced greenhouse effect may have major consequences on the climate.

Since the late 19th century a mean global warming of 0·4° to 0·8° of the atmosphere at the surface has been observed. The increase in temperature took place in two distinct phases: the first one between 1910 and 1945, and recently since 1976. Surface temperature records indicate that the 1990s are likely to have been the warmest decade of the millennium in the Northern hemisphere (IPCC(3)). Possibly related, among other factors, to an increase in cloud cover, recent years have been exceptionally warm, with a larger increase in minimum than in maximum temperatures. During the 20th century the sea level has risen by 10 to 20cm and glaciers worldwide, except in a few maritime regions, e.g. Norway and New Zealand, have retreated.

It is justified to question whether these observed climate changes are a consequence of increased greenhouse gas concentrations or simply an effect of natural variations. Employing detection and attribution studies, model simulations imposing different assumptions can be compared with measured data. Three different cases of model simulations are compared with observed data in IPCC(3): (a) only natural forcing (solar variation and volcanic activity), (b) only anthropogenic forcing (greenhouse gases and an estimate of aerosols) and (c) both natural and anthropogenic forcings. According to IPCC(3), natural forcings may have contributed to the observed warming during the first half of the 20th century. On the contrary, simulations of the response to natural forcing alone do not explain the warming during the second half of the 20th century. In IPCC(3) it is claimed: 'In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the past 50 years is likely to have been due to the increase in greenhouse gas concentrations.'

Looking at what might happen in the future, using model simulations and applying various scenarios of the future, IPCC(3) projects that the global average temperature will increase by 1·4° to 5·8° over the period 1990 to 2100. During this period global average water vapour concentrations and precipitation are projected to increase, and extreme weather and climate events, e.g. higher maximum temperatures, more intense precipitation events and increased summer continental drying, are expected to be more frequently occurring. Owing primarily to thermal expansion and loss of mass from icecaps, global mean sea level is projected to rise by 0·09 to 0·88 metres. There is also a concern that the ocean thermohaline circulation could weaken, which would lead to a reduction of the heat transport into high latitudes of the Northern Hemisphere. If the change in radiative forcing is large enough and applied long enough, the thermohaline circulation could completely shut-down in either hemisphere beyond 2100, with major consequences on the Earth's climate system.

2.2 Aircraft exhaust emissions

Provided that a conventional fuel containing both carbon and hydrogen is burnt, the gas turbine exhaust emissions comprise the primary combustion products: carbon dioxide (CO_2) and water vapour (H_2O), and the secondary combustion products: oxides of nitrogen (NO_x), unburned hydrocarbons (UHC), carbon monoxide (CO), oxides of sulphur (SO_x) (if the fuel contains sulphur) and particulate matter. In general, NO_x, CO, UHC and particles are relevant to local air quality issues, while CO_2, H_2O, NO_x, SO_x and particles are of most concern with respect to climate perturbations (Rogers *et al*(1)).

The emissions of CO_2 and H_2O are unavoidable end products of the combustion process, and their quantities are directly proportional to the fuel consumption. In order to alter any of these, either the fuel consumption or the fuel composition needs to be changed. The fuel consumption can be reduced by improving the overall efficiency of the engine and/or reducing the aircraft weight. Another option is to improve the aerodynamic efficiency of the aircraft. Both CO_2 and H_2O emissions contribute to global warming via the greenhouse effect (Section 2.1). Carbon dioxide is a long-lived gas with a residence time in the atmosphere of 100 years or more. An increased concentration of CO_2 alters the radiative balance of the Earth, and thereby contributes to global warming. Although the present CO_2 emissions from aircraft are only about 2% of that from the total anthropogenic emissions, and thereby contribute a small fraction of the total CO_2 radiative forcing, this fraction is expected to increase over the next 100 years (Rogers *et al*(1)).

