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Green Freighter –

Requirements and Selection of Design Concepts to be Investigated

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19. Kurzfassung

Gegenstand dieses Flugzeugentwurf-Forschungsprojektes ist der Entwurf und die Bewertung von unkonventionellen umweltfreundlichen und kosteneffektiven Frachtflugzeugen. Die wichtigsten Merkmale für Umweltfreundlichkeit sind geringe Emissionen (insbesondere Kohlendioxid und Stickstoffoxide) und ein niedriger Lärmpegel. Unkonventionelle Flugzeugkonfigurationen sind z.B. Entenflugzeuge, Dreiflächenflugzeuge, Flugzeuge mit verbundenen Flügeln, Multirumpf-, Nurflügel- und Blended-Wing-Body- (BWB-) Flugzeuge. Mögliche Arten von Antriebsystemen sind Strahl-, Propeller- und Propfan-Triebwerke in Kombination mit unterschiedlichen Kraftstoffen wie Kerosin, synthetischen Kraftstoffen, Biofuels, Alkoholen, Silane, flüssigem Erdgas und Wasserstoff sowie elektrische Antriebsysteme. Die Projektpartner haben den BWB als die unkonventionelle Flugzeugkonfiguration und die Boeing B777F als herkömmliches Referenzflugzeug gewählt. Die wichtigsten Flugzeuganforderungen sind 109 t Nutzlast, 4800 NM Reichweite und eine Reiseflug-Machzahl von 0,85. Neben dieser Ausgangsversion soll ein zweiter, propellergetriebener BWB untersucht werden, dessen Reiseflug-Machzahl bei ca. 0,5 liegen soll. Weitere Umweltanforderungen sind z.B. ein Lärmpegel von 25 dB unterhalb Chapter 3 sowie 30% weniger NOx und 50% weniger unverbrannte Kohlenwasserstoffe und Kohlenmonoxid-Emissionen als in CAEP/4 gefordert.

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19. Abstract
Scope of this joined aircraft design research project is the design and assessment of an unconventional environmentally friendly and cost effective freighter aircraft. The most important indicators for environmental friendliness are low emissions (especially carbon dioxide and nitrogen oxides) and a low noise level. Unconventional aircraft configurations are e.g. canard, three-surface, joined wing, multi-fuselage, flying wing and blended wing-body (BWB) aircraft. Possible types of propulsion systems are jet, propeller and propfan engines in combination with different fuels such as kerosene, synthetic fuels, Biofuels, alcohols, Silane, liquid natural gas and hydrogen as well as electric propulsion systems. The project partners have chosen the BWB as the unconventional aircraft configuration and the Boeing B777F as the conventional reference aircraft. The most important initial top level aircraft requirements are 109 t payload, 4800 nm range and a cruise Mach number of 0.85. Besides this initial version, a second propeller-driven BWB shall be investigated that cruises at a lower Mach number of about 0.5. Additional environmental requirements are e.g. a noise level of 25 dB below Chapter 3, 30% less NOx and 50% less unburned hydrocarbons and carbon monoxide emissions than required in CAEP/4.

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Abstract

Scope of this joined aircraft design research project is the design and assessment of an unconventional environmentally friendly and cost effective freighter aircraft. The most important indicators for environmental friendliness are low emissions (especially carbon dioxide and nitrogen oxides) and a low noise level. Unconventional aircraft configurations are e.g. canard, three-surface, joined wing, multi-fuselage, flying wing and blended wing-body (BWB) aircraft. Possible types of propulsion systems are jet, propeller and propfan engines in combination with different fuels such as kerosene, synthetic fuels, Biofuels, alcohols, Silane, liquid natural gas and hydrogen as well as electric propulsion systems. The project partners have chosen the BWB as the unconventional aircraft configuration and the Boeing B777F as the conventional reference aircraft. The most important initial top level aircraft requirements are 109 t payload, 4800 nm range and a cruise Mach number of 0.85. Besides this initial version, a second propeller-driven BWB shall be investigated that cruises at a lower Mach number of about 0.5. Additional environmental requirements are e.g. a noise level of 25 dB below Chapter 3, 30% less NOx and 50% less unburned hydrocarbons and carbon monoxide emissions than required in CAEP/4.

Table of Contents

List of Figures

List of Tables

Nomenclature

AAGR	Annual Average Growth Rate
AC	Alternating Current
ACARE	Advisory Council for Aeronautics Research in Europe
ACN	Aircraft Classification Number
AC20.30	Aircraft 2030
AFRL	(U.S.) Air Force Research Laboratory
AGE	Aviation Grade Ethanol
AOA	(British) Airport Operators Association
APU	Auxiliary Power Unit
ASD	Aerospace and Defence Industries Association of Europe
AUW	All-up Weight (= Total Weight)
BF	Block Fuel
BPR	Bypass Ratio
BtL	Bio(mass) to Liquid
CAEP	Committee on Aviation Environmental Protection

C_D	Drag Coefficient
C_L	Lift Coefficient
CMO	(Boeing) Current Market Outlook
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CtL	Coal to Liquid
D	Drag Force
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DLF	Distributed Load Freighter
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German; German Aerospace Center)
EC	Energy Converter European Commission
ECS	Environmental Control-System
EKIP	Ekologija i Progress (Russian; Ecology and Progress)
EREA	Association of European Research Establishments in Aeronautics
EU	European Union
EWADE	European Workshop on Aircraft Design Education
FAA	Federal Aviation Administration
FAME	Fatty Acid Methyl
FEU	Forty-Feet-Equivalent-Unit (40’-Standard-ISO-Container)
FFA	Flygtekniska Försöksanstalten (Swedish; Aeronautical Research Institute of Sweden; since 2003 part of FOI)
FOI	Totalförsvarets Forskningsinstitut (Swedish; Swedish Defense Research Agency)
FP(6)	(Sixth) Framework Programme (EU-funded R&D program)
FPO	Future Projects Office
FTK	Freight Tonne Kilometer
F-T (Process)	Fischer-Tropsch (Process)
GA	General Aviation
GF	Green Freighter
GHG	Greenhouse Gas
GLOW	Gross Lift-Off Weight
GMF	(Airbus) Global Market Forecast
GTF	Geared Turbofan
GtL	Gas to Liquid
H, H_2	Hydrogen
H	Fuel Specific Heat Content
HAW (Hamburg)	Hochschule für Angewandte Wissenschaften (Hamburg) (German; (Hamburg) University of Applied Sciences)

HC	Hydrocarbon
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCEPT	Imperial College Centre for Energy Policy and Technology
IFL	Institut für Flugzeugbau und Leichtbau (German; Institute of Aircraft Design and Lightweight Structures)
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
ISO	International Organization for Standardization
JAR	Joint Aviation Requirements
JP (JP4 – kerosene)	Jet Propellant
JTI	Joint Technology Initiative
L	Lift
LH2	Liquid Hydrogen
LL	Low Lead
LNG	Liquefied Natural Gas
LRC	Long Range Cruise
L/D	Lift-to-Drag Ratio
M	Mach Number
MOM	Measure of Merit
MTOW	Maximum Take-Off Weight
MWE	Manufacture Weight, empty
NACRE	New Aircraft Concepts Research
NASA	National Aeronautics and Space Administration
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (Dutch; National Aerospace Laboratory)
NM	Nautical Mile
NO_x	Nitrogen Oxides
NS	Number of Seats
OFW	Oblique Flying Wing
OWE	Operating Weight, empty
Pax	Passenger(s)
PEMFC	Proton Exchange Membrane Fuel Cell
PrADO	Preliminary Aircraft Design and Optimization program
PRC	People's Republic of China
psf	Pound per Square Feet
QGT	Quiet Green Tarnsport
QC	Quota Count
(NASA) RASC	(NASA) Revolutionary Aerospace Systems Concepts program
RTK	Revenue Ton Kilometer
R&D	Research and Development

SAAB	Svenska Aeroplanaktiebolaget (Swedish; Swedish Aeroplane Limited)
SFC	Specific Fuel Consumption
SOFC	Solid Oxide Fuel Cell
sqm	Square Meter
SRA	Strategic Research Agenda
STOL	Short Take-Off and Landing
TEU	Twenty-Feet-Equivalent-Unit (20’-Standard-ISO-Container)
TLAR(s)	Top Level Aircraft Requirement(s)
TUBS	Technische Universität Braunschweig (German; Technical University of Braunschweig)
T-O	Take-Off
UDF	Unducted Fan
UHB (Engine)	Ultra-High By-Pass (Engine)
ULD	Unit Load Device
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
V	Velocity
VELA	Very Efficient Large Aircraft
W	Weight
WIG	Wing in Ground-Effect (Aircraft)
WMO	World Meteorological Organization
WP	Work Package
η	Efficiency
(n)’	(n) Feet
(n)”	(n) Inch

Subscript

app	Approach
CR	Cruise
max	Maximum
min	Minimum
mo	Maximum Operation

Terms and Definitions

ACARE

The Advisory Council for Aeronautics Research in Europe (ACARE) was launched in 2001 after the need for it had been formulated in Vision 2020. ACARE is made up of about 40 members representing the EC, national ministries, industry, airlines, airports, research establishments and academia. Its main focus is to establish and carry forward a Strategic Research Agenda (SRA) that will influence all European stakeholders in the planning of research programs, particularly national and EU programs, in line with the Vision 2020 and the goals it identifies.

(**ACARE 2003**)

CAEP

> *ICAO's current environmental activities are largely undertaken through the Committee on Aviation Environmental Protection (CAEP), which was established by the Council in 1983, superseding the Committee on Aircraft Noise (CAN) and the Committee on Aircraft Engine Emissions (CAEE).*
>
> *...*
> *CAEP assists the Council in formulating new policies and adopting new Standards on aircraft noise and aircraft engine emissions. CAEP's Terms of Reference and Work Programme (pdf) are established by the Council.*
>
> *The current structure of the Committee includes five working groups and one support group. Two of the working groups deal with the technical and operational aspects of noise reduction and mitigation. The other three working groups deal with technical and operational aspects of aircraft emissions, and with the study of market-based measures to limit or reduce emissions such as emissions trading, emissions-related charges and voluntary measures (pdf). The support group provides information on the economic costs and environmental benefits of the noise and emissions options considered by CAEP.*
>
> *About once a year, CAEP meets as a Steering Group to review and provide guidance on the progress of the activities of the working groups. So far, CAEP has held six formal meetings: in 1986 (CAEP/1), 1991 (CAEP/2), 1995 (CAEP/3), 1998 (CAEP/4,) 2001 (CAEP/5) and 2004 (CAEP/6). Each formal CAEP meeting produces a report with specific recommendations for the consideration of the ICAO Council. These reports are saleable Publications. ...*

(**ICAO 2007a**)

Chapter 2, Chapter 3, Chapter 4

> *In 2001, the ICAO Assembly endorsed the concept of a "balanced approach" to aircraft noise management (Appendix C of Assembly Resolution A35-5 (pdf)). This consists of identifying the noise problem at an airport and then analysing the various measures available to reduce noise through the exploration of four principal elements, namely reduction at source (quieter aircraft), land-use planning and management, noise abatement operational procedures and operating restrictions, with the goal of addressing the noise problem in the most cost-effective manner. ICAO has developed policies on each of these elements, as well as on noise charges.*
>
> *...*
> *Much of ICAO's effort to address aircraft noise over the past 30 years has been aimed at reducing noise at source. Aeroplanes and helicopters built today are required to meet the noise certification standards adopted by the Council of ICAO. These are contained in Annex 16 — Environmental*

> *Protection, Volume I — Aircraft Noise to the Convention on International Civil Aviation, while practical guidance to certificating authorities on implementation of the technical procedures of Annex 16 is contained in the Environmental Technical Manual on the use of Procedures in the Noise Certification of Aircraft (Doc 9501).*
>
> *The first generation of jet-powered aeroplanes was not covered by Annex 16 and these are consequently referred to as non-noise certificated (NNC) aeroplanes (e.g. Boeing 707 and Douglas DC-8). The initial standards for jet-powered aircraft designed before 1977 were included in Chapter 2 of Annex 16. The Boeing 727 and the Douglas DC-9 are examples of aircraft covered by Chapter 2. Subsequently, newer aircraft were required to meet the stricter standards contained in Chapter 3 of the Annex. The Boeing 737-300/400, Boeing 767 and Airbus A319 are examples of "Chapter 3" aircraft types. In June 2001, on the basis of recommendations made by the fifth meeting of the Committee on Aviation Environmental Protection (CAEP/5), the Council adopted a new Chapter 4 noise standard, more stringent than that contained in Chapter 3. Commencing 1 January 2006, the new standard will apply to newly certificated aeroplanes and to Chapter 3 aeroplanes for which re-certification to Chapter 4 is requested.*
>
> *A Noise database Noise dB was developed in 2006 by the French DGCA under the aegis of the International Civil Aviation Organization (ICAO). The site is in its final experimental phase and data should be considered preliminary. The final Noise dB is expected to be available in October 2006. The goal of this database is to provide certification noise levels for each aircraft type guaranteed by certification authorities. The Noise dB application is intended as a general source of information for the public. ...*

(**ICAO 2007b**)

Cryoplane

Cryoplane was a joint European research project on hydrogen powered aircraft as part of the topic “Sustainable Growth” under the Fifth Framework Program. It comprised 35 partners from industry, research and academia coming from 11 European countries. It last from April 2000 until June 2002 and covered a broad field of detailed investigations, such as Aircraft Configuration, Systems and Components, Propulsion, Safety , Environmental Compatibility, Fuel Sources, Infrastructure, Transition Scenarios and Trade-off Slush Hydrogen.

(**Westenberger 2003**, **Faaß 2001**)

Emissions Trading

The British Airport Operators Association (AOA) cites the following statements of the IPCC in its Environmental Guidance Manual for Airports:

> *According to studies carried out in 1999 by the Intergovernmental Panel on Climate Change (IPCC), aviation in 1992 was responsible for 2% of global carbon dioxide emissions arising from fossil fuel combustion and 13% of the emissions from transport as a whole. However, due to the generation of other radiative forcing effects, including high altitude contrails and the effect of emissions of nitrogen oxides at high altitudes on upper atmospheric ozone concentrations (termed non-*CO_2 *effects), it has been estimated that the total radiative forcing effect of aviation emissions could be up to 2.7 times that of carbon dioxide alone. Accordingly, it has been estimated that aircraft were responsible for 3.5% of the total global radiative forcing effect in 1992. Future projections of the aviation contribution to the effect by 2050 suggested that the effect would be, at a maximum, 3.8 times larger than that in 1992, some 14% of total global radiative forcing.*

Furthermore, the AOA “believes that ‘mainstreaming’ aviation by incorporating it into an open emissions trading scheme is the most economically efficient and environmentally effective way of ensuring that aviation bears and fully internalises the cost of its CO_2 emissions.” (**AOA 2006**).

Inside aviation business, positions differ a lot on the topic ‘emissions trading’. The European Parliament proposed a “‘closed, aviation-only’ emissions trading scheme” (**Flight International 2006c**) and a cap on CO_2-emissions for all aircraft arriving or departing from EU airports from 2012. Many airlines argue against this proposal due to aviation’s small share of the global total CO_2-emissions and its great importance for economy (**von Heeremann 2007, Flight International 2007j**). In contrast, the International Air Transport Association (IATA) says that “emissions trading is the best way for Europe to meet its Kyoto treaty targets, but only with the right trading formula and if airlines take part in a multi-industry emissions market…” (**Flight International 2006c**). It is accounted that other business sectors have a lot more potential to reduce their CO_2-emissions and to do so in a much cheaper way (**Flight International 2007j**). Airlines already have every reason to reduce fuel burn and, hence, emissions.

In this context, the International Civil Aviation Organization (ICAO) says that “airlines increasingly look at ways to help passengers offset the environmental impact of flying”. Some airlines are already about to launch their own schemes, though there are still some difficulties to overcome (**Flight International 2007a**). Generally it can be observed that there is a passenger demand and willingness to pay for a reduction of air traffic’s CO_2-emissions.

IPCC

> *The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988 to: (i) assess available information on the science, the impacts, and the economics of, and the options for mitigating and/or adapting to, climate change and (ii) provide, on request, scientific/technical/socio-economic advice to the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC). Since then the IPCC has produced a series of Assessment Reports, Special Reports, Technical Papers, methodologies, and other products that have become standard works of reference, widely used by policymakers, scientists, and other experts.*
>
> (**IPCC 1999**)

NACRE

The acronym NACRE stands for “New Aircraft Concepts Research”. It describes a four years EU FP6-funded research program under Airbus lead together with 35 partners on

- New aircraft concepts to foster technological innovation,
- Novel Lifting Surfaces and Control for improved structure and aerodynamic efficiency through an integrated approach,
- Novel Powerplant Installation: challenging configurations for ambitious goals on environment protection and cost-efficiency,
- Novel Fuselage and Cabin to develop passenger-centered concepts and cost-efficient technologies.

(**Schmitt 2007**)

Radiative Forcing

> *Radiative forcing is a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square metre (Wm-2). Positive values of radiative forcing imply a net warming, while negative values imply cooling.*

(**IPCC 1999**)

VELA

The VELA (Very Efficient Large Aircraft) project was an EU FP5-funded research project of 16 partner establishments from 8 nations to enhance the knowledge on blended wing-body (BWB) configurations. Its duration was from 2002 to 2005.

(**Kresse 2006**)

Vision 2020

In 2001, a group of 14 personalities representing the major European stakeholders in aviation, as there are: the European Commission, national ministries, research agencies and aircraft and engine manufacturers, formulated a vision for the European air transport system in 2020 – the Vision 2020. Vision 2020 sets several goals to be achieved by 2020 in order to reach two top level objectives:

1. Responding to society's needs and
2. Securing Europe's global leadership in aeronautics.

Some of the direct goals are:

- Reduction of accidents in air transport by 80 percent,
- Handling of 16 million flights per year,
- Cost reduction in air transport by 30 percent,
- Reduction of passenger waiting time at the gate to less than 15 min for short-haul and less than 30 min for long-haul flights,
- Improvement of punctuality – less than 5 percent of all flights with 15 min or more delay,
- Reduction of noise by 50 percent,
- Reduction of CO_2- and NO_x-emissions by 50 percent resp. 80 percent

(**Szodruch 2006**)

1 Introduction

1.1 Motivation

The global climate is changing. Meteorological observations show increases in global air and ocean temperatures, glaciers and the arctic polar cap are melting and the global mean sea level is rising. Direct observations of the recent global climate change show a 100-year linear trend of 0.74 °C for 1906-2005 and an average ocean temperature increase to depths of at least 3000 m. The warming in the polar regions is even double that for the globe from 19th to 21st century. Furthermore, widespread changes in extreme temperatures, droughts, floods and heat waves have been observed (**IPCC 2007**). "Paleoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 metres of sea level rise" (**IPCC 2007**). "The understanding of anthropogenic warming and cooling influences on climate has improved ..., leading to very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming ..." (**IPCC 2007**). Furthermore, **IPCC 2007** says that "**most of the observed increase in globally averaged temperatures** since the mid-20th century **is very likely** due to the observed increase in **anthropogenic** greenhouse gas concentrations" and "continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century".

"Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere where they have an impact on atmospheric composition. These gases and particles alter the concentration of atmospheric greenhouse gases, including carbon dioxide (CO_2), ozone (O_3), and methane (CH_4); trigger formation of condensation trails (contrails); and may increase cirrus cloudiness—all of which contribute to climate change" (**IPCC 1999**, see Figure 1.1).

Since the beginnings of aviation, aircraft emissions have been increasing continuously as air traffic has been growing faster than the technological and operational improvements leading to fuel burn reduction. In 1992, **aviation's contribution to global CO_2-emissions was about 2%** (**IPCC 1999**, p. 6), however, the impacts of these emissions are more difficult to assess. "The best estimate of the radiative forcing [see Terms and Definitions; remark of this author] in 1992 by aircraft is 0.05 Wm-2 **or about 3.5% of the total radiative forcing** by all anthropogenic activities. For the reference scenario (Fa1), the radiative forcing by aircraft in 2050 is 0.19 Wm-2 ... (3.8 times the value in 1992). ... These estimates of forcing combine the effects from changes in concentrations of carbon dioxide, ozone, methane, water vapour, line-shaped contrails, and aerosols, but do not include possible changes in cirrus clouds" (**IPCC 1999**, p. 8).

Fig 1.1 Contrails behind a Boeing B747 (**airliners.net 2003**)

This knowledge about climate change and other environmental effects leads to a growing environmental awareness in politics, economy and society in general. Results of this awareness are increasing efforts to reduce greenhouse gas emission, like the implementation of emissions trading schemes (see Vision 2020 and Emissions Trading in Terms and Definitions), but also expand to other environmental issues such as aviation noise reduction. It is very likely that (CO_2-) emissions will become a larger, in terms of fees and taxes even major, expense factor for aircraft operators. Hence, the reduction of CO_2-emissions becomes, in addition to environmental aspects, more and more reasonable from an economic point of view. The same is valid for noise. Noise restrictions and noise-dependant landing fees are also about to become a more important factor for airlines and even more logistics companies that operate their cargo aircraft fleets mostly during nighttime.

Further improvements to the conventional aircraft configuration itself are only possible on a very small scale. Current improvements in aircraft efficiency and cost reduction mostly result from internal improvements such as more efficient engines and new materials. In contrast, there are other, unconventional aircraft configurations (see Section 2) which offer a lot more potential for further large improvements concerning noise, fuel burn and cost reduction.

1.2 Green Freighter Project Data

The Green Freighter project is a joint aircraft design research project on environmentally friendly and cost effective freighter aircraft of unconventional configuration. It was launched at the end of 2006 and has a duration of three years. The project partners are: Hamburg University of Applied Sciences (HAW), Institute of Aircraft Design and Lightweight Structures (IFL) at the Technical University of Braunschweig (TUBS), Airbus's Future Projects Office (FPO) and Bishop GmbH.

The aim of the project is to research unconventional cargo aircraft configurations and to compare these to conventional ones. Therefore, the investigations are based on a common technology level at a tentative date for the entry into service in 2025. Main focus is on environmentally friendly and economic aircraft operation. This includes technical aspects as follows:

- Low fuel consumption,
- Future fuels (liquid hydrogen (LH_2), synthetic fuels, Biofuel, …),
- Low noise level (nighttime operation),
- Low emissions (CO_2, NO_x, ..),
- Low operating costs (zero-pilot operation, no or reduced environmental control system).

1.3 Scope of Work Package 1

Work package 1, "Requirements and Selection of Design Concepts to be investigated", consists of three steps. The first one is a literature review to gain a broad database and knowledge about unconventional aircraft configurations. In the second step, these configurations shall be assessed concerning their potential for future improvements in terms of emissions reduction, noise reduction and cost reduction. Having set up this assessment, the final step of work package 1 is to make a selection of a design concept that appears to be able to achieve the largest improvements. For comparative reasons, a conventional reference aircraft shall be chosen to assess the results of the unconventional aircraft.

1.4 Literature Review

Many sources have been reviewed on the several aspects of this work package, and, as the general topic “answers to future challenges” will always stay up-to-date, many more are going to follow. Hence, the literature review can never be finished completely. Furthermore, even before the kick-off of the Green Freighter project several literature sources concerning previous investigations on comparable topics and the general state-of-the-art had been reviewed. The results of these early reviews are listed in the “Vorhabensbeschreibung” (project description) of the Green Freighter project (**Scholz 2006**).