Water vapour can cause partly a direct radiative impact on the climate system, and partly indirect effects by the formation of line-shaped ice clouds, so-called contrails, and by changing the cirrus cloud coverage, which may also affect the climate. Studying conventional aircraft, IPCC(4) and Morris *et al*(5) suggest that the direct impact of water vapour emissions from subsonic aviation on the radiative balance is negligibly small. Following Sausen *et al*(6) contrails occur when the ambient air temperature is cooler than some threshold value, which depends on the flight level, ambient humidity and aircraft propulsion efficiency. In addition, persistence of contrails requires that the ambient air is frost-saturated, i.e. supersaturated with respect to the ice phase and not saturated with respect to the water phase. Particles play an important role in contrail formation by acting as condensation nuclei for water vapour and other condensable species.

Aircraft emissions have the potential to change cirrus clouds in the following three ways (Sausen *et al*(7)): (1) if the background atmosphere is sufficiently supersaturated with respect to the ice phase, contrails can grow to larger cirrus clouds, (2) particles (e.g. soot) and precursors of volatile particles (e.g. sulphur oxides) can eventually be transformed into cloud condensation nuclei, which may trigger the formation of cirrus clouds much later than the original emission, and (3) aerosols may additionally modify the micro-physical properties of cirrus clouds, change cloud particle sizes and forms and the number of cloud particles. At this point it cannot be excluded that water vapour and particles from aircraft, including their secondary effects, play a major role in the climate impact of air traffic.

Most of the nitrogen oxides formed during combustion are in the form of NO; however, subsequently the NO oxidises to NO_2. Usually these are lumped together, and the result is expressed in terms of oxides of nitrogen (NO_x). The formation processes of NO in combustion are complex and generally comprise different mechanisms: thermal NO, prompt NO, nitrous oxide (N_2O) mechanism and fuel NO (Lefebvre(8)). Except for very fuel lean combustion systems, thermal NO, which is produced from the nitrogen and oxygen present in the air in the high-temperature regions of the flame and in the postflame gases, is the most contributing mechanism to the total

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[†] Radiative forcing (RF): imbalance due to either a change in solar radiation or the infrared radiation that changes the net radiation (IPCC(3)). A positive radiative forcing implies a warming of the Earth's surface.

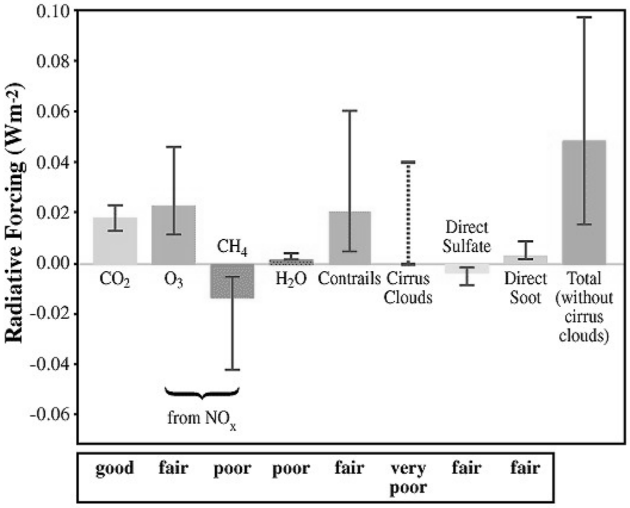

Figure 1. Estimates of the globally averaged radiative forcing from subsonic aircraft emissions in 1992 (IPCC(4)).

NO formation. In order to reduce the NO$_x$ emissions there are a number of different combustor concepts suggested aimed at reducing primarily the combustion temperature, but also the residence time in the hot combustion zone. As for possibilities for low NO$_x$ emissions when using hydrogen, this is discussed in Part II of the paper, whereas mitigation options for conventional engines are beyond the scope of the paper. For information on the latter the reader is directed to, for instance, Lefebvre(8).

At ground level the presence of NO$_x$ results in an increase in ozone concentration, which during prolonged exposure may cause respiratory illness, impaired vision, headaches and allergies (Lefebvre(8)). The influence of NO$_x$ emissions on the climate is indirect through its chemical impact on the atmospheric ozone and methane concentration: at altitudes below about 15km, NO$_x$ emissions cause an increase of the upper tropospheric ozone, thus contributing to the greenhouse effect, while at the same time increasing the atmospheric OH concentration, which decreases the methane (CH$_4$) (and CO) lifetime (e.g. Isaksen *et al*(9)). The latter lowers the atmospheric CH$_4$ concentration, and thereby reduces the greenhouse effect. Moreover, NO$_x$ emissions cause damage to plant life as well as add to the problem of acid rain. At high altitudes (above about 15km) NO$_x$ emissions cause ozone depletion, and hence increased ground-level ultra-violet radiation, which might cause skin cancer and eye diseases (Singh(10)).

Emissions of UHC and CO form due to incomplete combustion in regions of low temperature and/or short residence of the combustion chamber. These are circumstances that in most cases occur at low power conditions. The UHC and CO emissions are reduced by redistribution of the air flow to bring the primary zone equivalence ratio closer to the optimum value (about 0·8), and by an increase in the primary zone volume and/or residence time (Lefebvre(8)). Moreover, these are lowered by a reduction in liner wall-cooling air and by improved fuel atomisation. Emissions of UHC and CO are both toxic. Carbon monoxide reduces the capacity of the blood to absorb oxygen, and in high concentrations it can cause asphyxiation and even death (Lefebvre(8)). In addition to the human health concerns of these emissions, UHC combine with oxides of nitrogen to form photochemical smog.

All of the sulphur in the fuel is oxidised to oxides of sulphur, the main part becoming sulphur dioxide (SO$_2$). Oxides of sulphur are toxic and corrosive, and lead to the formation of sulphuric acid in the atmosphere (Lefebvre(8)), which contributes to the acidification. The only viable limitation strategy is to remove the sulphur from the fuel prior to the combustion. Theoretically, this can be done to a very large extent without any technical problem.

Particulate matter is a general term for various particles with varying chemical composition and many different sizes that can originate from a range of natural and man-made sources. With respect to particles from aviation, these can be divided into two different types: soot and volatile particles (Rogers *et al*(1)). The volatile particles are thought to form from condensed sulphuric acid and possibly condensable organic species. Soot consists mostly of carbon (96%) and a mixture of hydrogen, oxygen and other elements (Lefebvre(8)). It is formed in local fuel-rich regions within the engine's combustion chamber. The propensity to produce carbon is most severe at high pressures. In order to lower the soot emissions, attention should be paid to the fuel injector design and measures to enhance the mixing process of fuel and air.

Soot particles can pose human health concerns, especially the smallest which are suspected to be the most harmful. Studies by Seaton *et al*(11) indicate a strong association between asthma and other respiratory diseases, and concentrations of small particles measured in the microgram range. Moreover, chemicals adsorbed on particles may contribute to respiratory diseases. Larger particles give rise to visible smoke that soils the atmosphere (for modern engines, however, smoke trails have largely been eliminated).

Having discussed the climate impacts of anthropogenic sources in general, the attention is now turned to the contribution from aviation. According to the best estimate of the total climate impact of subsonic aviation in terms of radiative forcing in 1992, it was 0·05W/m^2 or 3·5% of the total radiative forcing by all anthropogenic activities (IPCC(4)). This assessment combines the effects from changes in concentrations of carbon dioxide, ozone, methane, water vapour, line-shaped contrails, and aerosols, but does not include possible changes in cirrus cloud coverage. In Fig. 1 the contributions to radiative forcing from the different emissions are shown. The bars indicate the best estimate, while the line associated with each bar indicates the uncertainty range. Using the best knowledge and tools available at the time for publishing this graph, it is claimed that there is a 67% probability that the true value falls within the uncertainty range (IPCC(4)). The level of scientific understanding for each emission is indicated at the bottom of the figure. Evidently from the figure, the magnitude of the climate impact from aviation, similarly as from other sources, is highly uncertain.