The sources used may be divided into different classes:

- General sources on the actual discussion about CO_2- and other emissions, the greenhouse effect and global warming such as the **IPCC** reports and articles in daily press, TV, radio and magazines like **Der Spiegel**,
- Press specialized on aviation also dealing with actual technological an environmental trends and discussions from an aeronautical perspective such as **Flight International**,
- Technical (aeronautical and non-aeronautical) papers on environmental issues and unconventional fuels and propulsion systems such as **AOA 2006** and **Brewer 1991**.
- Technical aeronautical papers and books on (cargo) aircraft design and operation, sometimes including issues of unmanned aircraft operation such as **Raymer 2006** and **Liebeck 2005**.

IPCC 1999, the IPCC Special Report: Aviation and the Global Atmosphere, has been prepared by the IPCC Working Groups I (scientific aspects of the climate system and climate change) and III (options for limiting greenhouse gas emissions and otherwise mitigating climate change). It followed a request by, amongst others, the International Civil Aviation Organization (ICAO) to assess the consequences of greenhouse gas emissions from aircraft engines. “The report considers all the gases and particles emitted by aircraft into the upper atmosphere and the role that they play in modifying the chemical properties of the atmosphere and initiating the formation of condensation trails (contrails) and cirrus clouds... This report was compiled by 107 Lead Authors from 18 countries... Over 100 Contributing Authors submitted draft texts and information to the Lead Authors and over 150 reviewers submitted valuable suggestions for improvement during the review process” (**IPCC 1999**, p. vii). It “... is the first IPCC report for a specific industrial subsector... The report does not consider the local environmental effects of aircraft engine emissions or any of the indirect environmental effects of aviation operations such as energy usage by ground transportation at airports” (**IPCC 1999**, p. 3).

Torenbeek 2005 is a collection of papers on innovative and unconventional civil aircraft concepts and technologies. It includes the collection of course notes from a lectures series on this topic held in 2005 with internationally recognized experts as lecturers such as E. Torenbeek, R. Liebeck and A. Frediani. Though only parts of this book can be referred to in this report, it represents one of the most valuable sources on the general topic of unconventional aircraft configurations.

Liebeck 2005 deals in detail with the technical development of the design of blended wing-body subsonic transport aircraft during several stages. The first design studies were conducted from 1988 on at McDonnell Douglas and funded by NASA Langley Research Center. The first result of a blended wing-body concept is shown in Figure 1.2.

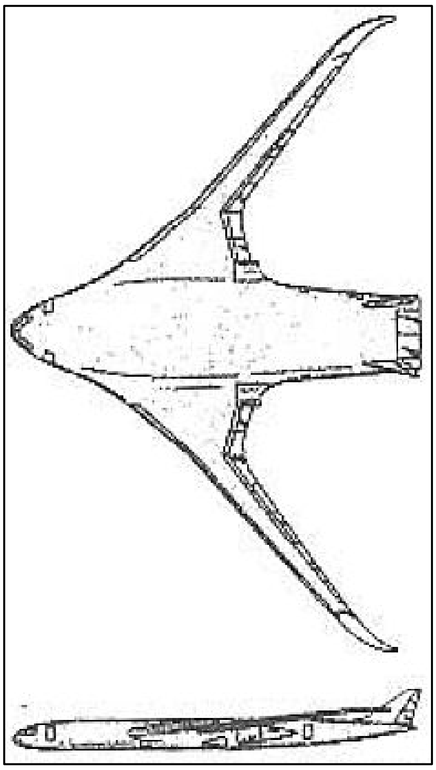


Fig 1.2 Early Blended Configuration Concept (**Liebeck 2005**)

About this initial version Liebeck says: “Here, the pressurized passenger compartment consisted of adjacent parallel tubes – a lateral extension of the double-bubble concept. Comparison with a conventional configuration airplane sized for the same design mission indicated that the blended configuration was significantly lighter, had a higher lift to drag ratio and a substantially lower fuel burn.” In the following years, this initial stage of a blended configuration experienced many changes and improvements during further design studies and lead to the Boeing BWB-450 Baseline Airplane design study. Based on the experiences during these studies, Liebeck gives valuable information about several general issues of BWB aircraft design and operation. This information already includes manufacturing and operational aspects down to the development of a BWB family concept, see Figure 1.3.

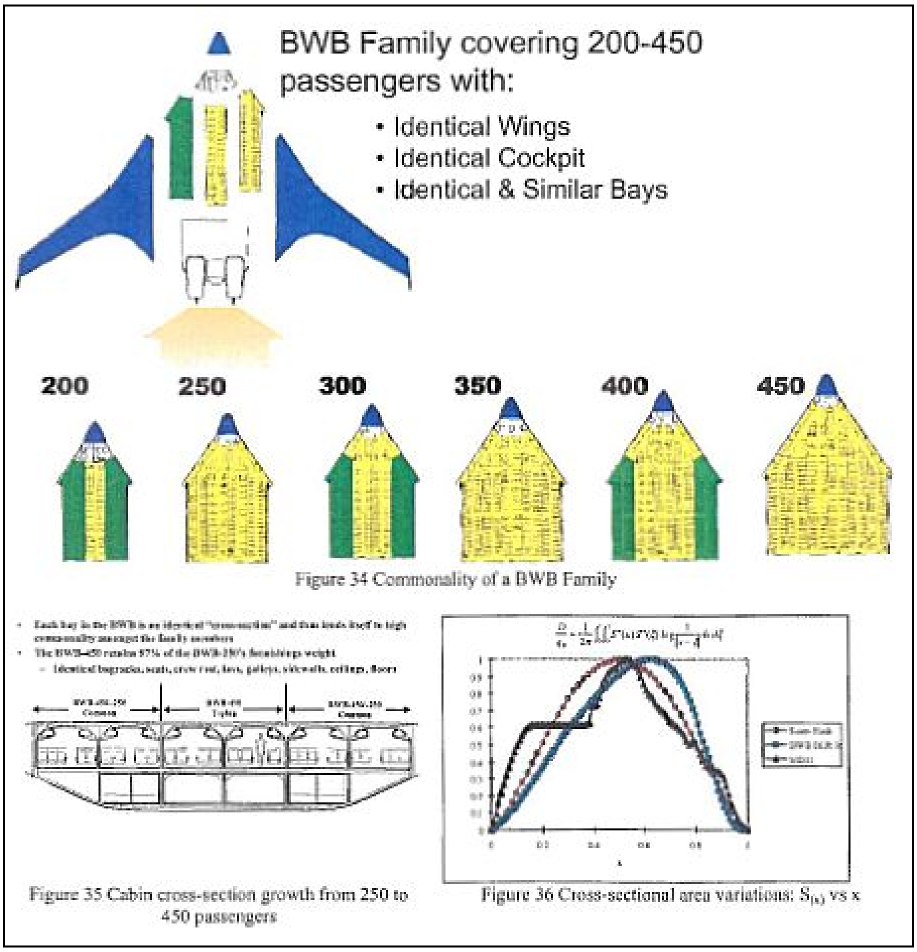


Fig 1.3 Commonality Aspects of a BWB Family (**Liebeck 2005**)

Guynn 2004 also deals with the evaluation of a BWB aircraft concept. However, here the main emphasis is put on noise and emissions reduction by means of a fuel cell propulsion system. This fuel cell powered BWB approach was one aspect of the “Quiet Green Transport” (QGT) study of the NASA Revolutionary Aerospace Systems Concepts (RASC) program. This paper gives valuable and well structured information on the study itself, technical details, methodologies and results of this evaluation.

Brewer 1991 may be regarded as the standard textbook on the use of hydrogen in aircraft technology. It covers practically all areas and aspects of hydrogen in aeronautics from the very beginning as a lifting gas in balloons and airships to aspects such as the potential of hydrogen as fuel for aircraft, subsonic transport aircraft, hypersonic aircraft, airport requirements, safety, environmental considerations, etc. Brewer describes all these aspects comprehensively and deals with many very detailed elements and systems like tank insulation, engine design, and engine cycle definition. It often compares the results of using hydrogen to the use of conventional or other fuels. Finally, this book gives a very sophisticated outlook for the use of hydrogen in the future including different scenarios and advices.

2 Unconventional Configurations

2.1 General

Practically all of today's transport aircraft show the conventional, or tail-aft as it is also called, configuration. It is defined by three main features:

1. A fuselage which carries the payload,
2. A wing attached to the fuselage that produces the lift and
3. An empennage, also called tailplane or just tails, at the aft end of the fuselage for stability and control.

So, every aircraft configuration that differs in one or more features from this is unconventional. Unconventional aircraft can be grouped as follows:

- Aircraft having an arrangement of wing(s) and tail(s) other than the described configuration like canard, tandem or biplane, three-surface, joined-wing and delta wing,
- Aircraft having more than one fuselage: multi-fuselage,
- Aircraft merging fuselage and wing: lifting fuselage, blended wing-body (BWB),
- Aircraft having no extra fuselage but only a wing (with or without tails) like flying wing, oblique flying wing (OFW) and EKIP.

Figure 2.1 shows a matrix representing these principal aircraft configurations. **Torenbeek 2005a** explains the same matrix as follows:

> *A configuration matrix (Figure 1* [here Fig. 2.1, remark of this author]*) depicts a collection by Deutsche Airbus of existing and hypothetical general arrangements. Some of these have been studied in the past decennia and have already obtained been baptised.*
>
> - *Horizontally are shown the various combinations of one, two or three lifting surfaces to provide lift and trim longitudinally. The concept with joint wing tips has an unusual appearance, although it has some resemblance with the old biplane, adapted to high speeds.*
> - *Vertically are shown four alternatives to allocate the payload inside one or two fuselages, partly inside fuselage and wing, and completely inside the wing.*
>
> *The matrix clearly visualises the two choices on its scales. In theory any deviation from the dominant configuration increases the number of permutations considerably. But the designer's freedom has many practical limitations, reflected by the open positions. For example:* the outside has to be bigger than the inside *and thus only large aircraft may contain human payload inside the wing with acceptable comfort and possibilities to escape in case of emergency.*
>
> *The development and comparison of any of these new configurations is an enormous task and extremely challenging to a design community. It requires experienced, multidisciplinary teams,*

availing of extensive and expensive possibilities to simulate complete aircraft on computer systems, as well as experimental facilities.

Although today we focus on aerodynamic performance it should be noted that these unconventional concepts would have a major impact on items like structural loads, stiffness distribution and aero elastics, fabrication technology, maintainability, etc. The overall effect is not necessarily an improvement over the classical configuration. Comprehensive criteria must therefore be adopted to measure the advancements that new concepts will make relative to existing ones. One of these is fuel efficiency.

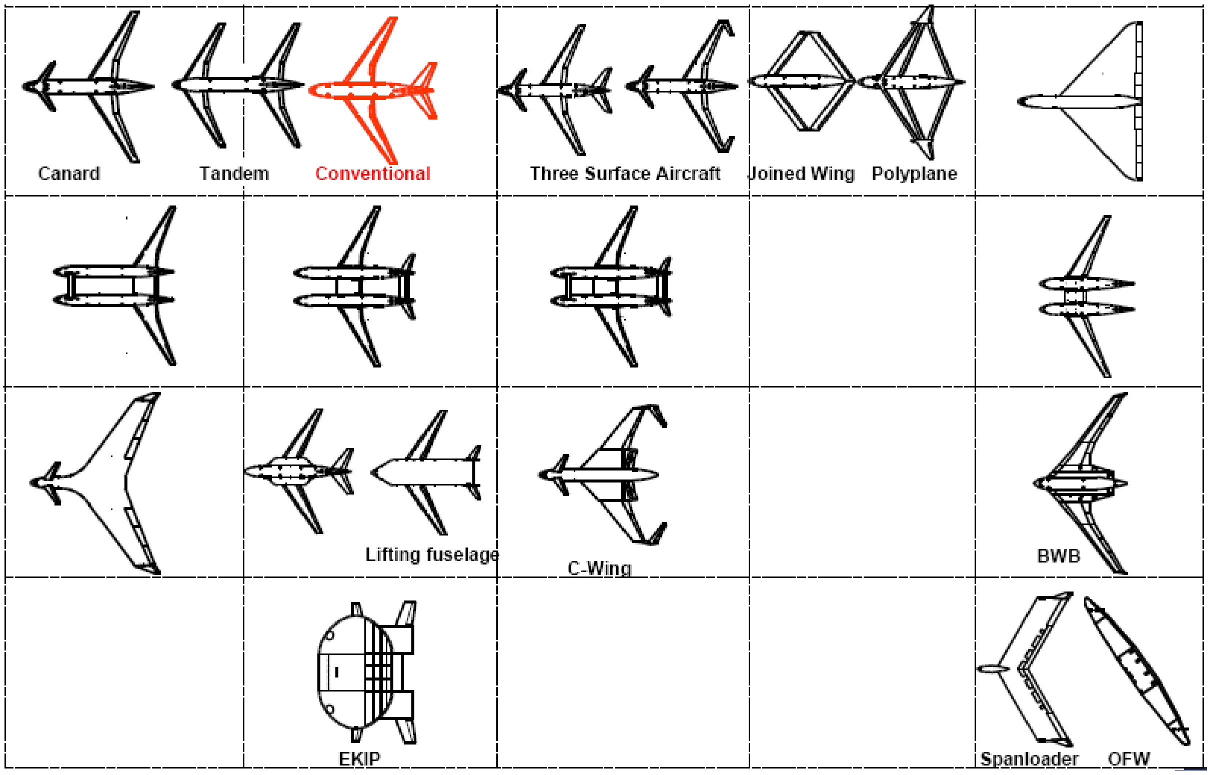


Fig 2.1 Aircraft Configuration Matrix (**Thramer 2004**)

2.2 Fuselage plus Wing(s) and Tail(s)

As shown in Figure 2.1, the conventional configuration is only one member of this group of aircraft. Others are.

- Canard,
- Tandem or biplane,
- Three-surface,
- Joined-wing, Prandtl Wing
- Delta wing.

Canard, and Tandem Wing or Biplane

Canards may be subdivided into control-canards and lifting-canards. “In the control-canard, the wing carries most of the lift, and the canard is used primarily for control as is the case for an aft-tail design. … In contrast, a lifting-canard aircraft uses both the wing and the canard to provide lift under normal flight conditions.” **Raymer 2006** (p. 80). Hence, the lifting-canard may be regarded as the intermediate stage between control-canard and tandem wing. Figure 2.2 shows the Beechcraft Starship as an example of a (lifting-) canard aircraft.

The principal idea behind a canard is to balance the nose-down pitching moment resulting from the aircraft longitudinal stability requirement by an upward force at the front end of the aircraft which leads to less total lift required and relieves the wing. In consequence, the wing may become smaller, lighter and produces less drag. This is the theory, but reality also holds several further negative effects.

Fig 2.2 Picture of the Beechcraft Starship (**bobscherer.com 2007**)

One of these negative effects is that the positioning of the canard in front of the wing leads to an airflow over the wing (root) which is deflected downwards by the canard's downwash. Hence, the deflected airflow over the wing (root) produces less lift and even more drag, as the resulting force vector stands perpendicular on the airflow and is deflected as well. In consequence, a larger wing is needed and large parts of the lift are produced at the outer parts of the wing, which increases the bending moment and weight of the wing. In addition, a canard configuration has several negative effects on the stability and controllability of an aircraft – especially in combination with flaps. All these aspects are being discussed in more detail e.g. in **Raymer 2006** (p. 78ff).

Three-Surface

Raymer 2006 (p. 82) makes the following statement on three-surface aircraft:

> *A three-surface arrangement includes both aft-tail and control-canard surfaces. This allows use of the canard for efficient trim and pitch control without the difficulty of incorporating wing flaps as seen on a canard-only configuration.*
>
> *The three-surface aircraft theoretically offers minimum trim drag. A canard or aft-tail, when generating lift for trim purposes, will change the aircraft total lift distribution, which increases total induced drag. On a three-surface configuration the canard and aft tail can act in opposite directions, thus canceling out each other's effect upon the total lift distribution. For example, to generate a nose-up trim the canard can generate an upward lift force while the tail generates an equal downward lift force. The combined effect upon total lift distribution would then be zero.*
>
> *However, this reduction in trim drag is a theoretical far-field effect and might not be fully realized in an actual design. The drawback of the three-surface arrangement is the additional weight, complexity, and interference drag associated with the extra surfaces.*

The best-known example of a three-surface aircraft is the Piaggio P-180 Avanti (see Figure 2.3), but there are some more aircraft featuring such configuration, like the Peterson Katmai, a modified Cessna C182 (see Figure 2.4).

Fig 2.3 Picture of the Piaggio P-180 Avanti (**piaggioaero.com 2007)**

Fig 2.4 Picture of the Peterson Katmai (**260sepilots.org 2006**)

Joined Wing, Prandtl Wing

As the name implies, joined wing aircraft have two wings which are somehow joined – either in the form of vertical connectors or directly by means of dihedral and anhedral (= negative dihedral) angles of the two wings, which leads to a triangular shape in the front view. Typically, there is a lower, aft-swept forward wing and an upper, forward-swept aft wing, often mounted on the top of one or two vertical tails.

Raymer 2006 (p. 676f, see Figure 2.5) says about the triangular version:

> *Unlike normal biplanes, such an arrangement can have good transonic and aerodynamic characteristics. Additional tails are probably not required, and trailing-edge surfaces on both wings provide pitch and roll and can provide direct lift and side force, if desired. The main benefit, though, is the substantial reduction in wing structural weight that is achievable, on the order of 30%. This results from the triangulation, with the back wing acting as strut for the front wing. … On the negative side, it is difficult to get a trimmed maximum lift coefficient equal to a normal wing-tail configuration, and there can be excess wetted area and interference drag with so many component intersections.*

The joined wing version having two (almost) parallel wings which are joined at their wingtips by means of vertical connector elements is called a "box-wing" configuration, due to its shape when looking from the front. Among all possible box-wing configurations the so-called "Prandtl Wing" or Prandtl's "Best Wing System" is of most importance. **Frediani 2005** writes about a proposed transport aircraft concept called the "PrandtlPlane":

> *The main starting property of this aircraft configuration is a very high reduction of the aerodynamic induced drag, based on an intuition of Prof. Prandtl, at the beginning of the history of aeronautics. According to Prandtl, the lifting system with minimum induced drag is a proper box-like wing (named as "Best Wing System"), in which the following conditions are satisfied:*

> *same lift distribution and same total lift on each of the horizontal wings and butterfly shaped lift distribution on the vertical tip wings.*
>
> …
>
> *The Best Wing System is more efficient than a biplane and, also, from the structural point of view, the connection of the tip wings provides a high structural stability. The practical interest of the results of the best wing system lays on the fact that… the induced drag of the* Best Wing System *reduces from 20% to 30% with respect to the optimum monoplane.*

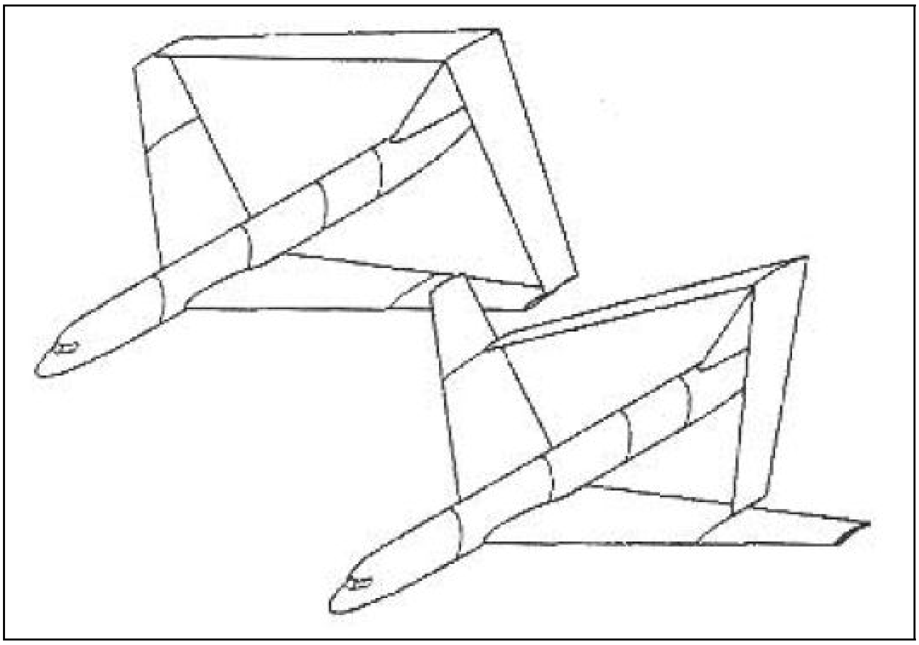


Fig 2.5 Joined Wing Aircraft Concepts (**Raymer 2006**)

Figure 2.6 shows an example of the PrandtlPlane concept applied to a large, A380-like transport aircraft.

Fig 2.6 PrandtlPlane Concept (**Frediani 2005**)

Delta Wing

The delta wing is marked by a low aspect ratio, positive (aft) wing sweep and a taper ratio near zero. It is mostly used for tailless aircraft traveling at supersonic speeds, as a low aspect ratio significantly reduces wave drag compared to wings with higher aspect ratio. In addition, the delta wing leads to "…structural weight savings compared to a conventional swept wing because, with the delta, the internal structure need not be swept…", and "…since the wing has relatively small aspect ratio and a near-zero taper ratio, the wing root chord is very large, and so the root thickness is very deep. This reduces structural bending loads and provides extra room for fuel, landing gear, and structure." (**Raymer 2006**, p. 666).