Based on recent results obtained within the EC-sponsored project TRADEOFF and other studies, the figures on the radiative forcing contribution from air traffic (Fig. 1) have been revised (Schumann(12); Sausen *et al*(7)). The main changes originate from a reduced optical thickness of line-shaped contrails and a first estimate of aviation-induced cirrus cloud cover changes. The effect of CO$_2$ is expected to be larger and the contrail effect smaller, while the level of scientific understanding has not changed significantly. Recent studies suggest that the global mean radiative forcing effect (including the cirrus cloud effects) of aviation is higher than assessed in IPCC(4), though the impact of supersonic transport is expected to be lower than assessed in IPCC(4).

In the future, aviation's share of the radiative forcing is expected to increase, mainly as an effect of significant air traffic growth and an expected decline in emissions from other sources. By 2050, aviation's contribution to radiative forcing is expected to increase to between 3·4 and 14·7% of the total radiative forcing by all anthropogenic activities (IPCC(4)). The figure in 2050 depends on which scenario of the air traffic development is applied and on assumptions about the development of non-aviation emissions.

3.0 INTRODUCTION OF AN ALTERNATIVE FUEL IN CIVIL AVIATION

The challenge is to develop an environmentally sustainable transportation system for aviation, in the long term based on renewable energy sources, capable of coping with the increasing traffic demand and at the same time limiting the emissions of greenhouse gases. In order to achieve this, several changes need to be applied. Incentives to change people's travelling habits and the introduction of external means of control will probably play an important role. However, these are issues beyond the scope of this paper.

Taking a completely new approach for civil aviation by fuelling with liquid hydrogen, in the longer term produced from renewable energy sources, would enable compatibility with the environment. The civil aviation would be powered by an energy carrier (in contrast to an energy source, which kerosene is) that may be produced from any energy source, by electrolysis of water. It would reduce the unhealthy emissions in the airport vicinity, and, even more importantly, allow a significant reduction of civil aviation's contribution to global warming. When hydrogen is burnt the emissions consist of only water vapour (H_2O) (which increases by a factor of about 2·6) and oxides of nitrogen (NO_x) (NO_x emissions are discussed in Part II). All emissions containing carbon and sulphur are eliminated. However, looking from a systems perspective, the hydrogen usage may, depending on the hydrogen production method, entail that also other pollutant emissions than H_2O and NO_x are generated.

A fundamental difference between kerosene and liquid hydrogen concerns the fuel energy density. In order to carry the same amount of energy, which is the most relevant parameter when comparing two aircraft for the same mission, the mass of the fuel is 2·8 times less for liquid hydrogen, whereas the volume is four times larger (Fig. 2). The high energy content per mass of liquid hydrogen will lower the total fuel weight for a certain mission, i.e. the fuel weight will be 2·8 times lower, and thus potentially allow for a higher payload or longer range compared with an equivalent kerosene-fuelled aircraft. This effect is, however, counteracted by increased structure weight of the cryoplanes, owing to a somewhat larger aircraft needed to carry the bulky fuel and additional facilities required to handle the fuel, e.g. isolation of fuel tanks and a heat exchanger required to evaporate the fuel prior to the combustor. The low energy content per volume of liquid hydrogen will require a new aircraft design, provided with roughly four times larger fuel tanks compared with conventional aeroplanes.

Engines must be re-designed for the new fuel, particularly with respect to minimisation of NO_x emissions. The fuel system will be completely new, and its components will need dedicated technology development.

Hence, while offering great prospects, use of liquid hydrogen as an aviation fuel poses formidable challenges regarding technical development, energy requirement for producing hydrogen, handling, aircraft design and making liquid hydrogen (LH_2) economically compatible with kerosene.

Looking at the prospect of alternative fuels, there are a few more candidates in addition to hydrogen worth mentioning. These include alcohols, such as, ethanol and methanol, liquid methane and synthetic kerosene. Alcohols offer environmental benefits as they are renewable energy sources, and since they are liquid fuels, they do not impose any major infrastructure changes at airports. Moreover, an experimental study of ethanol blended Jet-A fuels indicates marked reductions in carbon dioxide, oxides of nitrogen and soot formation with increasing blend rates (Eiff *et al*(13)). However, as an aviation fuel their usage carries a number of drawbacks. At low power condition the combustion of alcohols produces organic acids and aldehydes, with attendant health hazards to ground support personnel (Eiff *et al*(13)). Introducing it in aviation on a large scale would require an extensive supply of hydrocarbons from renewable energy sources; a supply which is questionable whether it is available or even possible to obtain. The overall disadvantage, however, with alcohols, which makes them a less attractive substitute to kerosene, is their very low heat contents, both in terms of mass and volume (these are about half the corresponding values for kerosene), thus imposing significant penalties in aircraft range and/or payload capacity.

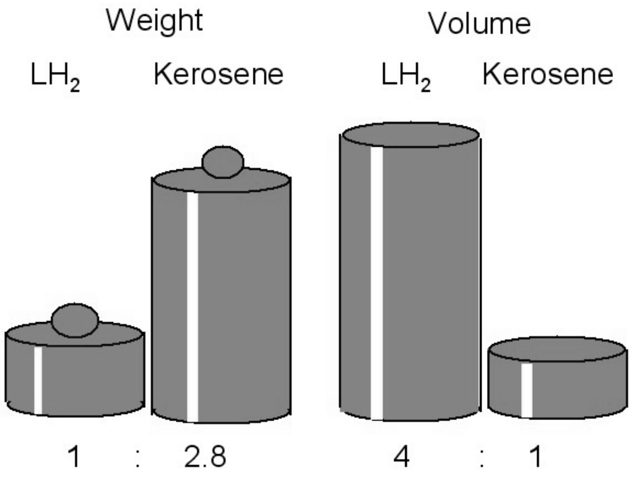

Figure 2. The weight and volume of kerosene and liquid hydrogen, respectively, containing the same energy content. (Illustration idea from Heinz-Günter Klug, retired from Airbus Germany).

Another candidate, which is cryogenic just like hydrogen, is liquid methane. Since it is a cryogenic fuel, it does impose similar challenges as hydrogen with respect to fuel handling and aircraft design. In terms of energy content methane shows similar trends as hydrogen, although the differences are smaller compared with kerosene, i.e. both the penalty in energy density and the gain in specific energy are smaller. The main advantage with methane is that it is an energy source that does not need to be produced. However, since it is a fossil fuel, it might be difficult to find reasonable justification to introduce this novel fuel, taking into account its major consequences on the aircraft and airports with only a small environmental benefit, originated in its higher hydrogen/carbon ratio compared with kerosene. Methane could also be produced from renewable energy sources by digesting processes, but it is questionable if these are feasible methods for large-scale production. In addition, it is possible to produce methane from biomass via synthesis gas. It is true that gas resources will be available for another few decades after the oil is depleted, but as the climate change due to anthropogenic sources is anticipated to raise the environmental concerns in the future, it seems unlikely that cryogenic methane will become an attractive option for civil aviation, at least not for large-scale applications.

The third and last alternative fuel discussed here is synthetic kerosene, which may be renewable if produced from renewable energy sources. The efficiency for producing the fuel is about the same as for producing liquid hydrogen (see Part III). It is a liquid fuel with about the same energy content as kerosene, and would therefore impose the smallest required changes in aircraft and fuel systems compared with the other alternative fuels discussed here. Owing to a small content of aromatic hydrocarbons in synthetic kerosene, it is less unhealthy to handle and produces less toxic unburned hydrocarbons emissions when burnt than conventional kerosene. Furthermore, the low content of aromatic hydrocarbons is likely to reduce the NO_x and soot emissions, where the former is an effect of lowered combustion temperature. More details on the prospects of using synthetic kerosene for aviation can be found in Eklund and Hedemalm(14).