Wikipedia 2007 adds the following:

> *The disadvantages, especially marked in the older tailless delta designs, are a loss of total available lift caused by turning up the wing trailing edge or the control surfaces (as required to achieve a sufficient stability) and the high induced drag of this low-aspect ratio type of wing. This causes delta-winged aircraft to 'bleed off' energy very rapidly in turns, a disadvantage in aerial maneuver combat and dogfighting.*
>
> …
> *Pure deltas fell out of favour somewhat due to their undesirable characteristics, notably flow separation at high angles of attack (swept wings have similar problems), and high drag at low altitudes. This limited them primarily to high-speed, high-altitude interceptor roles. Some modern aircraft, like the F-16, use a cropped delta along with horizontal tail surfaces. A modification, the compound delta such as seen on the Saab Draken* [see Figure 2.7; remark of this author] *fighter or the prototype F-16XL "Cranked Arrow", or the graceful ogee* [= S-shaped; remark of this author] *delta used on the Anglo-French Concorde* [see Figure 2.8; remark of this author] *Mach 2 airliner, connected another much more highly swept piece of the delta wing to the forward root section of the main one, to create the high-lift vortex in a more controlled fashion, reduce the drag and thereby allow for landing the delta at acceptably slow speed.*

Fig 2.7 Picture of the SAAB Draken (**Wikipedia 2007**)

Fig 2.8 Picture of the Concorde (**Wikipedia 2007**)

2.3 Multi-Fuselage

Torenbeek 2005a discusses the issue of multi- or twin-fuselage aircraft as follows:

> *A twin fuselage configuration has the useful load distributed laterally and axially in such a way that wing and fuselage bending is reduced considerably compared to the classical lay-out (Figure 5,* [here Figure 2.9; remark of this author]*). For the same wing span and AUW the maximum wing bending moment is reduced by 50% typically, dependent on the lateral distance between the fuselages.*
>
> …
>
> *A study initiated by the European Aeronautical Research Establishments (EREA) has shown promising technical and economical results. A medium range twin fuselage airliner, carrying a passenger load of 250-300 in two modified A318 fuselages (Figure 6;* [here Figure 2.10; remark of this author]*) was conceived by the consulting company ADSE, with contributions from DLR, FFA and NLR. The overall gains in fuel consumed, thrust required and AUW relative to a conventional design are significant (Figure 7;* [here Table 2.1; remark of this author]*).*
>
> *The twin fuselage configuration does not require major advances in design technology and alleviates or completely avoids some of the potential showstoppers for other unconventional configurations. Since it is feasible for both medium and high capacity airliners it offers a low-risk alternative. It has received very little attention from airplane manufacturers. The reason could be that they think that (airlines will not like them because they think that) this lay out will lack passenger appeal.*

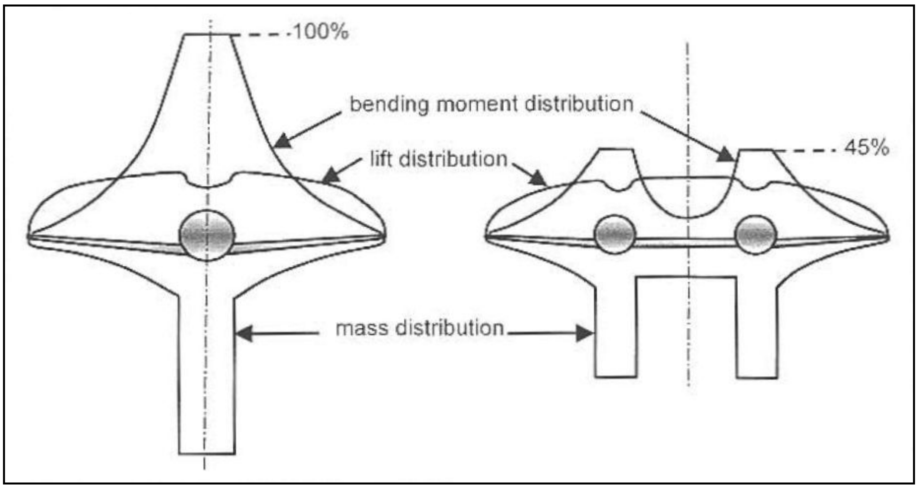


Fig 2.9 Distribution of Lift, Mass and Bending Moment for a Twin-Fuselage Aircraft (**Torenbeek 2005a**)

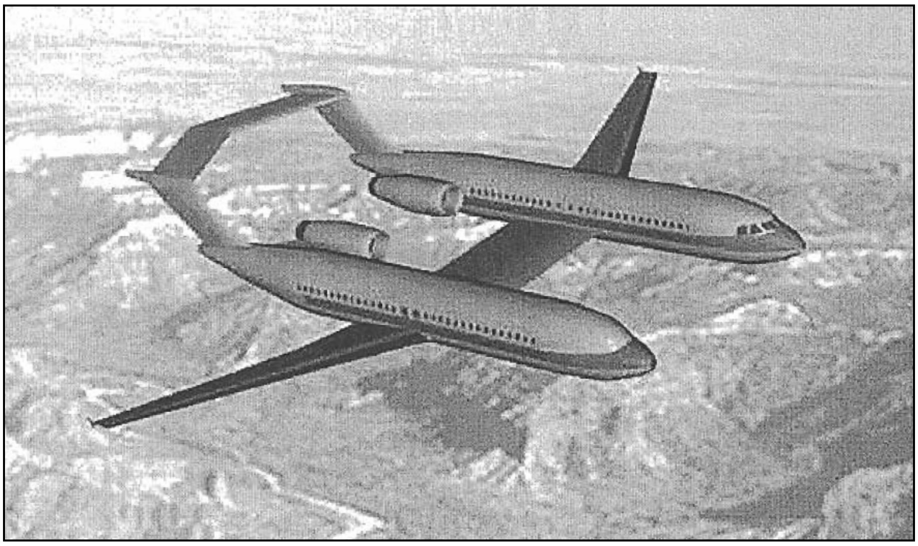


Fig 2.10 250-300 Pax Twin Fuselage Airliner Design (**NLR 2001** cited in **Torenbeek 2005a**)

Table 2.1 Design Characteristics of the Conceived Twin-Fuselage (2-F) Design Compared with a Conventional Wide Body Design (**Torenbeek 2005a**)

Design Mass (kg)	Conventional	2-F	Δ (%)
MTOW	155,000	134,000	-13.5
MLW	128,000	113,000	-11.7
MZFW	120,000	106,000	-11.7
OEW	84,000	70,000	-16.7
Payload (Struct. Limit)	36,000	36,000	0
Block Fuel (8,000 km)	40,715	34,245	-15.9
Installed Thrust (kN)	2 x 222.5	2 x 178.0	-20.0

Figure 2.11 shows a proposed layout of a twin-fuselage cargo aircraft having two Lockheed C-5 Galaxy fuselages. Taking into account that a standard C-5 fuselage has a length of 75 m, one gets an impression of the huge dimensions of this proposal. A military airlifter has to be capable to operate from, at least, conventional airports, but this configuration would have

asked for special infrastructure like extra-wide runways. The need for extra-wide runways and other requirements concerning airport infrastructure is very often one of the major showstoppers for multi-fuselage, as well as other configurations. Another drawing of a might-be multi-fuselage aircraft layout is shown in Figure 2.16.

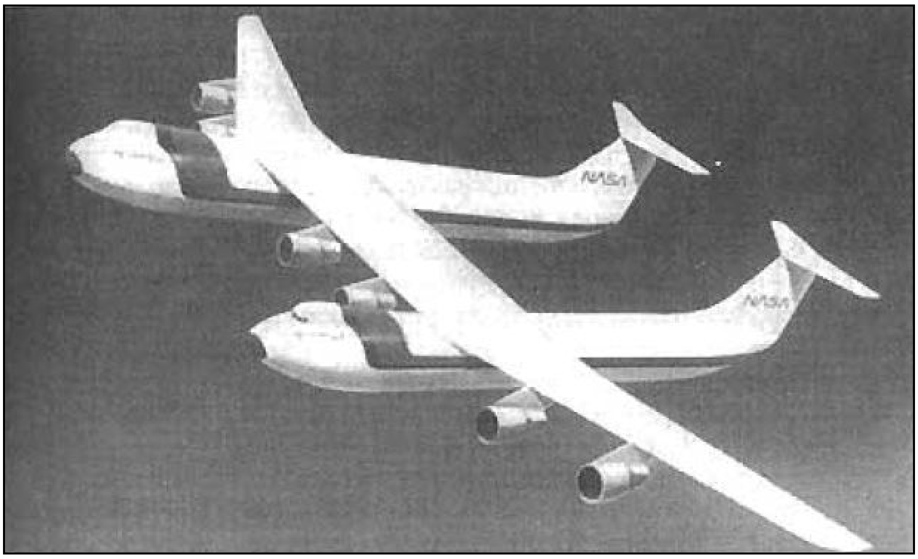


Fig. 2.11 Layout of a C-5 Galaxy Twin-Fuselage Airlifter (**Raymer 2006**)

2.4 No Fuselage

Flying Wing

Wikipedia 2007 makes the following statements on flying wing aircraft:

> *Flying wing is the generic designation given for a fixed-wing aircraft configuration which is capable of stable, controllable flight without the aid of lifting surfaces other than the main wing itself, that is, without auxiliary surfaces such as "tails" and "canards".*
>
> *In it strictest sense, the Flying Wing also lacks a fuselage, or has only a rudimentary fuselage 'pod' barely extending from the wing itself. In this layout, most of the payload is transported inside the main wing, the latter comprising most of its structural volume. A pure flying wing also lacks any vertical stabilizers, although some aircraft comonly known as 'flying wings' have a vertical tail fin, vertical tail plates or a set of vertical stabilizers on the back part of their wings to aid their stability in turns.*
>
> …
>
> *Historically, the flying wing has been defended by many as potentially the most efficient aircraft configuration from the point of view of aerodynamics and structural weight. Such a notion usually comes from the idea that the absence of any aircraft components other than the wing should naturally provide those benefits. On the other hand, the aircraft's wing should be able to provide flight stability and control "by itself", a requirement which in principle imposes additional constraints to the wing design problem. Therefore, the expected gains in weight and drag reduction may be partially or wholly negated due to design compromises needed to provide stability and control.*

> *Although the discussion about flying wing aircraft usually surrounds the balance between aerodynamic/weight performance and stability/control requirements, those are by no means the only important design factors. Other issues such as (but not limited to) high-speed compressibility effects, useful payload volume, cabin pressurization, satisfaction of certification safety requirements and industrial/commercial risk must also come into play to determine whether or not the flying wing configuration is the best solution for a given aircraft mission.*

Raymer 2006 (p. 663) gives more detailed information on flying wings as follows:

> *Flying wing design is similar to the design of other aircraft, with a few key differences. Obviously, the planform wing geometry, twist and airfoil shaping must be carefully considered and analyzed as quickly as possible, and a detailed stability and control analysis should be done early in the project. Center-of-gravity location is critical. Use of sweepback and twist to attain pitch stability has been discussed. Alternatively, a "reflexed"* [S-shaped; remark of this author] *airfoil can be selected, having the trailing edge lifted slightly to provide a naturally stable airfoil. Such airfoils tend to be less efficient, and are typically limited to slower aircraft.*

Today's probably widest known, though highly classified until 1988, flying wing aircraft is the stealth bomber Northrop-Grumman B-2 Spirit, which is shown in Figure 2.12.

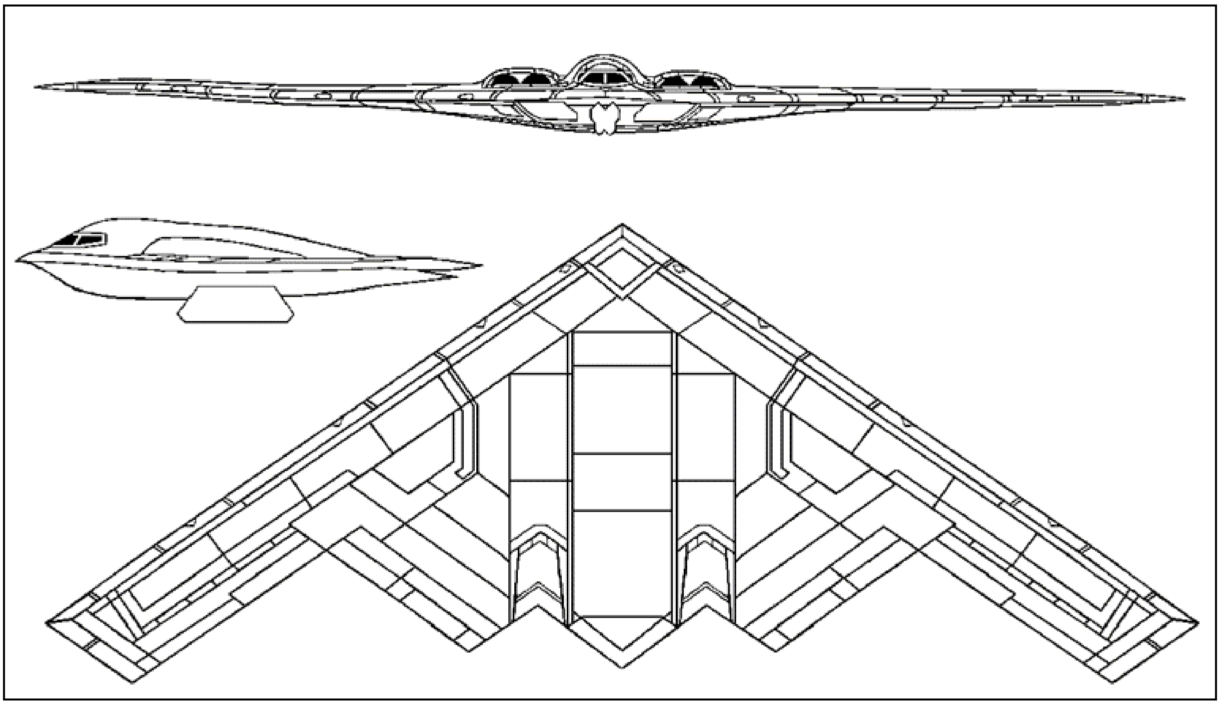


Fig 2.12 Tree-View Drawing of the Northrop-Grumman B-2 Spirit (**Wikipedia 2007**)

Distributed Load Freighter (DLF)

Boeing 1976 provides information on the so called DLF (distributed load freighter) configuration (see Figure 2.13). This configuration's most obvious characteristics are an unswept wing of constant chord and tail surfaces supported by twin booms extending aft from the wing rear spar. This study was undertaken in parallel to investigations on swept tailless, thus flying wing, configurations in the 1970s. One of the DLF's design constraints was the capability to carry standard ISO containers (see Section 6.1) and even US M60 tanks as a military version.

The study's central outcomes are "that increasing design payload and, hence airplane size had both the greatest and most favorable effect on the economics" (**Boeing 1976**, p. 1). As a consequence, the aircraft concept studies showed maximum payloads of up to 800 t and maximum take-off masses of up to more than 1500 t. Also, huge external dimensions of more than 300 m wingspan resulted for the DLF configurations, which would lead to major adaptations necessary to airport infrastructure. "Following the parametric study, a configuration with the best economics was selected for a net payload of 272 155 kg (600 000 lb) ... with a wing span of 83.8 m. ... Ultimately, these huge aircraft would be used almost entirely in intercontinental airfreight and the most likely system configuration would be to connect a small number of worldwide hub cities. Practical networks, each connecting as few as 10 cities, appear feasible." (**Boeing 1976**, p. 2-3).

Final conclusions of this study are that the distributed-load freighter concept has further potential in sweep, reduced cargo bay height requirement, optimum payload size and weight reduction. At about 272 t payload, the lower production costs of the DLF balance the lower fuel costs of a conventional advanced freighter. At about 544 t payload, the fuel costs of the DLF equals those of a conventional advanced freighter.

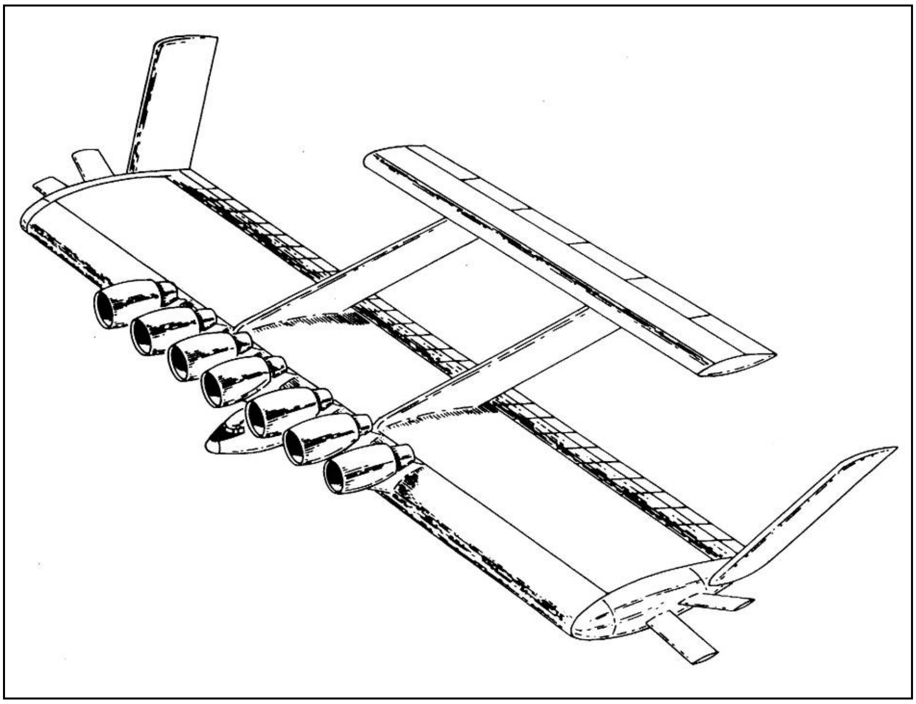


Fig 2.13 Boeing's 1976 Span-distributed Loading Freighter Aircraft Concept (**Boeing 1976**)

EKIP

Another very unconventional aircraft configuration is the Russian flying vehicle EKIP (Russian acronym for Ecology and Progress, see Fig. 2.14). Due to its very uncommon shape of a low aspect ratio flying wing it is also often called the “flying saucer”. The EKIP’s fuselage is shaped as a wing of low aspect ratio. It is intended for airfield-independent or even water-based operation having STOL capabilities.

EKIP Aviation 2004 describes the principle design of this vehicle as follows:

> *The "EKIP" aircrafts can carry heavy large-scale loads (100 and more tons) at long distances (thousands of kilometers) at a speed of 500-700 km/h at the altitude of 8-13 km. These flying vehicles can move near the surface of ground or water using the air cushion at a speed up to 160 km/h and glide at a speed up to 400 km/h as a "screen-plane"[wing in ground-effect (WIG) airplane; remark of this author].*
>
> *The flying vehicles "EKIP" do not require an airfield. They can land on airfields of any category, including ground and water surfaces. The length of the runway for heavy vehicles (several hundred tons) does not exceed 600 meters, take-off and landing are performed at steep descent trajectory, which decreases the level of noise affecting the vicinity.*
>
> *An air cushion device is used for takeoff and landing of flying vehicles "EKIP". The profound air cushion research developments made at the State Scientific Research Center TSAGI (Moscow Branch of Central Air-hydrodynamic Institute), could not be used in traditional existing airplanes due to absence of large planer area.*
>
> *The flying vehicles "EKIP" have large planer area and the air cushion landing gear ideally fits with the structure of the aircraft. It is located under the body of the vehicle and ensures that low pressure is exerted on the vehicle itself and on the runway (ground, water surface) during takeoff and landing.*
>
> *This pressure is equivalent to the pressure of a layer of water 220-270 mm thick. For the flying vehicles "EKIP" with a load-carrying capacity of hundred tons there is no necessity to build special airfields with concrete runways 5 km long, as it is necessary for heavy airplanes like B-777 (Boeing) and A3-XX (Airbus Industry).*

Having read this general description of the EKIP vehicle, it must be pointed out that all this information appears to be very optimistic. Some Russian sources like **inauka.ru 2004** claim that lot production shall be launched by the Russian aviation company Saratov in cooperation with the US Naval Air Systems Command, but searching for keywords like “Saratov” and/or “EKIP” leads to no results on the US Naval Air Systems Command’s website or other information from official sources.

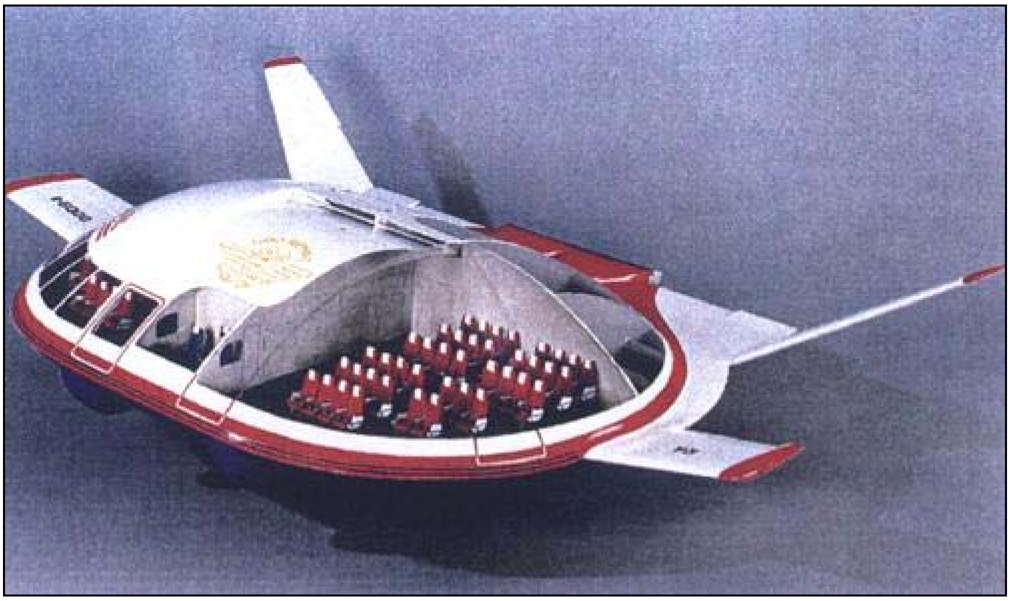


Fig 2.14 Russian Flying Vehicle "EKIP" (**EKIP Aviation 2004**)

Oblique Flying Wing (OFW)

Wikipedia 2007 gives the following information on the oblique flying wing (OFW) (see Figure 2.15):

> *The general idea is to design an aircraft that performs with high efficiency as the Mach number increases from takeoff to cruise conditions (M ~ 0.8, for a commercial aircraft) Since two different types of drag* [are] *dominant in each of these two flight regimes, uniting high performance designs for each regime into a single airframe is problematic.*
>
> *At low Mach numbers induced drag dominates drag concerns. Airplanes during takeoff and gliders are most concerned with induced drag. One way to reduce induced drag is to increase the aspect ratio of the lifting surface. This is why gliders have such long, narrow wings. An ideal wing has infinite span and induced drag is reduced to a two dimensional property. At lower speeds, during takeoffs and landings, an oblique wing would be positioned perpendicular to the fuselage* [resp flight direction in case of OFW; remark of this author] *like a conventional wing to provide maximum lift and control qualities. As the aircraft gained speed, the wing would be pivoted to increase the oblique angle, thereby reducing the drag and decreasing fuel consumption.*
>
> …
>
> *Fundamentally, it appears that no design can be completely optimized for both flight regimes. However, the oblique wing shows promise of getting close. By actively increasing sweep as Mach number increases, high efficiency is possible for a wide range of speeds.*

Remark: The principal idea of a pivoting (oblique) wing is not limited to flying wing aircraft. The following pictures show two examples of oblique wing aircraft which are no flying wings. So far, the NASA AD-1 (Figure 2.17) is the only aircraft that has been built as an oblique wing aircraft.