Blending conventional and synthetic kerosene based on biomass with up to 50% vol synthetic fuel, i.e. the maximum amount which is allowed according to the '*Standard Specification for Aviation Turbine Fuels*' (Eklund and Hedemalm(14)), would be a efficient way to reduce immediately aviation's contribution to global warming. In the very long run, however, synthetic kerosene seems to be a less attractive alternative to kerosene than hydrogen, as its production requires large quantities of one single energy source, namely, biomass. In order to mitigate the climate impacts of the greenhouse effect it would be reasonable to increase CO_2 absorbing sources, of which the biosphere is one of the most important, rather than decrease or keep them at a constant level. Which alternative candidate will be the most attractive in the future is highly dependent on available future fuel production methods. That fuel, for which viable, efficient and renewable production methods for large-scale applications are available, is likely to be the more attractive candidate.

4.0 PREVIOUS WORK ON THE CONCEPT OF USING HYDROGEN FOR AVIATION

The history of hydrogen as an aircraft turbojet fuel started in 1937, when a Heinkel HeS-2 experimental turbojet engine was rig tested running on hydrogen (Dahl and Suttrop(15)). At that time, the reason for choosing hydrogen was actually that the gasoline-fuelled combustor turned out to require lengthy development efforts, whereas gaseous hydrogen combustion proved to be applicable in spite of the restricted combustor volume conditions, and hence could be used immediately for an early demonstration of the feasibility of the jet engine principle.

About 20 years later in 1956, Pratt & Whitney Aircraft was commissioned by the United States Air Force to conduct a program to investigate the feasibility of using LH_2 as a fuel for aircraft engines. These efforts comprised among other things the testing of the J57 engine modified for hydrogen operation, and the development of a hydrogen-fuelled demonstration engine to be used for supersonic reconnaissance (Dahl and Suttrop(15)).

Stimulated by military needs of longer range and higher altitude, testing with hydrogen was performed at the NASA Lewis Research Centre from the mid 1950s (Dahl and Suttrop(15); Conrad(16)). Three different turbojet engines were evaluated in altitude test chambers (J47, J65-B-3 and J71-A11). After that, the J65 engine and hydrogen supply system components were installed on the B-57 aeroplane. With one of the engines operated on hydrogen the aircraft was successfully flown in February 1957 (Fig. 3). The left engine which was configured for hydrogen was able to run on JP-4 fuel for take-off and initial cruise. At high altitudes the transition to hydrogen operation was performed in two steps: purging of hydrogen lines and dual fuel operation for two minutes before switching to hydrogen alone. Over 40 transitions were performed in the program. The helium in the right wing tip mounted tank was used to pressurise the ullage above the LH_2 in the left wing tip mounted tank, thus forcing it through the heat exchanger.

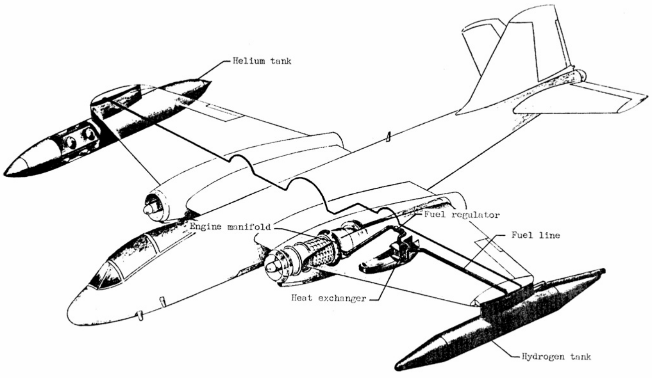

Figure 3. B-57 aeroplane equipped with hydrogen system (Conrad, 1979).

Having accomplished the tests, it was concluded that various technology advances were required and some technical problems needed to be solved before application to civil aviation would be feasible. Engine re-designs to better capitalise on the hydrogen characteristics to improve performance needed to be studied further. One problem that occurred was that the transition to hydrogen was accompanied by significant fluctuations in engine speed, which was believed to be a consequence of unsteady boiling in the heat exchanger and thus causing rapid changing of hydrogen flow to the engine. The activities were closed in 1958 because military studies indicated that the costs of providing hydrogen to all strategic aircraft bases would be excessive.

In the 1970s, the General Electric Company participated in design studies and research and development programs concerning using hydrogen for aircraft propulsion systems (Payzer and Renninger(17)). These efforts were mainly a consequence of the OPEC oil price dictation which caused the world to become conscious of the possibility that the availability of fossil fuels may be restricted. During this period also various other studies supported by the NASA Langley Research Center were accomplished (Brewer(18,19)). These studies comprised investigations of both subsonic and supersonic aircraft designed to use synthetic aviation grade kerosene (synjet), liquid hydrogen and liquid methane. Various engine designs employed in this study were evaluated in a study performed by AiResearch-Arizona Division (Baerst and Riple(20)). Another study initiated due to the energy crisis is Pratt *et al*(21), looking at the technical, economical and environmental impact of using hydrogen as a turbojet engine fuel.

Further tests with aircraft using hydrogen were performed in the 1980s by the Russian TRUD† who jointly developed an experimental Tu155 aircraft. On this aircraft one of the three engines was converted to the dual fuel engine, NK88, burning either kerosene and LH_2 or liquid natural gas (LNG) and kerosene (Sosounov and Orlov(22)). This experimental aircraft, which is based on the Tu154 passenger aircraft, is provided with a hydrogen tank of $18m^3$ in the rear fuselage. For safety reasons the aircraft fuel section is either filled with nitrogen or constantly purged with air from the aircraft conditioning system. The aircraft is also provided with a helium system used for pipeline purging as well as for control of the hydrogen fuel system valves. The first flight was accomplished in April 1998 and it lasted for 21 minutes. As opposed to earlier flight tests with aircraft using hydrogen, the whole flight mission was performed with the NK88 running on hydrogen. This experimental aircraft conducted several flights with the NK88 engine and all its systems running well without any shut-downs, using both LH_2 and LNG.

More recently, environmental concerns, as well as the expected depletion of fossil fuel resources, have become the driving forces for research and development towards the introduction of hydrogen energy into air traffic. During the 1990s Airbus Germany and the Russian aircraft manufacturer Tupolev put much effort on resolving these issues (Klug(23); Klug *et al*(24); Klug and Grassl(25)). These studies looked at hydrogen from a systems perspective including various fields which are affected by introducing hydrogen as an aviation fuel. In January 1992 a 58-month programme, named Euro-Québec Hydro-Hydrogen Pilot Project (EQHHPP), involving industry and research establishments was initiated. This programme

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† TRUD: Kuibyshev scientific-production association (KSPA) and Central Institute of Aviation Motors (CIAM).

was aimed at establishing the NO_x reduction potential when burning hydrogen and at providing design guidelines for later development of real aero engine combustors (Shum *et al*(26)). In the third phase of EQHHPP, analytical modelling and experimental tests of low-NO_x combustors for aero engines were performed (Ziemann *et al*(27,28)); Dahl and Suttrop(29)). As a result of the project, combustor configurations burning hydrogen which offered very low NO_x emissions were suggested (see Part II).

In 2000 the EC-sponsored project CRYOPLANE was initiated. The project covered a period of two years and involved 36 partners from industry, research institutes and universities. It was a system analysis of using liquid hydrogen for civil subsonic aviation, covering a range of subjects from hydrogen production methods to the environmental compatibility. An overview of the results is given in the project final technical report (Westenberger(30)). As for the engine and combustor design when burning hydrogen, a number of papers and theses which condense results obtained within or after the CRYOPLANE project are published: Haglind and Singh(31,32), Svensson(33), Svensson and Singh(34) Corchero and Montañes(35), Boggia and Jackson(36), Boggia *et al*(37), and Boggia(38). Examples of studies covering the environmental effects of introducing hydrogen for aviation are Ponater *et al*(39), Svensson *et al*(40), and Marquart *et al*(41).