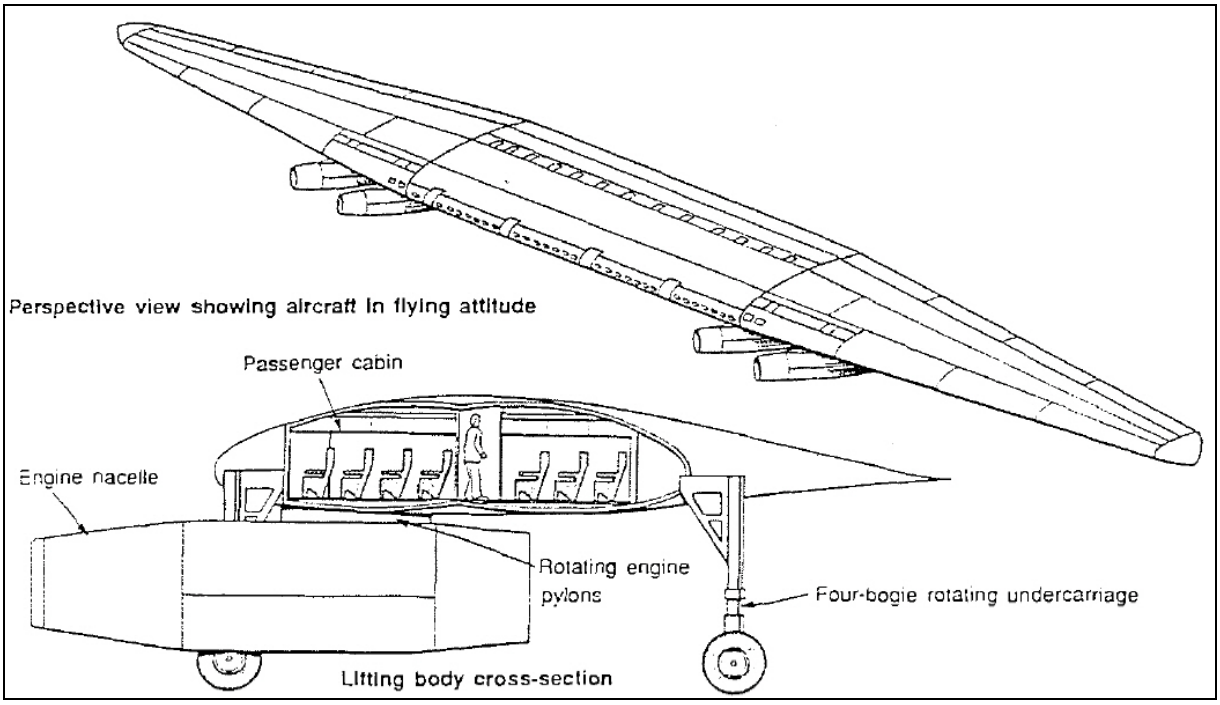


Fig 2.15 NASA Ames Design for a Supersonic Oblique All-Wing Transport (**Waters 1992** cited in **Hirschberg 2005**)

Fig 2.16
Twin-Fuselage Oblique Wing Transonic Transport Aircraft (**Hirschberg 2005**)

Fig 2.17
Ames-Dryden AD-1 Oblique Wing Demonstrator (**NASA 1980**)

2.5 Merged Fuselage and Wing

Merging Fuselage and Wing leads to two main advantages:

- A reduction of the aircraft's wetted area and, hence, an increase of the lift-to-drag ratio or aerodynamic performance.
- A relief in wing bending moment due to the more span-wise load distribution and, hence, a reduction of the structural weight.

Lifting fuselage and blended wing-body (BWB) aircraft have a fuselage, which is shaped like an airfoil and, hence, contributes to the overall lift. In case of the lifting fuselage one can still determine the intersection of fuselage and wing, whereas the fuselage and wing of the BWB are blended so that it is no more clearly visible from the outside where the fuselage ends and the wing begins. That is why BWB aircraft often are already called flying wing aircraft.

Raymer 2006 (p. 664f) gives the following information on BWB aircraft. In addition, Raymer's statements on flying wing design cited in Section 2.4 are also valid for BWB aircraft:

> *The BWB has about half of the root bending stresses of a conventional configuration. The wing-tip-mounted vertical tails also act as winglets to reduce drag due to lift. BWB requires relaxed static stability and an automated flight control system to fly efficiently, optimize span loading, and avoid the need for a tail. The BWB optimizes at awing loading of about 100 psf {488 kg/sqm, much less than the 160 psf {781 kg/sqm} of most airliners. This low wing loading permits the elimination of high-lift flaps, and only a leading-edge slat on the outboard wing is needed in addition to the wing trailing-edge controls.*
>
> *Boeing studies predict, compared with an equivalent conventional configuration, a 15% reduction in sized takeoff weight, a 20% improvement in L/D, and a 27% reduction in fuel usage.... A crucial problem to solve is the attainment of a cabin pressure vessel without a huge weight penalty, since the cabin is not a capped cylinder as in conventional airliner. Boeing plans to carry both pressure and bending loads by a 5-in.-thick {13-cm} composite structural sandwich or a deep hat stringer structural shell. Also, for packing reasons it seems that BWB is most suitable for a very large airliner (800 passengers), and there is concern that the dearth of windows may be claustrophobic to some passengers.*

In general BWBs appear to be the most probable next leap towards future aircraft, though there are still some challenges to overcome, especially for passenger transport aircraft:

- Emergency passenger evacuation,
- No outside-view for many/all passengers,
- Maneuver accelerations at outboard seats,
- Cabin pressurization,
- Airport infrastructure,
- Certification.

Currently there are many studies of a large number of institutions in progress which deal with BWB aircraft design. Two of these are mentioned in the following paragraphs: the AC20.30 project of the Hamburg University of Applied Sciences and the X-48B of Boeing, NASA and the U.S. Air Force Research Laboratory.

The AC20.30 project is student project of the Hamburg University of Applied Sciences (HAW). The aims of the project are:

- Basic research on next generation civil transports,
- Flight testing theoretical solutions on a model scaled 1:30,
- Detailed flight data and information on control of a BWB configuration gained through integrated measurement equipment,
- Development of concepts for cabins for up to 900 passengers.

Technical details of the AC20.30 model:

- wing span: 3.24 m
- length: 2.12 m
- take off mass: 12.5 kg
- wing loading: 6.3 kg /m^2
- engines: 2 electric impellers
- thrust: 2 x 30 N
- power consumption: 2 x 1.4 kW

The project aims and technical data are taken from **Schmidt 2006**. Figures 2.18 and 2.19 show two pictures of the flying model of the AC20.30 while Figure 2.20 shows some sketches for the new engine arrangement of HAW's new to-build flying BWB test bed.

Fig 2.18 Picture of the taxiing AC20.30 (**AC20.30 2006**)

Fig 2.19 Picture of the approaching AC20.30 (**AC20.30 2006**)

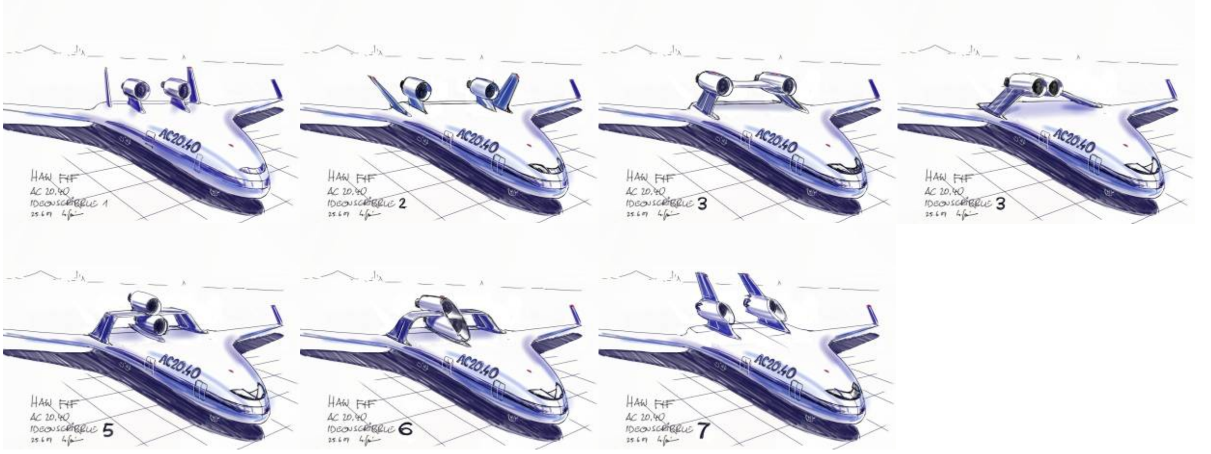


Fig 2.20 Sketches of different Engine Arrangements on HAW's AC20.40 (**Granzeier 2007**)

Boeing 2006 describes Boeing's current studies on the X-48B BWB in cooperation with NASA and the U.S. Air Force Research Laboratory (AFRL) as follows. A cutaway drawing of the model is pictured in Figure 2.21. Figure 2.22 shows a photo of the flying model.

> …
> *Two high-fidelity, 21-foot* [6.4 m; remark of this author] *wingspan prototypes of the BWB concept have been designed and produced for wind tunnel and flight testing this year. The Air Force has designated the vehicles as the "X-48B," based on its interest in the design's potential as a flexible, long-range, high-capacity military aircraft.*
>
> *X-48B Ship No. 1 began wind tunnel testing on April 7 at the Langley Full-Scale Tunnel at NASA's Langley Research Center. When testing is completed in early May, it will be shipped to NASA's Dryden Flight Research Center in California to serve as a backup to Ship No. 2, which will be used for flight testing later this year. According to the team, both phases of testing are focused on learning more about the low-speed flight-control characteristics of the BWB concept.*
>
> *"The X-48B prototypes have been dynamically scaled to represent a much larger aircraft and are being used to demonstrate that a BWB is as controllable and safe during takeoff, approach and landing as a conventional military transport airplane," said Norm Princen, Boeing Phantom Works chief engineer for the X-48B program.*

> *The X-48B cooperative agreement by Boeing, NASA and the Air Force Research Laboratory (AFRL) culminates years of BWB research by NASA and Boeing. AFRL is interested in the concept for its potential future military applications.*
>
> *"We believe the BWB concept has the potential to cost effectively fill many roles required by the Air Force, such as tanking, weapons carriage, and command and control," said Capt. Scott Bjorge, AFRL X-48B program manager. "This research is a great cooperative effort, and a major step in the development of the BWB. AFRL is inspired to be involved in this critical test program."*
>
> *NASA also is committed to advancing the BWB concept. NASA and its partners have tested six different blended wing body models of various sizes over the last decade in four wind tunnels at the Langley Research Center.*
>
> *"One big difference between this airplane and the traditional tube and wing aircraft is that -- instead of a conventional tail -- the blended wing body relies solely on multiple control surfaces on the wing for stability and control," said Dan Vicroy, NASA senior research engineer at the Langley Research Center. "What we want to do with this wind-tunnel test is to look at how these surfaces can be best used to maneuver the aircraft."*
>
> *The two X-48B prototypes were built for Boeing Phantom Works by Cranfield Aerospace Ltd., in the United Kingdom in accordance with Boeing requirements and specifications. Made primarily of advanced lightweight composite materials, the prototypes weigh about 400 pounds* [141.4 kg; remark of this author] *each. Powered by three turbojet engines, they will be capable of flying up to 120 knots and 10,000 feet in altitude during flight testing. …*

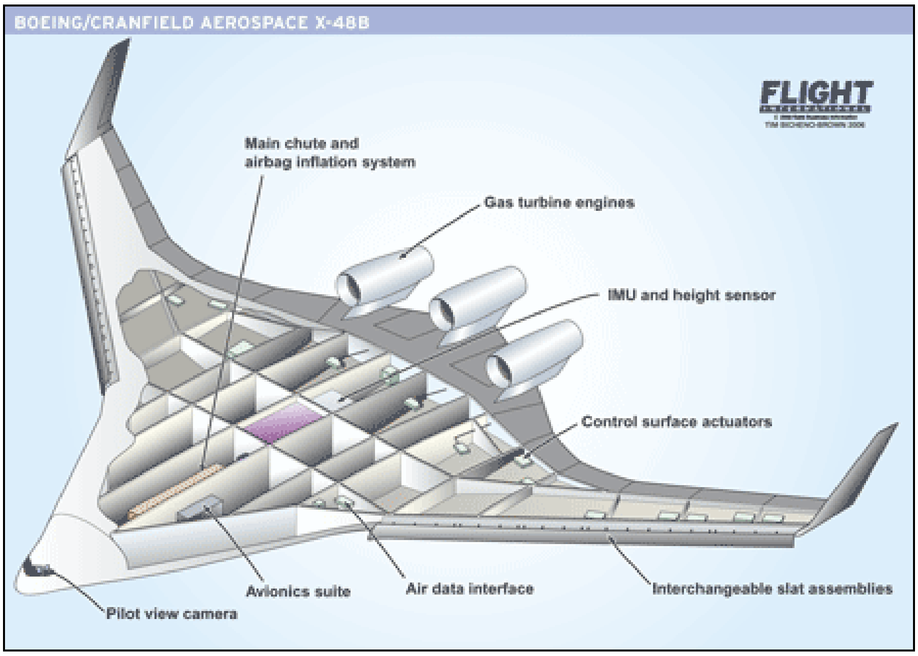


Fig 2.21 Cutaway-Drawing of the Boeing X-48B (**Flight International 2006d**)

Fig 2.22 Picture of the Boeing X-48B Flight Model (**Flight International 2007b**)

3 Propulsion Systems and Integration

The task of the propulsion system is to deliver thrust – the force required to overcome drag and move the aircraft forward. Basically, the thrust is produced by accelerating an air-mass flow in the opposite flight direction which pushes the aircraft forward, according to Newton's third law of motion: "action = reaction". Nowadays, acceleration of the air-mass flow in air transport is achieved by two different means: propeller engines or jet engines.

This chapter introduces the following engine types:

- Jet Engines,
- Propeller Engines,
- Propfan / Unducted Fan Engines,
- Contra-Rotating Propeller / Propfan Engines and
- Electric Propulsion Systems.

Afterwards, a brief overview is given concerning the various aspects of propulsion system integration.

3.1 Propulsion Systems

3.1.1 Jet Engines

Nowadays, transport aircraft traveling at high subsonic speeds use jet engines as propulsion system. They can be diveded into turbojet and turbofan engines.

Wikipedia 2007 defines turbojet (see Figure 3.1) and turbofan (see Figure 3.2) engines as follows:

Turbojet

> *A turbojet engine is a type of internal combustion engine often used to propel aircraft. Air is drawn into the rotating compressor via the intake and is compressed, through successive stages, to a higher pressure before entering the combustion chamber. Fuel is mixed with the compressed air and ignited by flame in the eddy of a flame holder. This combustion process significantly raises the temperature of the gas. Hot combustion products leaving the combustor expand through the turbine, where power is extracted to drive the compressor. Although this expansion process reduces both the gas temperature and pressure at exit from the turbine, both parameters are usually still well above ambient conditions. The gas stream exiting the turbine expands to ambient pressure via the propelling nozzle, producing a high velocity jet in the exhaust plume. If the jet velocity exceeds the aircraft flight velocity, there is a net forward thrust upon the airframe.*

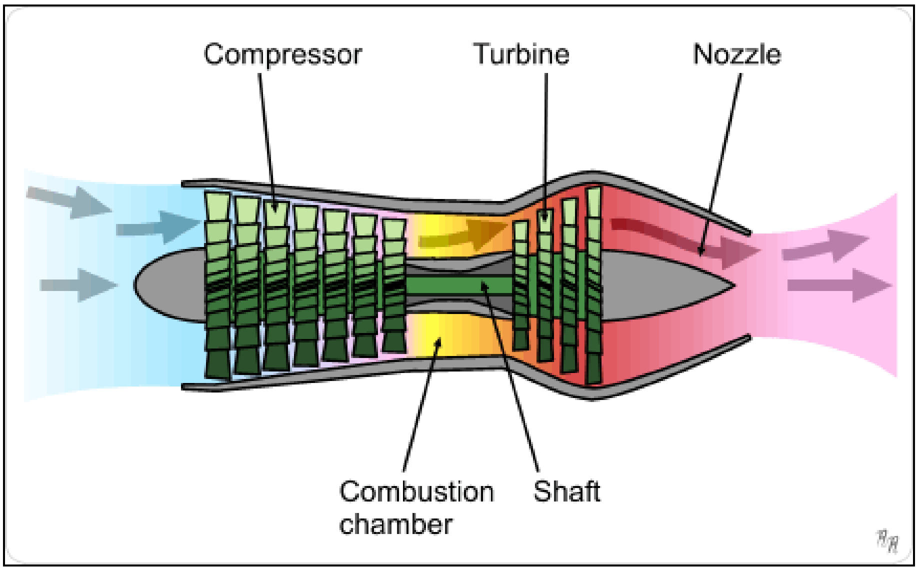


Fig 3.1 Schematic Drawing of a Turbojet Engine (**Wikipedia 2007**)

Turbofan

> *Most modern jet engines are actually turbofans, where the low pressure compressor acts as a fan, supplying supercharged air to not only the engine core, but to a bypass duct. The bypass airflow either passes to a separate 'cold nozzle' or mixes with low pressure turbine exhaust gases, before expanding through a 'mixed flow nozzle'.*
>
> *Turbofans are used for airliners because they give an exhaust speed that is better matched to subsonic airliner's flight speed, conventional turbojet engines generate an exhaust that ends up travelling very fast backwards, and this wastes energy. By emitting the exhaust so that it ends up travelling more slowly, better fuel consumption is achieved. In addition, the lower exhaust speed gives much lower noise.*

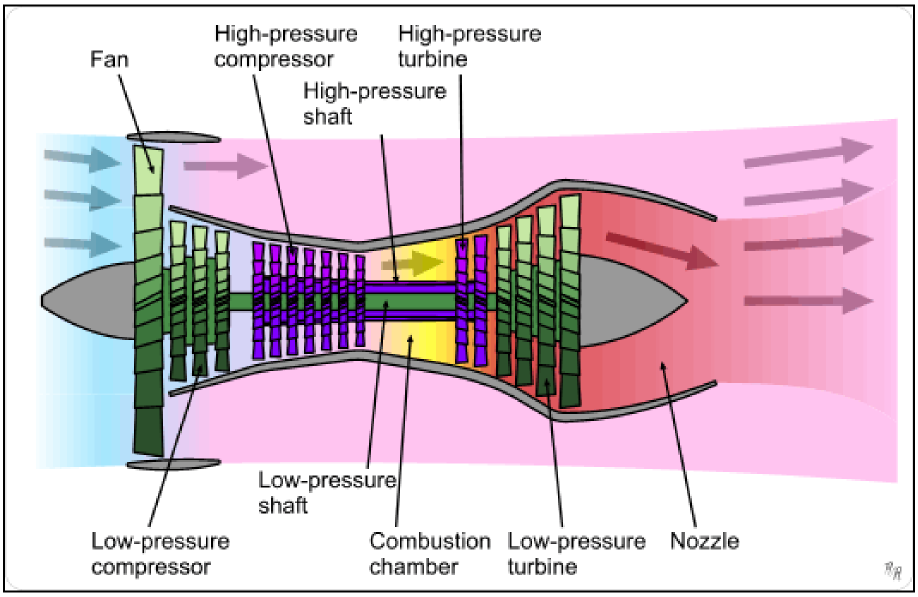


Fig 3.2 Schematic Drawing of a Turbofan Engine (**Wikipedia 2007**)

Some future concepts for turbofan engines include a geared fan. "P&W has targeted a 12% fuel consumption reduction for the geared turbofan (GTF) against current engines such s the V2500 or CFM56, a 40% reduction in maintenance costs, noise levels of around 15 dB below

Chapter 4 and emissions as much as 70% below the CAEP2 limit...", says **Flight International 2007h**.

3.1.2 Propeller Engines

Propeller engines are typically used for aircraft traveling at less high Mach numbers (≈0.6, see Fig. 3.3). The propeller may be driven by several types of engines:

- Internal combustion engine:
    - Turbines (turboprop),
    - Piston engines (piston-prop)
- Electric motor (see Section 3.1.4).

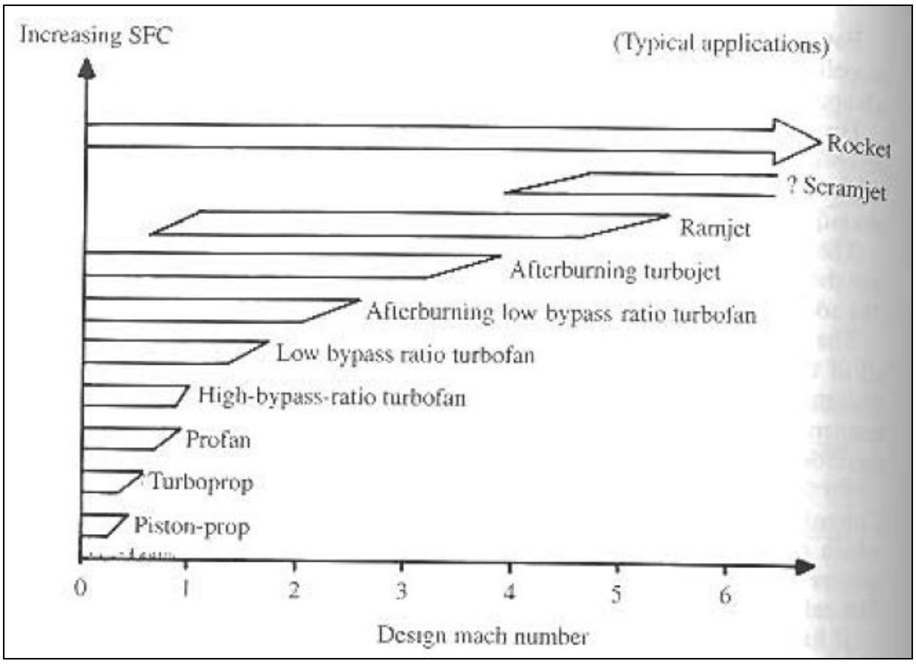


Fig 3.3 Propulsion System Speed Limits (**Raymer 2006**)

Wikipedia 2007 defines propeller and turboprop (see Figures 3.4 and 3.5) engines as follows:

Propeller

> *A propeller is essentially a type of fan which transmits power by converting rotational motion into thrust for propulsion of a vehicle such as an aircraft, ship, or submarine through a fluid such as water or air, by rotating two or more twisted blades about a central shaft, in a manner analogous to rotating a screw through a solid. The blades of a propeller act as rotating wings (the blades of a propeller are in fact wings or airfoils), and produce force through application of … Newton's third law, generating a difference in pressure between the forward and rear surfaces of the airfoil-shaped blades.*

Turboprop

A Turboprop engine is a type of gas turbine engine used in aircraft. Most of a turboprop engine's power is used to drive a propeller, and the propellers used are very similar to the propellers used in piston or reciprocating engine-driven aircraft (with the exception that turboprops usually use a constant velocity propeller).

A turboprop engine is similar to a turbojet, but has additional stages in the turbine to recover more power from the engine to turn the propeller. Turboprop engines are generally used on small or slow subsonic aircraft, but some aircraft outfitted with turboprops have cruising speeds in excess of 500 kts (926 km/h, 575 mph).

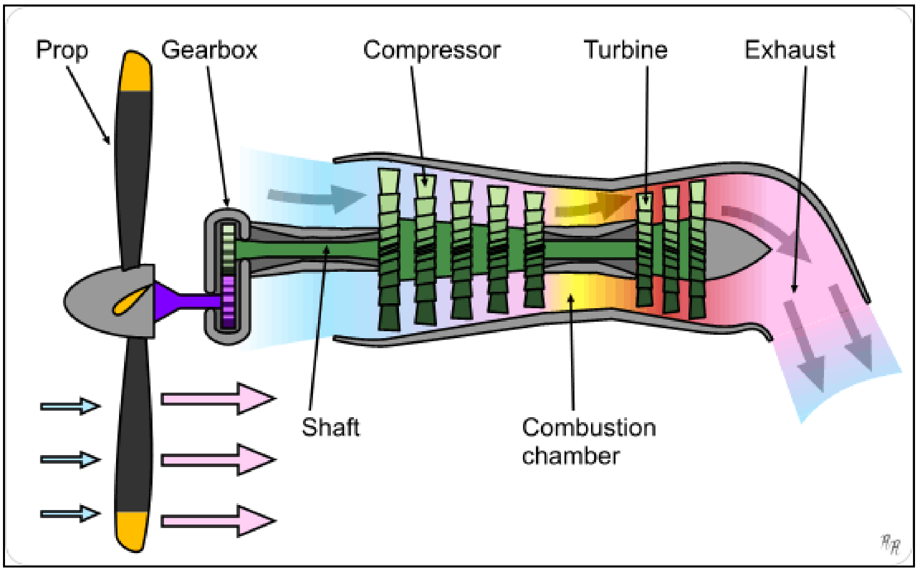


Fig 3.4 Schematic Drawing of a Turboprop Engine (**Wikipedia 2007**)

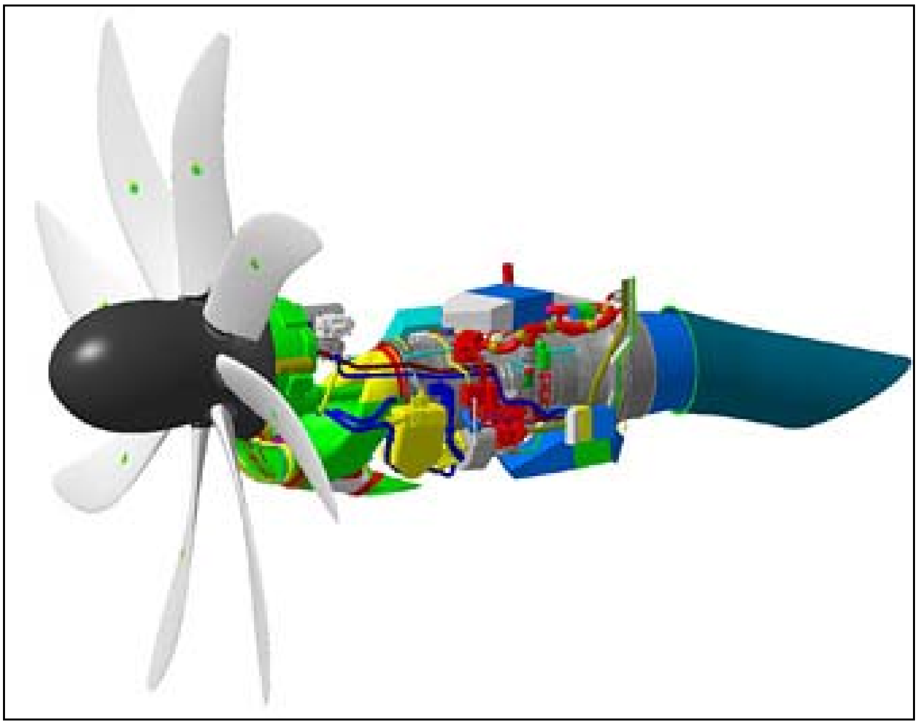


Fig 3.5 Schematic Drawing of a modern A400M Turboprop Engine (**EADS 2007**)

Raymer 2006 (p. 221, p. 224f) makes the following statements:

> *Piston-prop engines have two advantages. They are cheap, and they have the lowest fuel consumption. However, they are heavy and produce a lot of noise and vibration. Also, the propeller by its very nature produces less and less thrust as velocity increases.*
>
> *The choice between a piston-prop and a turboprop can depend upon several additional factors. The turboprop uses more fuel than a piston prop of the same horsepower, but is substantially lighter and more reliable. Also, turboprops are usually quieter. For these reasons turbine engines have largely replaced piston engines for most helicopters, business twins, and short-range commuter airplanes regardless of design speed.*

3.1.3 Propfan / Unducted Fan Engines

Wikipedia 2007 defines propfan engines as follows:

> *A propfan is a modified turbofan engine, with the fan placed outside of the engine nacelle on the same axis as the compressor blades. Propfans are also known as ultra-high by-pass (UHB) engines. The design is intended to offer the speed and performance of a turbofan, with the fuel economy of a turboprop.*

Raymer 2006 (p. 223) adds: “The ‘prop-fan’ or ‘unducted fan’ is essentially a turboprop with an advanced aerodynamics propeller capable of near-sonic speeds.” A schematic drawing of a propfan engine is shown in Figure 3.6. Another expression for this type of engine is open-rotor engine.

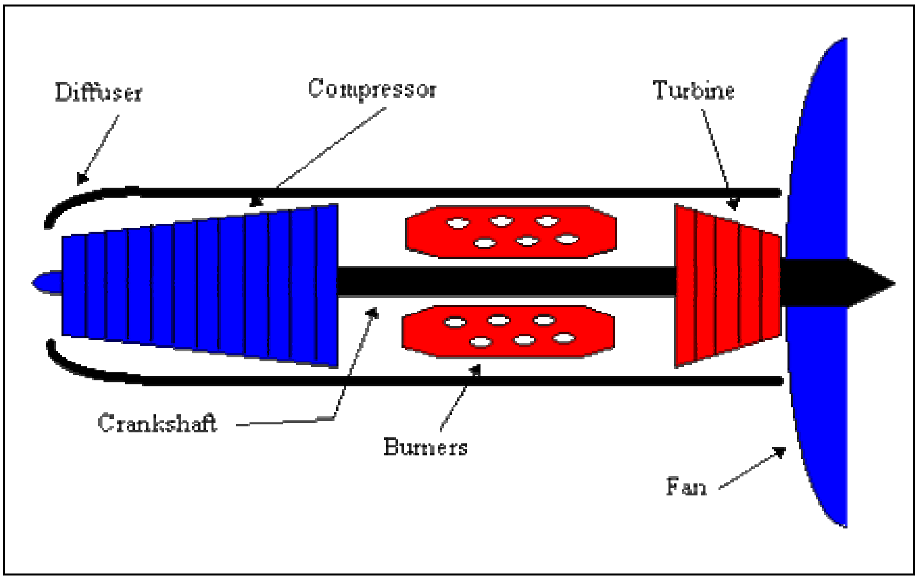


Fig 3.6 Schematic Drawing of a Propfan Engine (**allstar 2007**)

When dealing with unducted fan or propeller engine concepts, they very often show not only one open rotor but two contra-rotating ones. Contra-rotating propellers/propfans (see Fig. 3.7) are sometimes also referred to as *counter*-rotating propellers/propfans. **Wikipedia 2007** defines contra-rotating propellers as follows:

> *Contra-rotating propellers, also referred to as coaxial contra-rotating propellers, are a complex way of applying the maximum power of a single piston or turboprop aircraft engine. … Two propellers are arranged one behind the other, and power is transferred from the engine via a planetary gear transmission* [or a second shaft, remark of this author]. … *Contra-rotating propellers should not be confused with Counter-rotating propellers, a term which describes twin-engined aircraft with the airscrew on one engine turning clockwise and the other anti-clockwise.*
>
> *When airspeed is low the mass of the air flowing through the propeller disk (thrust) causes a significant amount of tangential or rotational air flow to be created by the spinning blades. The energy of this tangential air flow is wasted in a single propeller design. To use this wasted effort the placement of a second* [contra-rotating, remark of this author] *propeller behind the first takes advantage of the disturbed airflow.*
> *If it is well designed, a contra-rotating propeller will have no rotational air flow, pushing a maximum amount of air uniformly through the propeller disk, resulting in high performance and low induced energy loss. It also serves to counter the asymmetrical torque effect of a conventional propeller. Some contra-rotating systems were designed to be used at take off for maximum power and efficiency, and allowing one of the propellers to be disabled during cruise to extend flight time.*
>
> *The efficiency of a contra-rotating prop is somewhat offset by its mechanical complexity.*

Citing the engine manufacturer CFM's executive vice-president Bill Clapper, **Flight International 2007g** says that "... any open-rotor design would not be ready for service until 'very late in the second decade at the earliest'...". The first applications of open-rotor engines are intended for smaller narrowbody aircraft. Other engine manufacturers like Pratt & Whitney, however, favor more conventional geared turbofan (GTF) engines for the next-generation narrowbodies (**Flight International 2007h**).

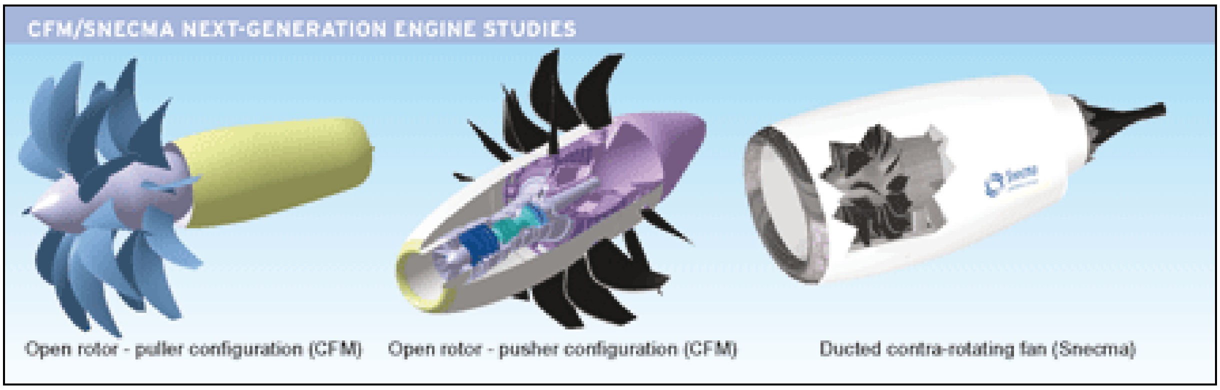


Fig 3.7 CFM/SNECMA Next-Generation Engine Studies (**flightglobal.com 2007**)

3.1.4 Electric Propulsion Systems

A general alternative to a combustion engine to drive a propeller is an electric motor. Just like a piston engine or a turbine it delivers shaft power that is converted into thrust power by the propeller. Modern Electric motors feature many advantages compared to piston engines and especially turbines. In general, they are very reliable, very efficient and require significantly less maintenance effort. The most important means to deliver electric energy are batteries, fuel cells or solar cells.

Electric Motors

Electric motors can be found in a vast number of different construction types. For use in vehicles, such as electrically powered General Aviation (GA) aircraft, especially brushless permanent-magnet direct current (DC) types are used (**Seeckt 2006**). According to **Farschtschi 2001**, DC motors' most important advantages are:

- Simple and cost-effective adjustment of engine speed,
- Large range of possible engine speeds,
- Applicable, where no alternating current (AC) is available (e.g. in vehicles), and
- Direct current electric energy is easy to store (e.g. batteries).

Batteries

> *Batteries are the most common known devices to store electric energy. Rechargeable batteries are also called secondary batteries or accumulators. The energy is not directly stored as electric energy, but as chemical energy in galvanic elements/cells and is converted into electric energy by means of a chemical reaction.*
>
> *Several different types of batteries exist, which also have large differences in storage capacity and handling characteristics (recharging procedure, auto-ignition, memory-effect, etc.). Today, the most often used types are: lead acid, nickel cadmium (NiCd), nickel metal hydride (NiMH) and lithium ion (Li-Ion). More modern types are e.g. lithium polymer (LiPoly, LiPo) and reusable alkaline batteries.*

(**Seeckt 2006**)

Solar Cells

When talking about electric motors, solar cells usually are one of the first thoughts to cross one's mind for energy supply. They are becoming more and more attractive and popular for terrestrial applications on houses and solar powered cars and small aircraft are widely known.

The **maximum total** solar radiation, measured by a satellite for a plate **perpendicular to radiation direction**, lies about 1412 Watt per square meter (**Wikipedia 2007**), of which, for technical reasons, only parts are usable. So this value defines an absolute maximum value. Assuming this total radiation applied to a transport aircraft of moderate wing loading and, hence, large wing top surface, such as a 200 t BWB of 488 kg/m^2, leads to the following, **never achievable** values of total electrical power:

$$1412\frac{W}{m^2}\cdot\frac{200000kg}{488\frac{kg}{m^2}}=\underline{\underline{579kW}} \tag{3.1}$$

It is apparent that even this **far too high** value is still too low for a 200 t BWB aircraft to justify the installation of solar cells on its upper surfaces when taking into account the aerodynamic penalties, extra masses for control devices, extra costs, extra maintenance, etc. Realistic values for the efficiency of solar cells of today's technology standard and average solar radiation in Germany lie at about 20 percent and 500 W/m^2 (**Seeckt 2006**). These values lead to 41 kW of additional power for the whole 200 t BWB aircraft.

Consequently, it is safe to say that solar cells are not feasible for transport aircraft, and they will not be regarded any further in this report.

Fuel Cells

Wikipedia 2007 gives the following general information on fuel cells; Figure 3.8 shows a schematic drawing of a Proton Exchange Membrane Fuel Cell.

> *A fuel cell is an electrochemical energy conversion device. It produces electricity from external supplies of fuel (on the anode side) and oxidant (on the cathode side). These react in the presence of an electrolyte. Generally, the reactants flow in and reaction products flow out while the electrolyte remains in the cell. Fuel cells can operate virtually continuously as long as the necessary flows are maintained.*
>
> *Fuel cells differ from batteries in that they consume reactant, which must be replenished, while batteries store electrical energy chemically in a closed system. Additionally, while the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are catalytic and relatively stable.*
>
> *Many combinations of fuel and oxidant are possible. A hydrogen cell uses hydrogen as fuel and oxygen as oxidant. Other fuels include hydrocarbons and alcohols.*

Guynn 2004 adds:

> *Using a propulsion system based on H_2 fuel cells has two primary advantages over burning H_2 in gas turbine engines... Because the fuel cell process is at a much lower temperature than combustion with air, NO_x emissions can be eliminated. When using pure hydrogen as the fuel, H_2O is the only emission from a fuel cell propulsion system. The second benefit is the potential for increased fuel efficiency.*
>
> *...*
> *Different types of fuel cells are generally categorized by the elctrolyte used. Five common types of H_2 fuel cells are presented in table 1 [here Table 3.1; remark of this author]: alkali, molten carbonate, phosphoric acid, proton exchange membrane, and solid oxide. ... The PEM fuel cell is favored for automotive application because of its high power density and its short start-up time. PEM fuel cells have been used by a variety of car manufacturers in am number of prototype vehicles, and a few plan to offer PEM fuel cell powered cars on a limited commercial basis in the near future. Interest in the solid oxide fuel cell (SOFC) has been increasing recently. The focus of*

> *SOFC applications has generally been large stationary power plants, but recent advances have increased interest in use a mobile power source, including aircraft auxiliary power units (APUs).*
>
> ...
>
> *In addition to the primary components of the propulsion system (fuel cell, electric motor, and ducted fan), there are also a significant number of ancillary systems such as power electronics, power distribution, and fuel distribution.*

However, the biggest drawback of using H_2 fuel cells for electric aircraft propulsion is the very poor specific power of the whole system. Based on 2004's technology level, **Guynn 2004** draws the following conclusions for a fuel cell powered BWB aircraft:

> *It is important to note that the fuel cell system only accounts for about 30% of the total power system weight and volume. To achieve significant reductions in system weight and volume it will be necessary to advance not only fuel cell technology, but also electric motor and power electronics technology.*
>
> *The large weight penalty associated with the current technology fuel cell power systems becomes clear when the specific power (power output per unit weight) is compared to conventional aircraft propulsion systems. The specific power of the current technology fuel cell power system is only 0.14 kW per lb* [aircraft piston engines: about 0.5 kW per lb, turboshaft engines: about 1.5 to 3.0 kW per lb; remark of this author]. *...The specific power of the fuel cell based system is at least an order of magnitude lower than conventional gas turbine based systems. Very substantial weight reduction (70-95%) is necessary for the fuel cell power system to be comparable to today's conventional aircraft propulsion systems. One of the expected benefits of a fuel cell based system is an increase in efficiency. An increase in efficiency over conventional propulsion systems would offset to some extent the propulsion system weight penalty by reducing the fuel weight required to perform the mission.*

Guynn 2004 illustrates the effects of the poor specific power of a fuel cell power system by means of the following concrete numbers for the investigated BWB aircraft:

> *The sea level static thrust-to-weight ratio (T/W) of the current technology fuel cell based propulsion system is only 0.23. The aircraft as a whole needs a T/W of about 0.27 to meet the design mission requirements. Even if the rest of the aircraft weighed nothing, the propulsion system would still be too heavy for the design to work.*

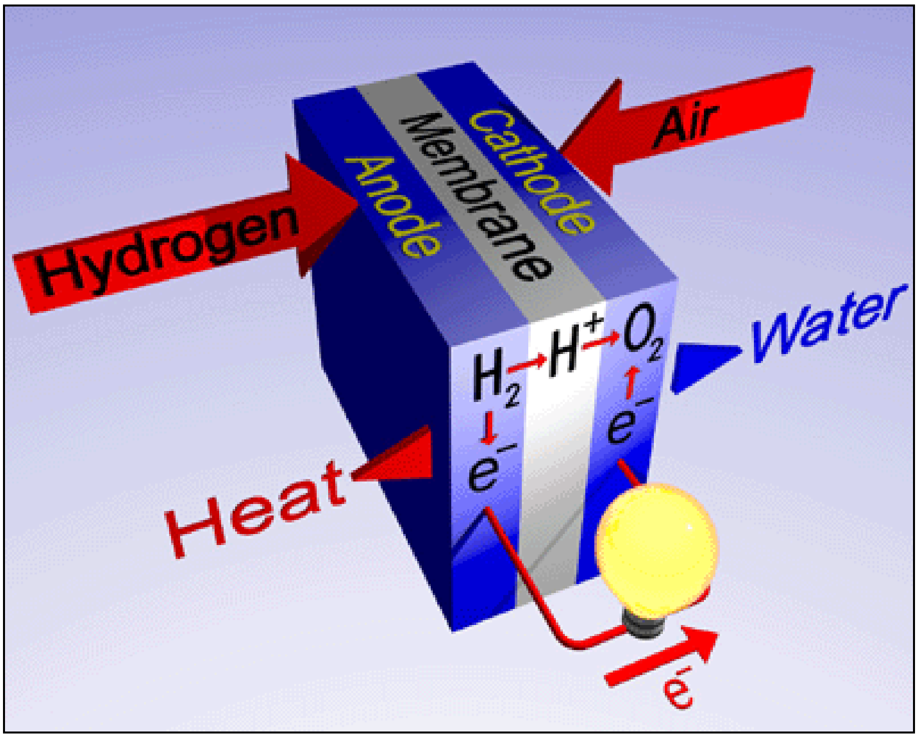


Fig 3.8 Schematic Drawing of Electricity Generation inside a Proton Exchange Membrane Fuel Cell (PEMFC) (**fuelcelltoday 2005**)

Table 3.1 Common Types of H2 Fuel Cells (**Guynn 2004**)

	Electrolyte	Operating Temperature	Typical Applications	Comments
Alkali	Potassium hydroxide	150-200 °C	Space (Apollo, Shuttle)	Expensive, requires pure H_2 and O_2
Molten Carbonate	Carbonate salts	650 °C	Large stationary power plants	Complex, needs CO_2 source or recycling system
Phosphoric Acid	Phosphoric Acid	150-200 °C	Small stationary power, mobile power	Extended warm-up period, large and heavy
Proton Exchange Membrane	Polymer membrane	~80 °C	Small stationary power, mobile power	Quick start-up, high power density
Solid Oxide	Ceramic	Low T: 650-800 °C High T: 1000 °C	Large stationary power plants	Some interest in use for mobile power (APU)

3.2 Propulsion System Integration

Engine or propulsion integration is always a big issue in aircraft design. There are many aspects and effects on the aircraft as a whole that have to be accounted for. The following three examples of engine integration shall illustrate these aspects.

Engines beneath the Wings

Figure 3.9 shows a top view on the passenger transport version of the Airbus A380 including all possible ground vehicles that have to access the aircraft during turn-around and may endanger the engines if these are poorly positioned.

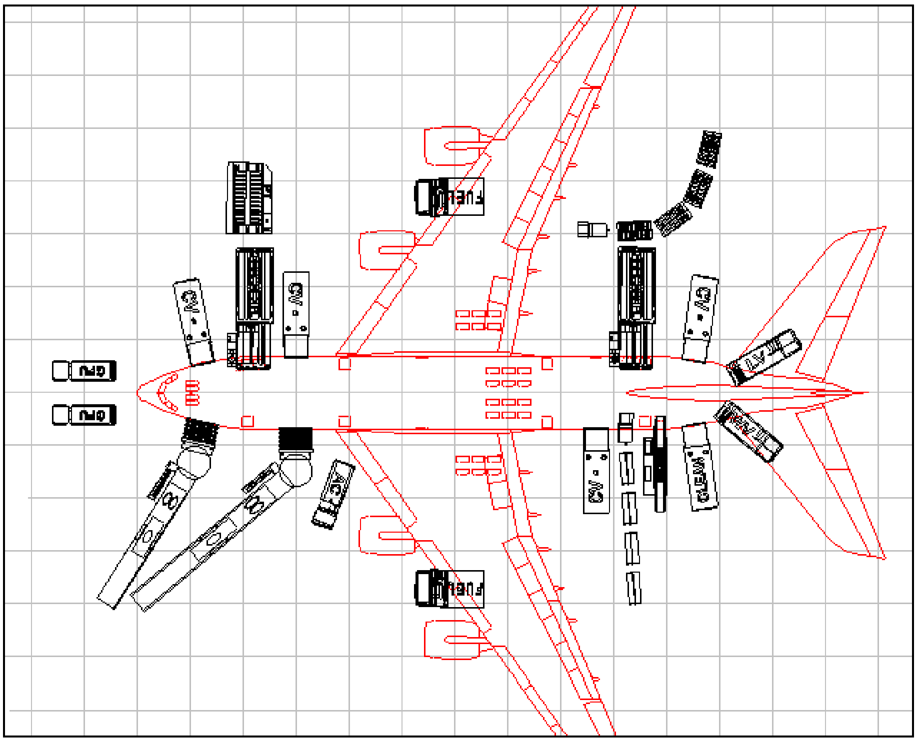


Fig 3.9 Top View on Passenger A380 including Ground Vehicles during Turn-Around (**Rivoire 2007**)

Another important issue about engine integration is engine burst. The loss of an engine blade may cause severe damages to the surrounding structure. Hence, there may be no security-relevant installations in the imperiled areas. For example, each engine has to be located in such a position that in case of an engine burst other aircraft systems or engines will not be damaged. The drawing in Figure 3.10 shows these endangered zones.