5.0 CONCLUSIONS AND DISCUSSION

In this first part of the paper (constituting three parts), the background motivating why it is essential to find an alternative kerosene in the long run is outlined. In addition, the prospects, challenges and previous work of using hydrogen fuel are discussed.

Global warming due to anthropogenic sources seems to be a serious concern that needs to be dealt with in order to mitigate the consequences. Conventional aircraft produce a number of different emission species that affect both the local air quality and the global climate. The climate impact in terms of radiative forcing from aviation today is quite small in relation to all anthropogenic sources. However, as aviation is expected to grow faster than other sectors that generate greenhouse gases, the aviation share is expected to grow significantly over the next few decades. It is therefore essential to find an alternative to kerosene.

Looking at the prospect of alternative fuels, there are a number of candidates: liquid hydrogen, liquid methane, alcohols, such as, ethanol and methanol, and synthetic kerosene. Alcohols offer environmental benefits as they are renewable energy sources, and since they are liquid fuels, they do not impose any major infrastructure changes at airports. However, they have very low heat contents, both in terms of mass and volume (these are about half the corresponding values for kerosene), thus imposing significant penalties in aircraft range and/or payload capacity. Liquid methane is based on a fossil resource and it imposes similar challenges with respect to fuel handling and aircraft design as hydrogen does. Moving to methane would therefore only generate a small environmental benefit, originated in its higher hydrogen/carbon ratio compared with kerosene.

Synthetic kerosene is a liquid fuel with about the same energy content as kerosene, and would therefore impose the least required changes in aircraft and fuel systems compared with the other alternative fuels discussed here. It can be produced from biomass, which would imply that it can be considered as a CO_2 neutral fuel. Liquid hydrogen can be produced from any energy source and the pollutant emissions are reduced to water vapour and NO_x emissions (provided that renewable energy sources are used for the hydrogen production); all emissions containing carbon and sulphur are eliminated. The fuel handling infrastructure and aircraft configurations need, however, to be changed.

Considering the prospects of introducing alternative fuels in order to reduce the climate impact of aviation, synthetic kerosene offers the possibility of an immediate change without imposing the fuel infrastructure changes or aircraft re-design. Blending conventional and synthetic kerosene based on biomass with up to 50% vol synthetic fuel, seems a feasible and efficient way to reduce aviation's contribution to global warming in the short run (within about 20 years from now). Based on this rather brief, qualitative analysis of potential future fuels in addition to hydrogen and looking mostly from an environmental perspective, hydrogen seems the more attractive alternative in the long run (more than about 20 years from now). The main reason being that it can be produced from water using any energy source, whereas renewable kerosene (i.e. kerosene produced from biomass) requires large quantities of one single energy source, namely, biomass. In order to mitigate the climate impacts of the greenhouse effect it would be reasonable to increase CO_2 absorbing sources, of which the biosphere is one of the most important, rather than decrease or keep them at a constant level.

Powering aero engines and aircraft with hydrogen has been done successfully in a number of occasions in the past. Most of these experiments have involved aircraft that have been only partly adapted to hydrogen, e.g. the Russian Tu-154 aircraft of which one of three engines was converted to dual fuel use. What remains to be done is to evaluate this technology for an aircraft completely adapted for hydrogen fuel use. Realising this technology change for a fleet of aircraft poses formidable challenges regarding technical development, energy requirement for producing hydrogen, handling, aircraft design and making liquid hydrogen (LH_2) economically compatible with kerosene.

In Part II of the paper the fundamental effects on aero engine pollutant emissions, performance and design of changing to hydrogen fuel is covered. Moreover, the subject of designing an aero gas turbine using hydrogen for low environmental impact is raised. In the last part, Part III, the optimum cruising altitudes for minimum global warming for a liquid hydrogen-fuelled aircraft and a conventional aircraft are found. Furthermore, in Part III, the feasibility of introducing cryoplanes on a regional level is explored. The infrastructure changes and possible hydrogen production methods at Stockholm/Arlanda airport are discussed.

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† 'Fredrik Svensson' has changed his surname to 'Haglind'.