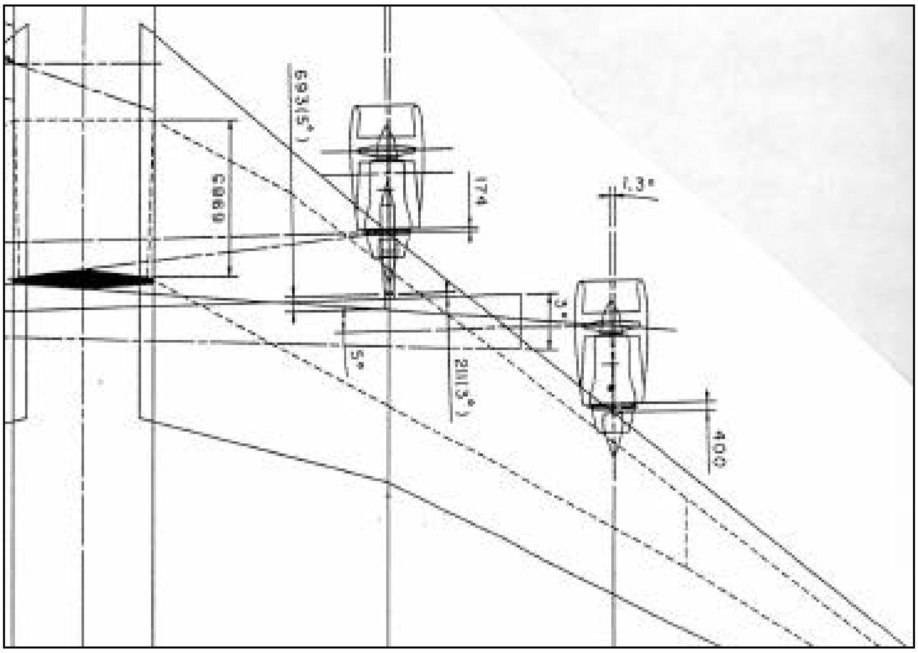


Fig 3.10 Drawing of Engine Burst-endangered Zones (**Rivoire 2007**)

Engines on Top of the Fuselage

The risk of an engine to engine damage is especially high, of course, when the engines are placed very close together as is the case in many newer design layouts like the Boeing X-48B, HAW's sketches for the new AC20.30 model (see Figures 2.18 -2.22) or the aircraft pictured in Figure 3.11.

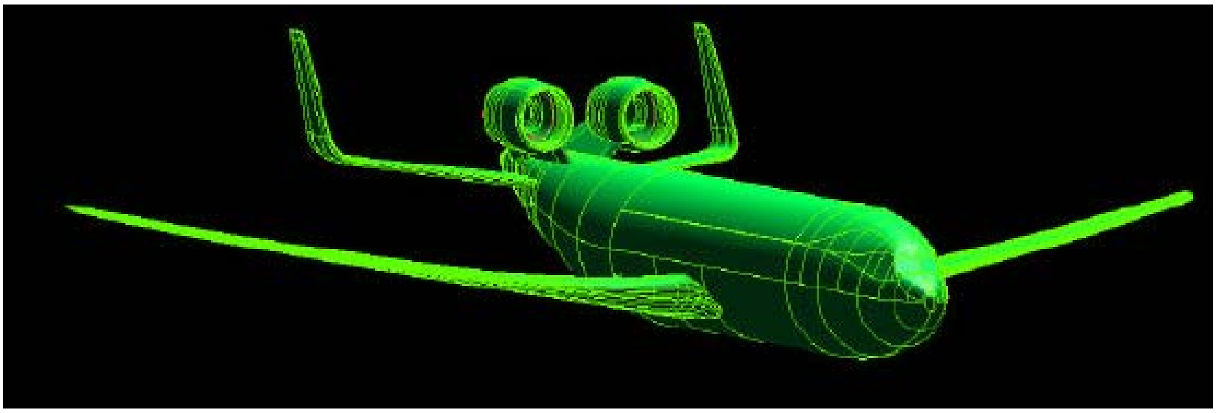


Fig 3.11 Engine Integration on Top of the Fuselage (**Rivoire 2007**)

Nevertheless, this type of engine integration features several advantages compared to engine installation beneath the wings. One of the most important ones is noise shielding. Noise reduction is a major objective for future aircraft and thus also laid down in the Vision 2020 with a value of 50% (see Terms and Definitions).

Further advantages of this type of integration are:

- No adverse interference on the wing (better C_D and $C_{L,max}$),
- Better lateral control in case of one engine failure,
- Relaxed nacelle ground clearances,

whereas the following points are rather drawbacks:

- More restricted A/C loading /CG travel,
- Rear doors arrangement on fuselage,
- Weight penalty : fuselage, empennage,
- Air inlet behavior at high angle of attack,
- Rear fuselage aerodynamic interference,
- Poor engine accessibility/maintainability.

Engine Integration in Wing Root

Engine integration into the wing root (see Figure 3.12) combines some positive effects of the two already mentioned types of propulsion integration. The most important ones are:

- Interference with wing, ground and fuselage is small,
- The lever arm in case of an engine failure is very small, which causes only little yaw moment,
- Ground vehicles do not get obstructed, hence the engine nacelles are less imperiled to be damaged, and
- The engine position is very close to the CG position, thus low restrictions regarding loading and CG travel.

In contrast, the most important disadvantages are:

- Poor engine accessibility and maintainability,
- Interruption of wing spars resulting in an interruption of wing loads paths and therefore heavier structure and
- Low interference only in case of small engine diameters (= low BPR and large SFC).

Fig 3.12 Engine Integration in Wing Root (de Havilland Comet, **airliners.net 2007**)

4 Fuels

4.1 Overview

Nowadays kerosene is used as fuel for jet and turboprop engines. Other liquid fuels like Diesel or gasoline are used for piston engines of, in general, smaller sized aircraft than dealt with in the Green Freighter project. All these fuels are made from crude oil of diminishing resources. So, even without respect to environmental issues, aviation and other industries will have to find a replacement for these fuels in the medium term.

Muissus 2007 is a summarizing presentation of a study which has been undertaken in cooperation with Airbus to investigate the possible fuel alternatives in more detail. In a first step, the study distinguishes between conventional and unconventional alternatives. Conventional means that these fuels are largely similar in terms of energy density and their physical and chemical behavior to the kerosene types Jet-A1 and JP 4 (civ./milit.); e.g.:

- Gas to liquid, GtL
- Coal to liquid, CtL } Synthetic Fuels (F-T fuels)
- Bio to liquid, BtL
- Vegetable oils: FAME, hydro-treated oils.

Hence, unconventional types of energy carriers differ in one or more of the mentioned aspects from today’s kerosene types; e.g.:

- Ethanol,
- Methanol,
- Silane,
- Liquid natural gas,
- Hydrogen.

At the moment, there are several tests and studies being undertaken by a lot of different companies and institutes that deal with potential future fuels. The U.S. Federal Aviation Administration (FAA), for example, just finished a research on ethanol as fuel in aviation (**Flight International 2007c**, see Section 4.6). Another example for such studies is presented in **Flight International 2007i**. This article says that Virgin has joined Boeing and the engine manufacturer General Electric (GE) in biofuels trials. It is planned to test eight different types of biofuels on an engine on ground before one of these is chosen and tested on a Virgin Boeing 747 in flight. The article states that the eight “... candidate fuels to be tested would include soya- and vegetable-based biofuels and butanol – but not ethanol – and that the selected choice would be tested on one engine in a 40-50% mix with standard kerosene.”

Appendix A contains detailed physicochemical data on several gaseous and liquid fuels.

4.2 The Fischer-Tropsch (F-T) Process

Wikipedia 2007 defines the Fischer-Tropsch process as follows:

> *The* ***Fischer-Tropsch process*** *is a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms. Typical catalysts used are based on iron and cobalt. The principal purpose of this process is to produce a synthetic petroleum substitute, typically from coal or natural gas, for use as synthetic lubrication oil or as synthetic fuel.*

Due to the fact that all F-T fuels are derived from the same process it is, as a first approximation, safe to say that "F-T liquids produced from any starting material will be essentially the same" (**Muissus 2007**). In addition, they all have to face overall efficiency penalties due to the energy demanding transformation process. Figure 4.1 shows the generic process of the transformation of different starting materials into different fuels by means of the F-T process (**Muissus 2007**).

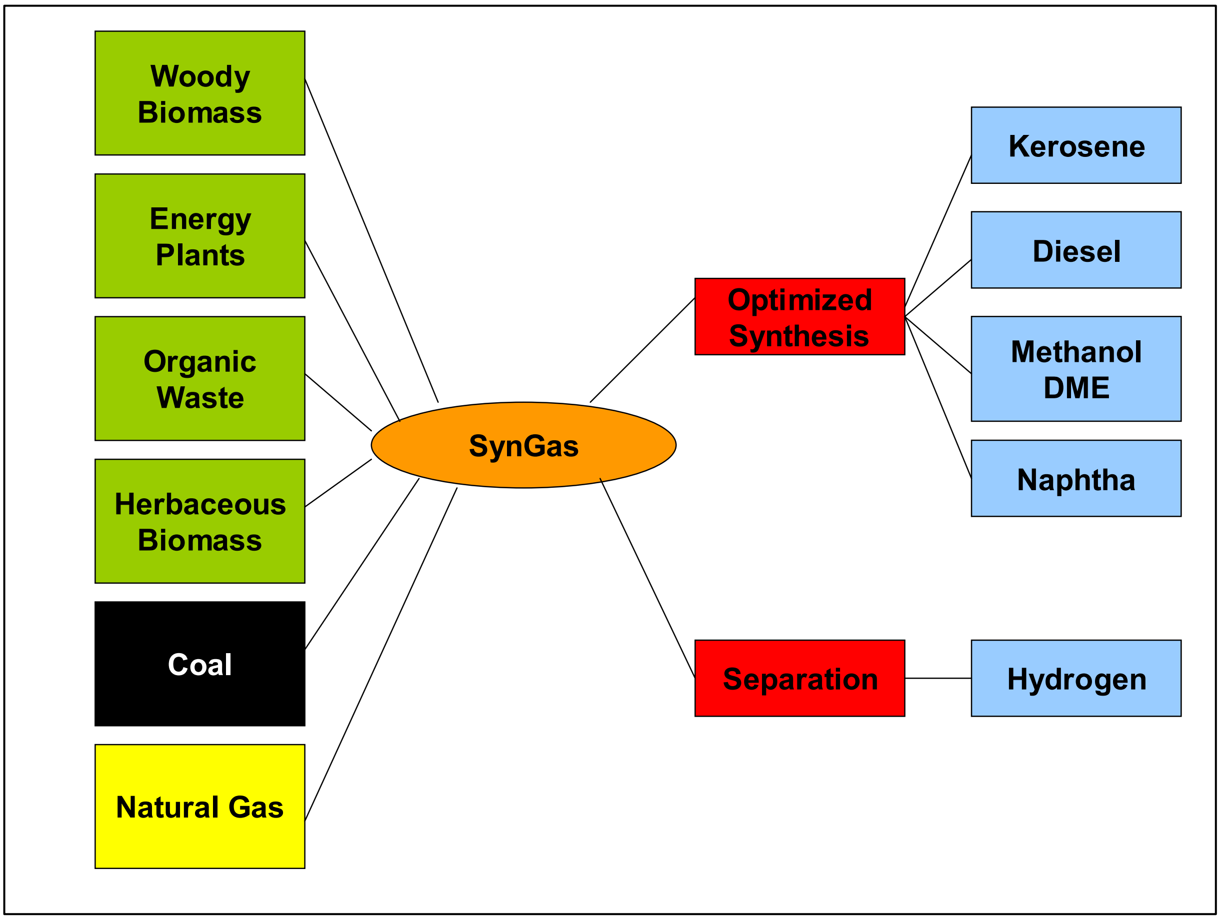


Figure 4.1 Generic Fischer-Tropsch Process (**Muissus 2007**)

4.3 Amount of Energy per Mass and Volume

Figure 4.2 includes a first comparison of different liquid fuels by means of their mass and volume needed to store an amount of energy of 100 MJ. It shows that Biodiesel and synthetic fuels (Synfuels), derived by means of the Fischer-Tropsch (F-T) process, have about the same volume and mass per energy unit as kerosene – represented by the aviation fuel Jet A/Jet A-1 in this graph. Ethanol and methanol, however, both show worse values in both aspects. Liquid methane shows slightly less mass per energy unit but needs, due to its smaller density, a significantly larger storage volume.

Liquid hydrogen is the big outlier in this graph. It holds a much better amount of energy per kg (almost factor 3) but its required storage volume for a certain amount of energy lies about a factor of 4 higher than for kerosene.

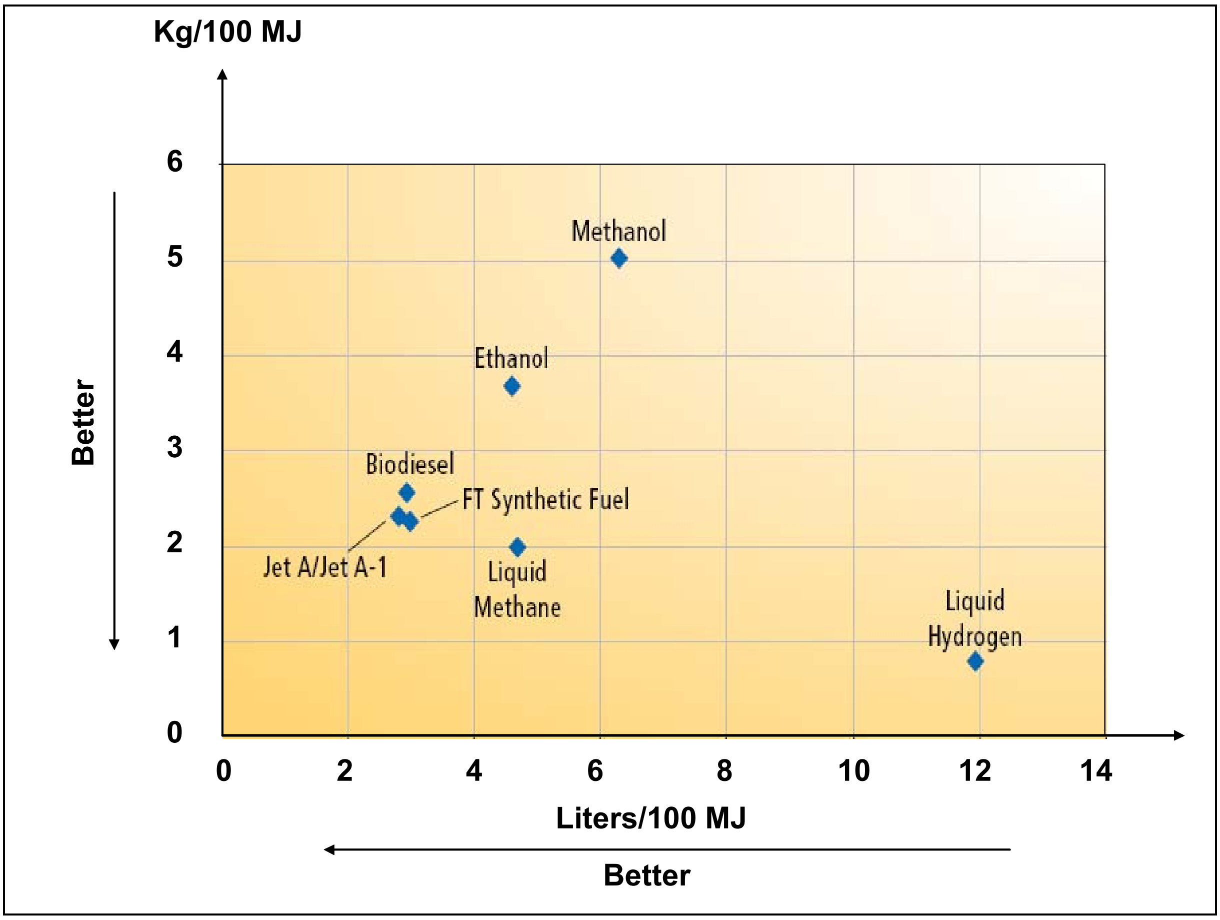


Fig 4.2 Mass of Fuel vs. Volume of Fuel per Energy Unit (**Chevron 2006**)

The comparison between kerosene and Synfuel derived from the F-T process with respect to energy per mass and volume is summarized in Table 4.1.

Table 4.1 Comparison of Kerosene and F-T Fuels with Respect to Energy per Mass and Volume (**Muissus 2007**)

Property	**Kerosene**	**F-T fuel**	**Delta in %**
Gravimetric value [MJ/kg]	43,2	44,2	+2,31
Volumetric value [MJ/l]	34,9	33,5	-4,01
Density [kg/l]	0,808	0,759	-5,94

Furthermore, **Chevron 2006** makes the following statements on the use of synthetic fuel compared to kerosene:

- Reduction in take-off weight for the aircraft due to its better energy per mass ratio.
- The energy per volume and the energy density is lower.
- Absence of aromatics and sulphur reduce soot emissions, but further investigations have to be accomplished to analyse minimum requirements.
- The environmental benefits of BtL fuel would be affected by the increased processing required to upgrade it.

4.4 Coal to Liquid (CtL) and Gas to Liquid (GtL) Synfuels

Both coal and natural gas are fossil fuels of limited resources. This means that both have to face similar disadvantages as crude oil, like rising prices with growing world energy demand and depleting resources and large CO_2-emissions during combustion. So, both CtL and GtL fuels would not be a cure-all, but they both would reduce the world energy market's dependency on the middle-east. Of all fossil fuels, coal is the one with the farthest reaching resources.

Compared to other alternative fuels, the transformation of coal to liquid has two major advantages: the F-T process has been used in South Africa for many years to produce aviation fuel, and a 50/50 blend of such fuel is already certified for use in aviation. Currently, the US Air force is undertaking test flights with a Boeing B52 bomber using different blends of GtL Synfuel (**Flight International 2006b**, **Flight International 2007d-f**). One of the results of using a (here 50/50) blend of Synfuel and JP-8 is a 50 percent reduction in produced smoke. "Because the F-T fuel contains no aromatics, it does not cause engine system O-rings and seals to expand during operation, the way that normal JP8 fuel does. Therefore, it was decided to test the engines using a 50-50 blend with JP8 so that the engine systems could be operated without modification." (**Flight International 2006b**).

The GtL process can be applied to methane-rich gases like natural gas to convert these into liquid fuels of a very high quality. The advantages of the GtL process are the low NO_x-emissions during combustion of these Synfuels and the possibility to use gaseous waste products of refineries in the GtL process. The biggest disadvantage of GtL Synfuel is the very expensive conversion process. Further negative aspects of CtL Synfuel are the large amount of hydrogen needed for the liquefaction of coal and the high CO_2-emissions which are even higher than for conventional kerosene. (**Muissus 2007**)

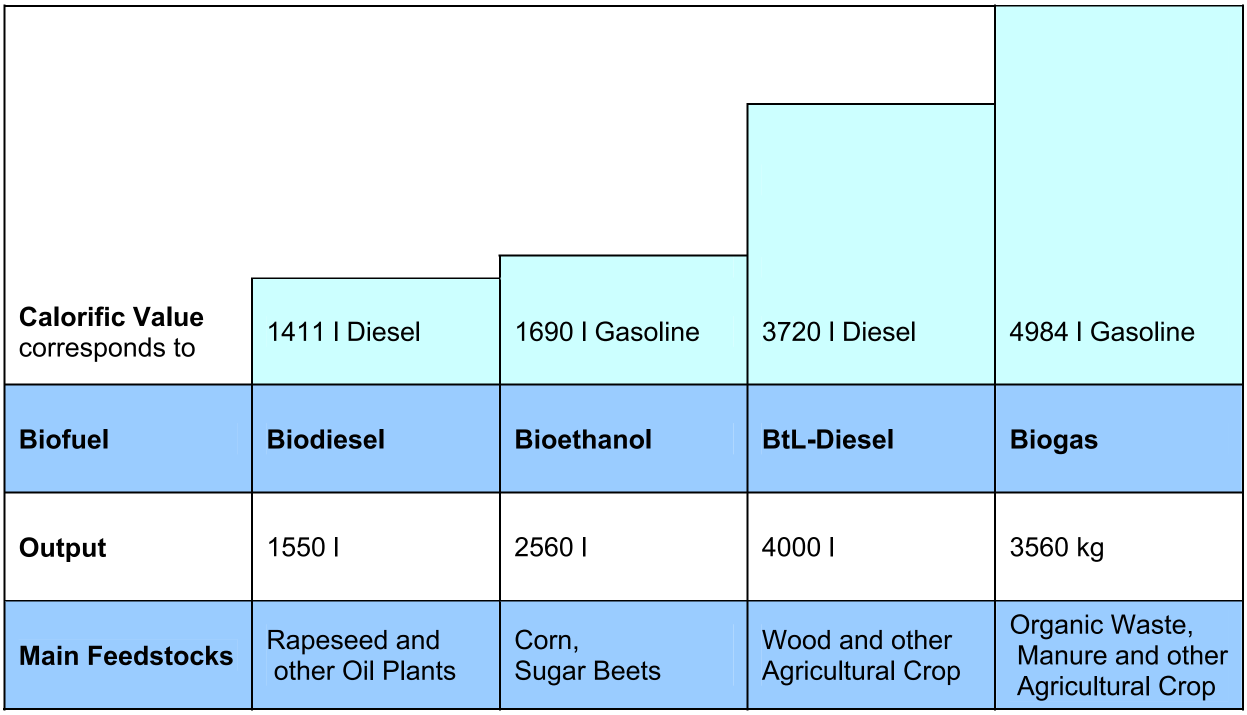
4.5 Biofuels

4.5.1 General

Biofuels share some similar disadvantages, which makes them all high in production costs. Especially vegetable oils and – as a consequence as they are derived from vegetable oils – Biodiesel and hydrogenated Biodiesel have to face a very low production output as only small parts of the feedstock plants contain the oil. Furthermore, they compete with food agriculture which leads to moral and social side effects which may not be neglected in an objective assessment. For a large-scale production of these fuels very large areas of agricultural cropland are needed. **Der Spiegel 2007** reports that in the USA, already today 20 percent of the overall cropland is used for ethanol production. In a few years, when all ethanol distilleries that are currently in planning have been completed, e.g. the state of Iowa will have to deliver its whole corn harvest to these fuel distilleries. This competition has global effects. In 2006, the global market price for corn has risen by 80 percent and even doubled in the beginning of 2007. This price increase has e.g. lead to mass demonstrations in Mexico where cornmeal is a very important staple food.

Another conflicting aspect of producing fuel from bio-feedstock is that if it is lucrative to cultivate e.g. industrial grass for ethanol production, it becomes very incentive for many countries to enlarge cropland into so far not agriculturally used area like the rain forest. In the long term, an alternative fuel candidate is biofuel derived from algae. Using this resource would significantly reduce this threat.

Figure 4.3 shows a comparison of different biofuels concerning their possible yearly output and the calorific value represented by the corresponding volume of conventional fuel per hectare cropland.



Calorific Value corresponds to	1411 l Diesel	1690 l Gasoline	3720 l Diesel	4984 l Gasoline
Biofuel	**Biodiesel**	**Bioethanol**	**BtL-Diesel**	**Biogas**
Output	1550 l	2560 l	4000 l	3560 kg
Main Feedstocks	Rapeseed and other Oil Plants	Corn, Sugar Beets	Wood and other Agricultural Crop	Organic Waste, Manure and other Agricultural Crop

Fig 4.3 Comparison of Yearly Output and Calorific Value per Hectare Cropland of different Biofuels (based on **Der Spiegel 2007**)

4.5.2 Bio(mass) to Liquid (BtL, Biofuel)

Biomass to liquid (BtL) fuel is also known as Sunfuel or Sundiesel; sometimes also the expression Synfuel is used. Its chemical and physical structure is very similar to Coal to liquid (CtL) and Gas to liquid (GtL) fuels, but in contrast to these, it is a sustainable fuel due to the biomass feedstock used for production. Biofuel has a slightly lower energy density than mineral kerosene and the absence of aromatics has to be compensated for use in practice (see Section 4.4). In general, a cost efficient production depends on cheaply available biomass and reduced capital costs.

For the moment, BtL fuel still tends to be 2-3 times more expensive than petroleum based fuels, especially due to low production rates. In general, Biofuel's future is highly dependent on governmental decisions on future taxes on CO_2-emissions (**Muissus 2007**).

4.5.3 Vegetable Oils, Biodiesel (FAME), Hydrogenated Biodiesel

Vegetable oils

In general, vegetable oils are cheaper in production than Biodiesel. They are biodegradable and no dangerous goods. In addition, they can be transformed into FAME or hydrogenated Biodiesel. The problems about vegetable oils are that their thermal stability is not clear and that they are very viscous which complicates handling and would, for example, require a heating as on ships using fat oil as fuel.

Biodiesel (FAME – Fatty Acid Methyl)

Roughly speaking, Biodiesel produces only as much CO_2 as it has absorbed during growth. It does not contain sulfur, therefore it does not support sour rain, dieing of forests and damage on historical architecture. Biodiesel is also biodegradable, which e.g. reduces the threat of tanker crashes. Biodiesel has the potential to be used as a "kerosene extender" by blending it with conventional kerosene up to a maximum of approximately 10% - 20% by volume (**ICCEPT 2003**, cited in **Muissus 2007**)

The problems about Biodiesel are its thermal stability below -20°C and its nature to damage sealing rubber and hoses which means that special rubber materials have to be used.

Hydrogenated Biodiesel

In general, all nondrying vegetable oils or animal fat can be used as feedstock. After a removal of impurities, the feed is heated and pumped into the hydro-treating reactors where oxygen is removed and the feed (triglyceride) is converted into three separate branched chain paraffin. Hydrogenated Biodiesel can either be used as a pure diesel fuel or mixed with diesel to be used as a fuel component. It is a pure hydrocarbon product which is similar to synthetic fuel and free of aromatics, sulfur and oxygen. It has suitable thermal stability and a low cloud point which can be adjusted from - 5 to - 28°C. Compared to BtL fuel, the CO_2-reduction potential of hydrogenated Biodiesel is about 38 to 79 percent inferior (**Muissus 2007**).

Table 4.2 shows a comparison of petrochemical kerosene to Biodiesel (FAME), ethanol and synthetic kerosene from an aeronautical point of view. It shows the large number of deficits of Biodiesel. However, the use of synthetic kerosene appears to be very interesting from a technological point of view but has to suffer from its two large deficits: its high costs and its poor short-term availability. Ethanol is looked at in more detail in the next section, but it is already worth noticing its large deficits in energy density and integration into aviation industry.

Table 4.2 Comparison of Petrochemical Kerosene to different Biofuels in Aviation (**Muissus 2007**)

Characteristic	Petrochemical Kerosene	FAME	Ethanol	Synthetic Kerosene
Energy Density by Mass [MJ/kg]	good (43.2)	good (38.9)	poor (27.2)	good (44.2)
Energy Density by Volume [MJ/l]	excellent (34.9)	excellent (33.9)	poor (21.6)	excellent (33.6)
Freeze Point	excellent	poor (0 °C)	excellent	excellent
Cost	low	medium	medium	high
Thermal Stability	excellent	poor	excellent	excellent
Oxidative Stability	excellent	poor	excellent	excellent
Resistance to Microbiological Attack	excellent	poor	excellent	excellent
GHG Benefit	no	medium	medium	excellent
Time Scale	current technology	available in short term	available in short term	available in middle term
Integration	current technology	difficult	very difficult	easy

4.6 Unconventional Fuels

Muissus 2007 deals with the following unconventional fuels:

- Alcohols (Ethanol, Methanol)
- Silane,
- Liquid natural gas,
- Hydrogen.

Alcohols: Ethanol and Methanol

Both ethanol and methanol are used in many industrial and chemical applications and are already produced in large commercial scale (ethanol approx. 25 billion liter/year, methanol over 47 billion liter/year). As can be seen in table 2.2 ethanol has got large deficits in energy density and integration into aviation industry, which is also true for methanol. In addition they both have less suitable handling properties than kerosene due their low flash points (ethanol 12 °C, methanol 18 °C) and the resulting risk potential. Furthermore, they present a risk to health when in contact with skin and produce noxious emissions, especially at low power settings (**ICCEPT 2003** cited in **Muissus 2007**).

Flight International 2007c gives information on the U.S. FAA's first extensive test of aviation grade ethanol (AGE) as fuel for aviation (piston) aircraft. The test confirms earlier results of other researchers: a decreased engine power when using AGE instead of conventional iso-octane fuel. According to the authors of the FAA report, D. Atwood and A. Ivanov, the use of AGE-85 leads to 9 percent more fuel weight for the same fuel volume and 35 percent less range compared to the use of conventional piston engine fuel 100LL (low lead).

Silane

Carbon (C) and Silicon (Si) are in the same main group of the periodic table (group IV). Analogically, they form the same hydrogen compounds:

- Methane: CH4, Monosilane: SiH4
- Propane: C3H8, Trisilane: Si3H8
- Pentane: C7H16, Pentasilane: Si7H16........SinH2n+2

During combustion Silane burns with N2 and O2 to Si_3N_4 + H_2O + Energy. The Problems about Silane(s) are that most of them are very explosive. Therefore, handling and production of higher Silane is dangerous and not yet technologically realised in large scale. For the production sand (SiO2) is used as raw material, but the production costs have only been estimated yet. In addition, Si_3N_4 is a solid that is left in the combustion chamber and blown into the air after combustion (**Muissus 2007**, **Wikipedia 2007**).

Liquid Natural Gas (LNG)

Liquid natural gas is produced at almost atmospheric pressure by cooling it to approximately -163 °C. Due to its low temperature it must be transported by special cryogenic sea vessels, cryogenic road tankers and be stored in special tanks. Its volume is about 1/614th the volume of natural gas at standard temperature and pressure. Natural gas is a fossil fuel of limited resources and. As of today, it is more expensive than kerosene.

Hydrogen, Liquid Hydrogen (H_2, H2, LH2)

First of all, hydrogen is not a fuel in the sense of an energy source; in fact it is an energy carrier – quite comparable to a battery. It is not just simply available, but energy has to be employed first to obtain hydrogen in a pure state, e.g. by means of electrolysis. This process is very energy consuming, and only parts of this previously needed energy can be regained afterwards. Nowadays, hydrogen is mostly produced from natural gas as this process is still much cheaper than electrolysis. In consequence, the use – or better the production – of hydrogen consumes fossil resources and also contributes to the greenhouse effect.

If produced from renewable energy sources, hydrogen offers the potential of extremely low emissions (zero CO_2 and very low NO_x) by lean combustion. As an alternative to kerosene,

H_2 has to be cooled down to -253 °C, to be stored in liquid form (LH2). Based on the same energy content, LH_2 only has one third of the mass of kerosene; but a four times greater volume. Safety analyses have proofed, that H_2 is at least as safe as a conventional hydrocarbon fuel (**Brewer 1991**, **Muissus 2007**, **Palaszewski 1997**).

As already mentioned, the production oh hydrogen is very energy intensive. Furthermore, there are several other problems about the use of hydrogen in aviation that would have to be solved. These are especially:

- The storage volume – even in liquid state the energy specific volume is 4 times the volume of kerosene.
- Hydrogen's boiling temperature lies at 20 K.
- The effects of contrails on climate change etc. are still unknown to a large extend.
- Hydrogen storages would suffer boil-off and diffusion losses.
- Hydrogen in an aircraft needs a completely different fuel system layout.
- A completely new infrastructure has to be created for the production and supply of hydrogen to aircraft.

Brewer 1991 deals extensively with the use of hydrogen in aircraft technology and summarizes the following advantages for hydrogen:

- A cleaner environment,
- Improved safety,
- Improved aircraft performance,
- Less Energy required from resources,
- Lower Direct Operating Costs,
- Universal availability,
- Favorable economic impact.

Furthermore, Brewer announces another question on what will happen after making fuel for aircraft becomes economically unattractive: how will the transition be made? This question is one of the most important ones in general and in particular for aviation, as an aircraft has a much longer life cycle than e. g. a car. This leads to the fact that many aircraft that are entering into service or even just being developed right now will still be in operation when the world production of crude oil has significantly reduced. “This implies, of course, that conventional petroleum-base fuel for these aircraft will be both very high in price and probably uncertain in availability in some parts of the world before the normal useful life of the aircraft is complete.” (**Brewer 1991**, p. 399).

Based on this scenario, Brewer discusses three options to airlines and aircraft industries of how to act and finally gives a clear recommendation:

> *In order to realize all of the advantages listed above, it is recommended that a LH_2-fueled aircraft technology development program … be implemented as soon as possible.*
>
> …
>
> *It is important that this program be instituted as soon as possible and that it be expedited throughout. It should be assigned the urgency of the "Man on the Moon in this Decade" program because of the cost in trade deficit dollars which will be incurred during the period of development. …*

(**Brewer 1991**, p. 403)

Palaszewski 1997 deals with the use of gelled hydrogen as fuel for aerospace vehicles. Main focus of this paper is on use as a rocket propellant. The following statements are taken from this paper:

- There are five major benefits: safety increases, boiloff reductions, density increases with the attendant area and volume related mass reductions for related subsystems (thermal protection system, structure, insulation, etc.), slosh reductions, and specific impulse (Isp) increases (in some cases).
- A higher viscosity reduces the spill radius of the gelled hydrogen and limits the potential damage and hazard from a fuel spill. Another important advantage is the potential for leak reduction or elimination.
- The boiloff reductions are up to a factor of 2 to 3 over ungelled liquid hydrogen.
- Significant density increases are possible with gelled hydrogen. A 10% density increase is possible with 10% added ethane or methane. These gellants are introduced into the hydrogen as frozen particles that form a gel structure in the hydrogen.
- For airbreathing vehicles, such as the National Aerospace Plane (NASP), the estimated reduction in GLOW [Gross Lift-Off Weight; remark of this author] for slush hydrogen [another high density hydrogen; remark of this author] was from 20 to 50%. Thus, a gelled hydrogen with a 10% density increase may deliver a significant fraction of these GLOW reductions and other subsystem mass savings.

5 Combinations of Propulsion Systems and Fuels

When talking about different combinations of propulsion systems and fuels, one again has to clearly distinguish between propeller and jet aircraft. The propeller propulsion system offers a lot of opportunities to design a hybrid propulsion system using different types of engines and/or different fuels. In contrast, there are two ways to make a turbo engine propulsion system hybrid: using different fuels on separate engines or using different fuels on one engine.

5.1 Hybrid Power Trains

Figure 5.1 shows the generic matrix of the different possibilities to combine fuels and energy converters/motors. Here, the word "energy converter" (EC) is used since the device could be e.g. a turbine, piston engine or electric power system. Besides the numbers of fuels and energy converters, the power trains are grouped by their number of couplings. This differentiation goes from zero, where all ECs are permanently connected to the propeller axis, to one coupling per EC so that every single EC may be coupled in or be decoupled absolutely freely.

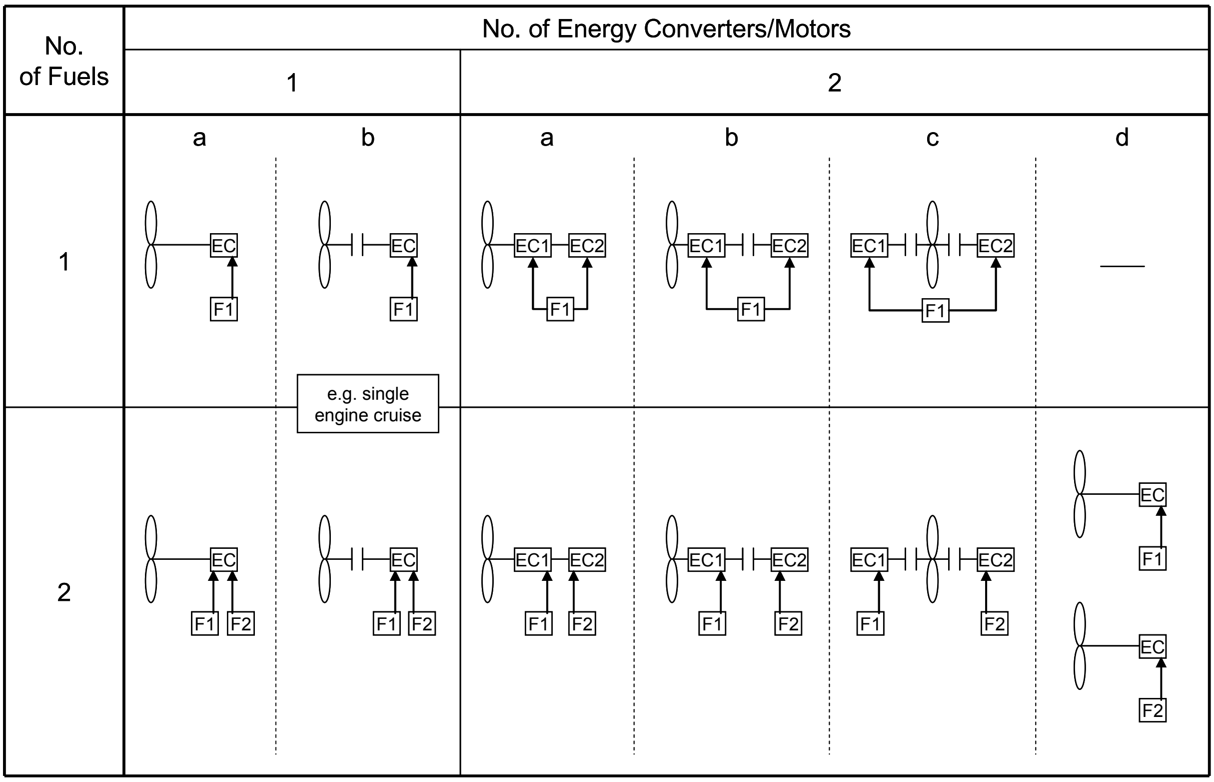


Fig 5.1 Matrix of Different (partly Hybrid) Power Train Arrangements

5.2 Bi-Fuel Turbo-Engines

Generally, it is possible to drive a turbo engine with two different fuels both at the same time or consecutively, whereas, of course, engine construction and control have to be adapted. Possible fuels for such operations are e.g. hydrogen, natural gas, kerosene and kerosene-like synthetic and Biofuels. Transferred into the schematic drawings of Figure 5.1, these are the options 1a/2 and 2d/2.

Examples of aircraft being able to burn two different types of fuel are the Tupolev Tu-155 and Tu-156, both modified versions of the Tu-154, a medium range transport aircraft of about 100 t MTOW. Figure 5.2 shows the Tu-156 which uses liquefied natural gas (LNG) in combination with kerosene. It is apparent that using (even liquefied) gaseous fuel leads to an enormous reduction in storage volume if the fuel tanks are to be stored inside the fuselage of a conventional aircraft. In case of the Tu-156, the maximum payload is reduced from about 18 t of the Tu-154 to only 14 t.

Fig 5.2 Drawing of the Tupolev TU-156 (**Tupolev 2007**)

6 Air Cargo

6.1 General

Typical examples of air freight are parcels, flowers and fruits and high-price technical equipment. These types of goods make up the largest part (by weight) of all air freight. But furthermore, there are some other types that are frequently transported by aircraft because of air transportation's very high safety and reliability standard and/or very short transportation time. Examples for these types of air freight are living animals, works of art and luxury goods.

Nowadays, air freight is mostly transported in so-called Unit Load Devices (ULDs). These are standardized containers and pallets of different shapes and sizes, depending on the type of aircraft and on the deck (main vs. lower deck) they are intended for. Pallets are used on the main deck of cargo aircraft, whereas there are container types for the main and for the lower deck compartments of several aircraft. Today's aircraft's cylindrical fuselages make it necessary to adopt the shape of the cargo containers to the aircraft contour (see Figure 6.1). Today's most important ULDs are the so-called LD 3 container and pallets of 125" x 96" (3.18 m x 2.44 m) base plate. In these ULDs about 95 percent of all of today's air freight is being transported (**Thramer 2004**). Figures 6.2 and 6.3 depict these types of load devices.

Fig 6.1 B757 Side Door Loading (**Massachusetts Institute of Technology 2004** cited in **Vrydag 2007**)

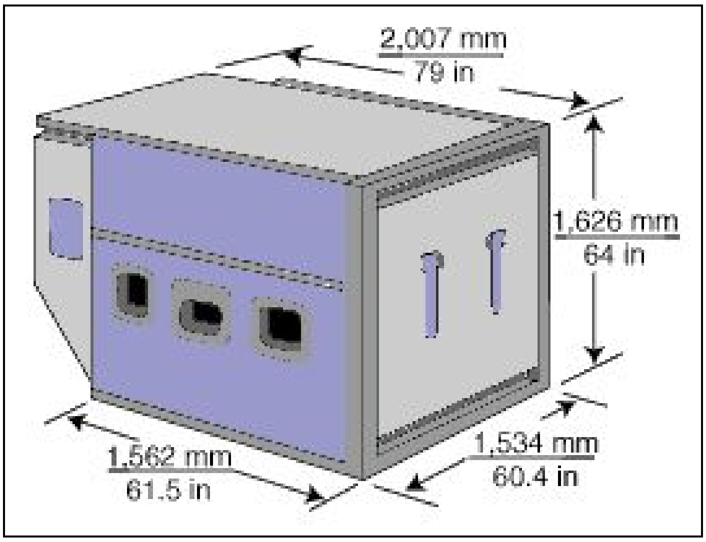


Fig 6.2 Lower Deck Container LD-3 (**Tradeway 2007**)

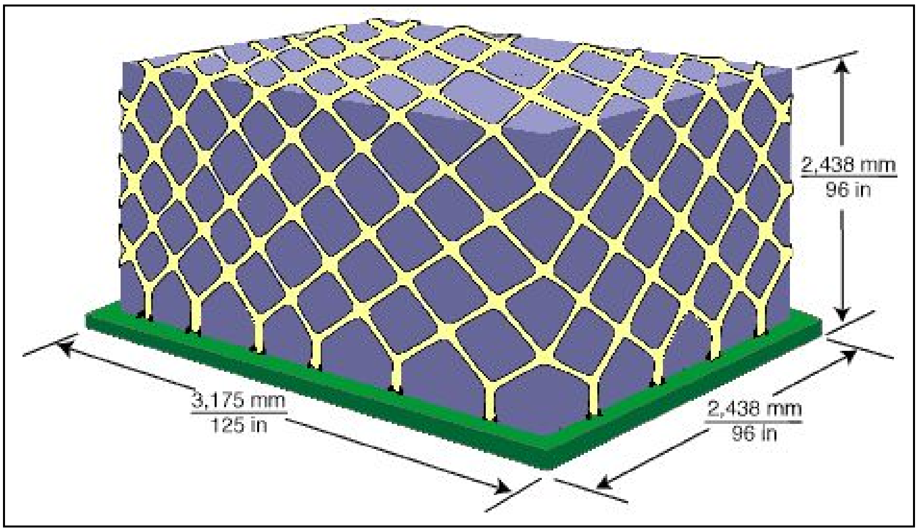
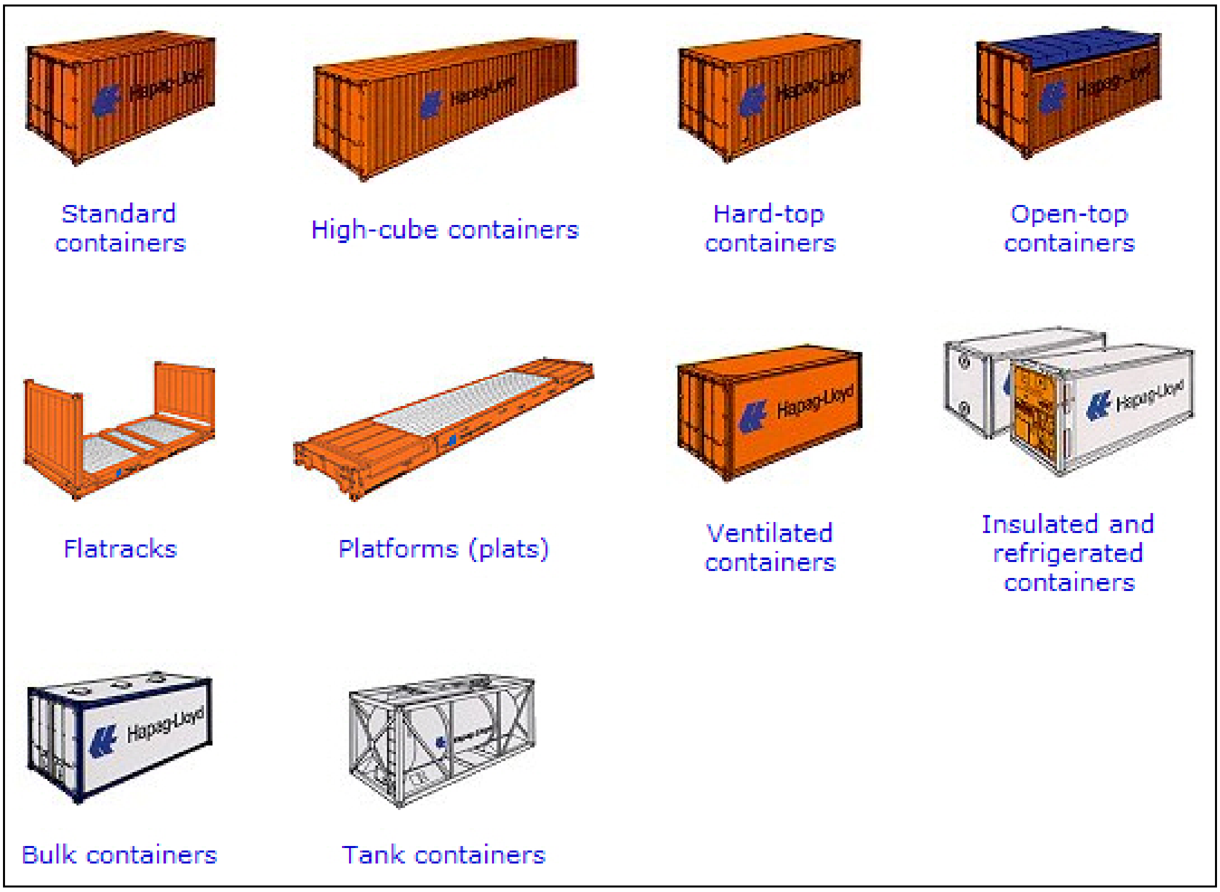


Fig 6.3 Main Deck Pallet PM (**Tradeway 2007**)

Outside aviation, the most important transport units are standard ISO containers. These block-shaped steel vessels are available in different sizes; one distinguishes between 20-feet standard containers (twenty-feet-equivalent-unit, TEU), 40-feet standard containers (forty-feet-equivalent-unit, FEU), 45-feet high-cube containers and special containers. Figure 6.4 shows some examples and Table 6.1 gives some technical data on these containers.


Standard containers

High-cube containers

Hard-top containers

Open-top containers

Flatracks

Platforms (plats)

Ventilated containers

Insulated and refrigerated containers

Bulk containers

Tank containers

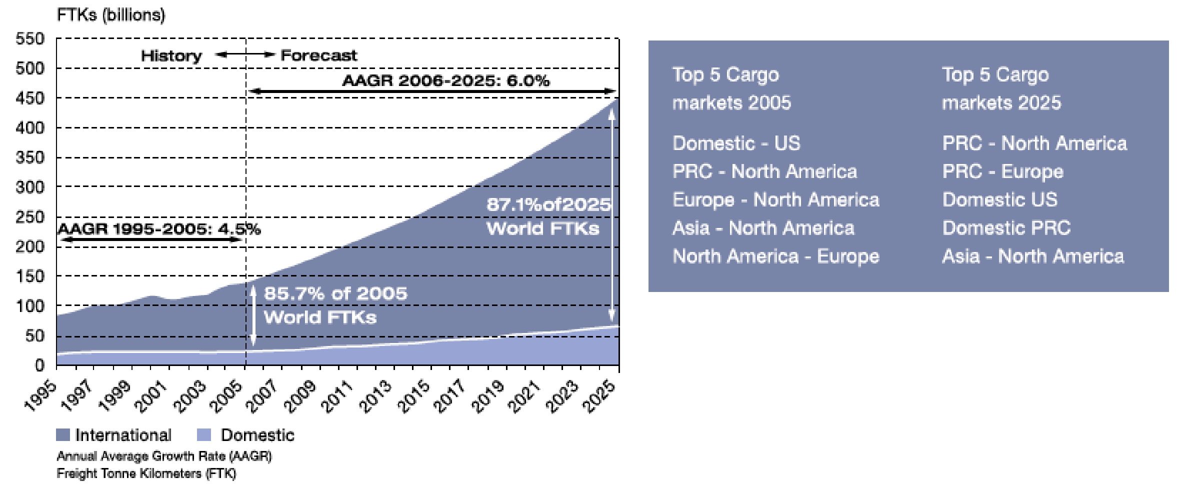
Fig 6.4 Examples of different ISO Standard Containers (**GDV 2007**)

Table 6.1 Technical Data on ISO Standard Containers (**Wikipedia 2007**)

		20′ Container		**40′ Container**		**45′ High-Cube Container**	
		imperial	**metric**	**imperial**	**metric**	**imperial**	**metric**
External Dimensions	**Length**	20′ 4″	6.198 m	40′ 0″	12.192 m	45′ 0″	13.716 m
	Width	8′ 0″	2.438 m	8′ 0″	2.438 m	8′ 0″	2.438 m
	Height	8′ 6″	2.591 m	8′ 6″	2.591 m	9′ 6″	2.896 m

6.2 Freighter Aircraft Market Forecast

Figure 6.5 is taken from the Airbus Air Cargo Forecast 2006 (**Airbus 2006**), which is part of Airbus’ annual Global Market Forecast (GMF). It shows the real development of the world air cargo traffic between 1995 and 2005 and its expected development until 2025.



Top 5 Cargo markets 2005	Top 5 Cargo markets 2025
Domestic - US	PRC - North America
PRC - North America	PRC - Europe
Europe - North America	Domestic US
Asia - North America	Domestic PRC
North America - Europe	Asia - North America

Fig 6.5 Forecast of the Global Air Cargo Traffic Development (**Airbus 2006**)

As can be seen in Figure 6.5 the predicted annual average growth rate (AAGR) of the world’s air cargo market adds up to 6.0 percent, causing to the total amount of annual freight tonne kilometers (FTK) to triple by 2025. The by far fastest growing market and most important market will be the People’s Republic of China (PRC). As a consequence, the Airbus GMF predicts the world’s freighter aircraft fleet to grow from 1,644 in 2005 to more than 4,000 aircraft (4,115) in 2025.

The Boeing annual Current Market Outlook (CMO) 2007 (**Boeing 2007a**) reads very similar:

> ***870 New Freighters Required by 2026***
>
> ***More Effective Use of Future Freighters***
> *The air cargo market is set for average growth of 6.1 percent per year, comprising 6.2 percent per year for air freight and 2.5 percent per year for airmail. This will triple the volume of world air cargo traffic (RTKs* [Revenue Ton Kilometers; remark of this author]*) over the 20-year period.*
>
> *The average size of freighter airplanes will increase to carry this increased amount of freight, and the dedicated cargo fleet will double from 1,980 to 3,980 airplanes* [in 2026; remark of this author].
>
> *Some of the increase in freighter capacity will be accounted for by the 2,480 passenger airplanes that will be converted to freighters. In addition, 870 new dedicated freighter airplanes will be delivered.*
>
> *The proportion of cargo carried in the belly holds of passenger airplanes will decrease, because dedicated freighters deliver more flexible and time-definite service.*

> ***Large Share of Widebody Freighters***
> *The improved efficiency of the new types of widebody freighter airplanes recently offered to the market (as exemplified by the 777 Freighter and 747-8 Freighter) provide air cargo carriers options for service that have not previously been feasible.*
>
> *This product response to market requirements has helped revitalize interest in new widebody freighter acquisitions, which will go some way toward mitigating the effect of sustained high fuel prices. By 2026, about 64 percent of the freighter fleet will be widebody types, as opposed to about 58 percent today.*
>
> ***Expanded Market Coverage***
> *As with the passenger airplane forecast, the CIS region is included in this year's Current Market Outlook numbers.*

Figure 6.6 illustrates the development of the world's freighter aircraft fleet in more detail.

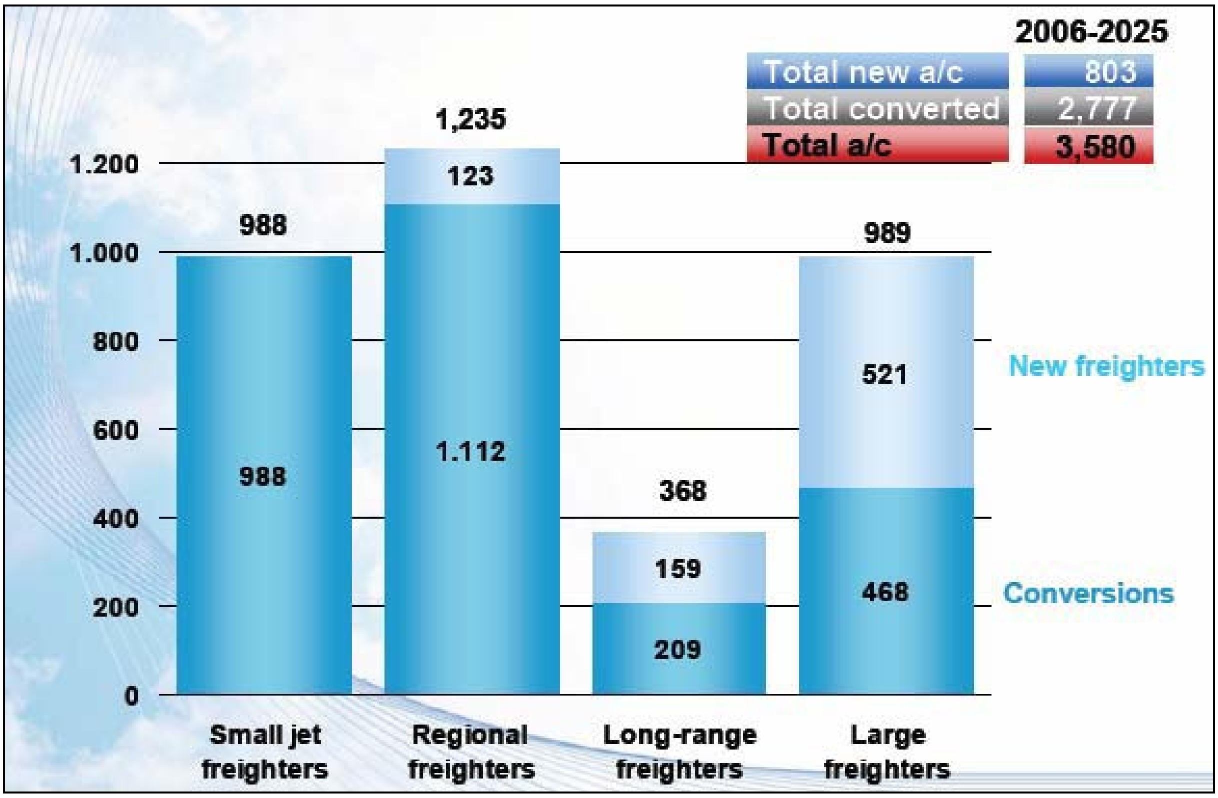


Fig 6.6 Freighter Market Forecast for 2006-2025 (**Habermann 2007** cited in **Zandstra 2007**)

All these forecasts show that the freighter aircraft market is a fast growing market for aircraft manufacturers. This makes it very interesting and promising for them to develop dedicated freighter aircraft instead of converting passenger versions into freighter aircraft. **Especially the large freighter segment shows great need for new aircraft.**

7 Selection of an Aircraft Concept

7.1 General

7.1.1 Measure of Merit

As implemented in the project name, the Green Freighter project's main topic shall be environmental friendliness in conjunction with improved cost efficiency. For both objectives one of the main measures of merit (MOM) is an aircraft's fuel efficiency. This section introduces shortly this MOM to illustrate the background of the selection of an aircraft concept.

Torenbeek 2005a defines fuel or energy efficiency as

$$E = \eta \cdot \frac{H}{g} \cdot \frac{L/D}{W/N_S} \text{ , with} \qquad (7.1)$$

η = overall efficiency of the installed propulsive device(s)
= fraction of fuel heat content converted into useful thrust power,
$\frac{H}{g}$ = fuel specific heat content in terms of a distance,
L/D = lift-to-drag ratio; measure of aerodynamic fineness in horizontal flight,
W/N_S = aircraft all-up weight (AUW) per seat.

Torenbeek 2005a further discusses the issue of fuel or energy efficiency as follows:

> *The overall efficiency η of the installed propulsive device(s) equals the fraction of the fuel heat content that is converted into useful thrust power, while H/g expresses the fuel specific heat content in terms of a distance (4300 km for kerosine). Both quantities have a major effect on fuel efficiency, but the configuration designer has no control over them, apart from selecting a type of propulsion. The contrary applies to the aerodynamic fineness ratio in horizontal flight L/D, i.e. the reciprocal value of drag/weight, to be discussed later.*
>
> *The aircraft all-up weight (AUW) per seat W/N_S depends on many factors associated with the type of airplane, structural properties such as materials and efficiency, systems technology, etc. The AUW of present day airliners varies typically between 5 kN and 8 kN per seat, for short and long ranges, resp. The higher value reflects the drag penalty that has to be paid for carrying the large fuel weight fraction required for very long ranges. Fuel efficiency is one of the most significant figures of merit to specify transportation economy and quantify the contribution to atmospheric pollution. Since 1960 there have been numerous technological improvements in all areas, but the greatest progress came from the increased aircraft seating capacities and from gas turbine engine developments, in particular high bypass turbofans. Modern engines achieve cruising efficiencies as high as 35%, and this figure is still being improved. Since 1950 the seat-km production per liter fuel has increased by a factor of almost four to about 40 to 50, comparable to a typical mid class automobile.*

> …
> *The energy content of hydrogen fuel is an order of magnitude higher than for kerosine. Future aircraft using cryogenic* LH_2 *the fuel will therefore be lighter than present day aircraft for the same range. But fuel tanks will be very voluminous since hydrogen has a very low specific mass and hence drag and empty weight will increase. Today hydrogen fueled aircraft would be costly to operate and they will not be used not until fossile fuels are unaffordable and* LH_2 *will become available in sufficient quantities.*

Concerning the designer's influence on the lift-to-drag ratio **Torenbeek 2005a** says:

> *The B707 had* $(L/D)_{max}=18$*. It is remarkable that between 1950 and 1990 this figure has increased to about 20 for the B777 and A340, an improvement of only 10%, or 0.25% per year. … Apparently the dominant configuration is more or less doomed by a complex optimization process to a geometry that will not allow significant improvements in L/D until fuel costs become dominating. Only unconventional concepts will offer an improvement of the order of 20% in L/D.*

7.1.2 Comparison of the different Configurations

Table 7.1 compares and assesses the different types of aircraft configurations regarding their potential to achieve improvements in aerodynamics, structural mass and noise versus their technical risks, requirements towards infrastructure, human psychology and other not easily tangible issues. The assessment is done allocating grades from very good (+++) via neutral (0) to very bad (---). Decision basis is a large civil freighter aircraft; grades for aircraft of different size or application, such as passenger or military transport, would differ from these.

Concerning noise, the BWB and flying wing configurations offer a large potential for significant reductions. First, they offer to make use of noise shielding by positioning the engines on top of the fuselage near its trailing edge. Second, these configurations make (due to flight mechanical reasons) special demands on their high-lift systems which, in consequence, allow for some noise reducing features like omitting trailing edge flaps. See **DLR 2004** for detailed information on noise reduction and silent air traffic.

Table 7.1 Assessment of the Potential of the Different Configurations

Configuration	Aerodynamics	Mass	Noise	Technical Risks	Infrastructure, etc.	**Overal**
Conventional	0	0	0	(+++)	(+++)	(**0**)
(Canard) Three-Surface	+	-	0	0	+	**0**
(Tandem Wing) Joined Wing	+	+	+	-	+	**+**
Delta Wing	--	--	-	-	0	**---**
Multi-Fuselage	+	+	0	-	--	**-**
BWB	++	++	++	-	-	**++**
Flying Wing EKIP OFW	++	++	++	--	--	**+**

In addition to these general aspects, the blended wing-body configuration suffers a lot less penalties (e.g. friction drag) resulting from the vast storage volume needed for liquid hydrogen tanks than a conventional configuration or a configuration derived from that.

7.1.3 Demands and Preferences of the Project Partners

Airbus

One prerequisite of the head of the Airbus Future Projects Office for the participation of Airbus in the Green Freighter project is not to develop into the direction of existing Airbus products. This means that the Green Freighter may not be intended to be a direct competitor or successor of any Airbus aircraft. It has to be made sure that the GF project is no product development but rather a feasibility study. Airbus will not deliver any performance or other data of any existing Airbus aircraft but is willing to share the results of redesigns of Boeing aircraft conducted by Airbus FPO.

IFL

The IFL has been developing and using the tool PrADO (Preliminary Aircraft Design and Optimization program) over the last two decades. Based on this experience, the IFL possesses a broad knowledge on modeling and analyzing many different types and configurations of aircraft. Amongst others, there are BWB aircraft that have been developed during previous projects in which the IFL was involved in (e.g. VELA, see Figure 7.1). If choosing the BWB as the unconventional configuration to proceed with, the IFL could largely reduce the effort to set up an input file holding e.g. all flight and geometry data and profit from previous experience.

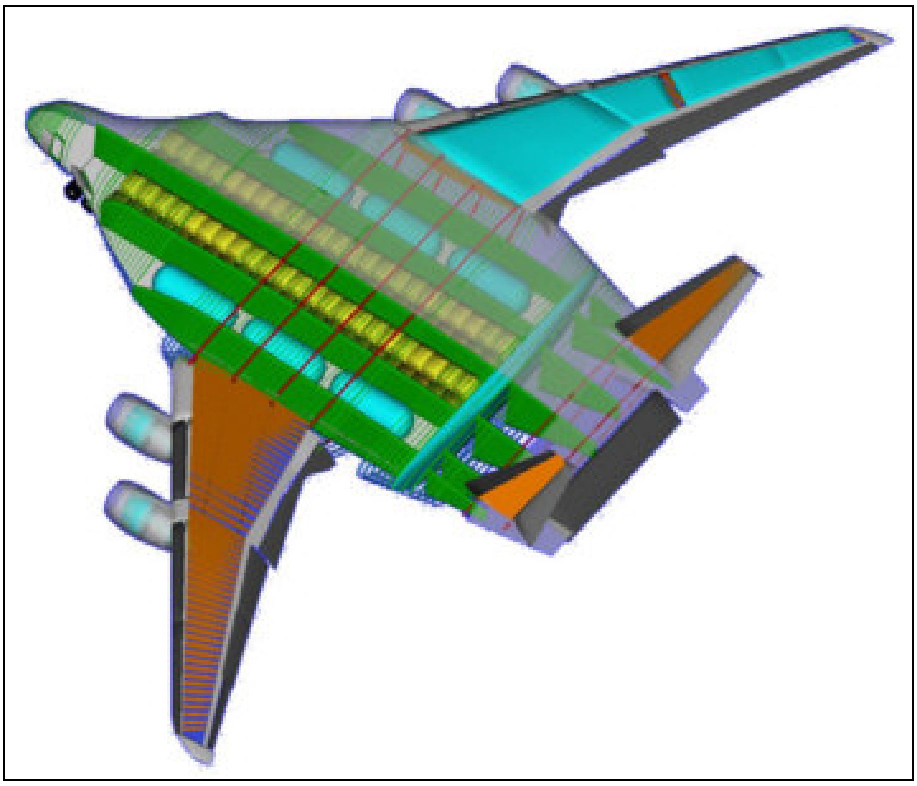


Fig 7.1 Existing BWB Model of the IFL

HAW

The HAW does not have any special preferences concerning the selection of an aircraft configuration but advocates a solution being able to transport containers having the external dimensions of at least 20'-Standard ISO Containers (TEU). This feature shall simplify the integration of air cargo and other forms of cargo (ship, rail and road).

Bishop

Bishop GmbH does not have any special preferences concerning the selection of an aircraft configuration.

7.2 Top Level Aircraft Requirements (TLARs)

Tables 7.2 and 7.3 list up the Green Freighter’s main aircraft requirements concerning flight performance and environment. Especially the definition of the payload has been influenced by the statements of Section 6 saying that there is a special future need for dedicated *large* freighter aircraft. Other requirements concerning range and performance result from the payload.

Table 7.2 Key Requirements

Range:	4800 NM
Payload:	109 t incl. tare
Performance rules/assumptions:	• JAR 3% flight profile • Mark ups: ·4% block fuel ·1% MWE ·0% OWE • Diversion: 200 NM, FL250, LRC • Holding: 30 min, 1500 ft • BF mission: 3000 NM, 4000 NM
Design Mach Number:	0.84
V_{mo}:	330 kn
M_{mo}:	0.89
Initial Cruise Altitude Capability: (T-O @ MTOW, ISA)	≥ 29,000 ft
Time to Climb (29,000 ft, ISA):	≤ 28 min
ACN (Flexible B)	70 (alpha = 0.720)
Take-Off Field Length	3200 m
V_{app} (MLW, SL, ISA):	≤ 150 kn
Operational:	• Zero-pilot and/or one-pilot operation • Ability to accommodate Standard ISO-Container-sized containers (l/w/h: 20’x8’x8.5’ (6.1mx2.5mx2.6m))

Table 7.3 Environmental Requirements

Noise:	• Cumulative noise:	Chap 3 -25 dB
	• Quota count departure:	QC 0.5 (QC 0.25)[*]
	• Quota count arrival:	QC 0.5 (QC 0.25)[*]
Emissions:	• NO_x:	CAEP/4 -30%
	• Smoke:	CAEP/4
	• HC and CO:	“50% lower than CAEP/4”

[*] In ( ): “Should” requirements

7.3 Selection of an Unconventional Configuration

In April 2007 the project partners decided to go ahead with the BWB as the unconventional configuration. The reasons for this choice are its good potential concerning improvements in aerodynamic efficiency and specific structure weight. In addition, the BWB configuration appears very promising to be technically and economically feasible.

In more detail it was decided to design two BWB aircraft: one traveling at a cruise Mach number of about 0.85 as defined in the TLARs and one traveling at a lower Mach number of about 0.5. This second aircraft's cruise Mach number was chosen to be more favorable for the application of a propeller propulsions system. It is expected to show further improved environmental and economic efficiency than a BWB aircraft traveling at high subsonic speeds. Both Cruise Mach Numbers shall only be regarded as starting numbers; both numbers may and shall be adapted and optimized for each reference mission during the design process.

7.4 Selection of Propulsion Systems and Fuels

The project partners decided to include two propulsion systems and two fuels into their investigations:

- Propulsions systems: Turbofan engine and
  Propeller engine,

- Fuels: Kerosene and kerosene-like liquid fuel (Synfuel, Biofuel) and
  Hydrogen.

Two types of fuel lead to the following four fuel combinations:

1. Kerosene (or kerosene-like fuel) only,
2. Hydrogen only,
3. Kerosene (or kerosene-like fuel) and hydrogen used simultaneously and
4. Kerosene (or kerosene-like fuel) and hydrogen used sequently.

Based on the power train arrangement matrix in Figure 5.1, the following four power train arrangements were chosen to be included into the investigations (see Figure 7.2):

I. 1a/1 - one engine per power train, one fuel, engine not decoupleable
II. 1a/2 - one engine per power train, two fuels, engine not decoupleable
III. 2b/2- two engines per power train, two fuels (one fuel each), one engine decoupleable

IV. 2d/2- two (or more) separate power trains, one fuel each

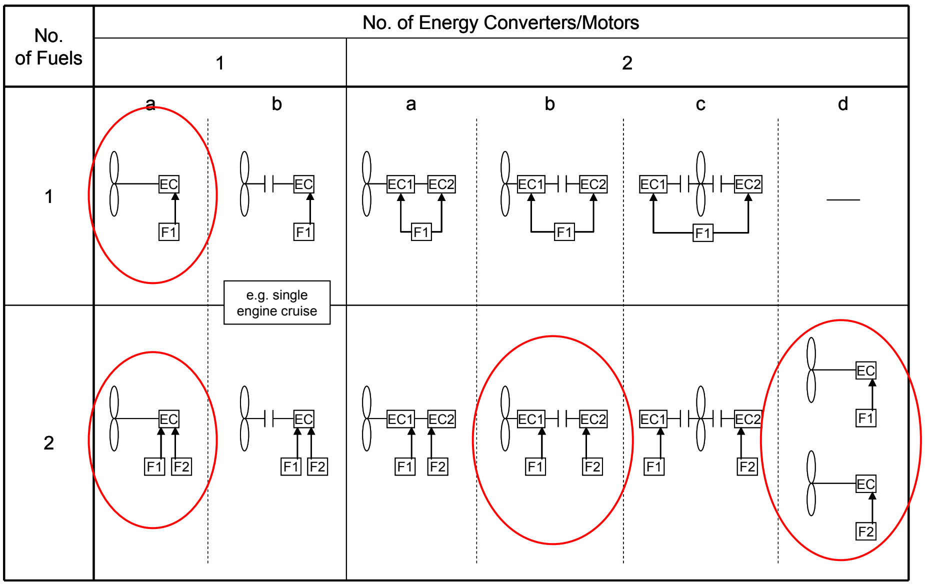


Fig 7.2 Chosen Power Train Arrangements

7.5 Selection of a Reference Aircraft

7.5.1 Comments on the Blended Wing-Body Configuration

The size of an aircraft results from its payload, of course. A heavy payload has to be carried by a large wing as the wing loading has to stay in certain margins. But while in preliminary sizing the payload is often only regarded as a mass and maybe a related volume, in reality the payload is no amorphous mass that can be shaped arbitrarily. There are some minimum dimensions that have to be provided. The height of the cabin of a passenger aircraft, for example, has to be fitted to the height of the passengers and crew. The same is true for freighter aircraft. In this case, especially the sizes of the different container and pallet types to be transported have to be taken into account. For a conventional aircraft, where the fuselage accommodates the passengers and/or cargo, only the fuselage is affected significantly. Not so for the selected blended wing-body configuration. Here, the fuselage which holds the payload is shaped as an airfoil and part of the wing (see Figure 7.3). This leads to several snowball effects.

The main driving number for a blended wing-body freighter aircraft in this context is the height of its highest container or cargo item that is intended to be transported as this defines the thickness of the chosen wing section shaped around the cargo compartment. Hence, a certain height of the cargo compartment leads to a resulting length of the fuselage.

Furthermore, the width of the fuselage and the span of the whole aircraft are affected if a certain aspect ratio shall be achieved.

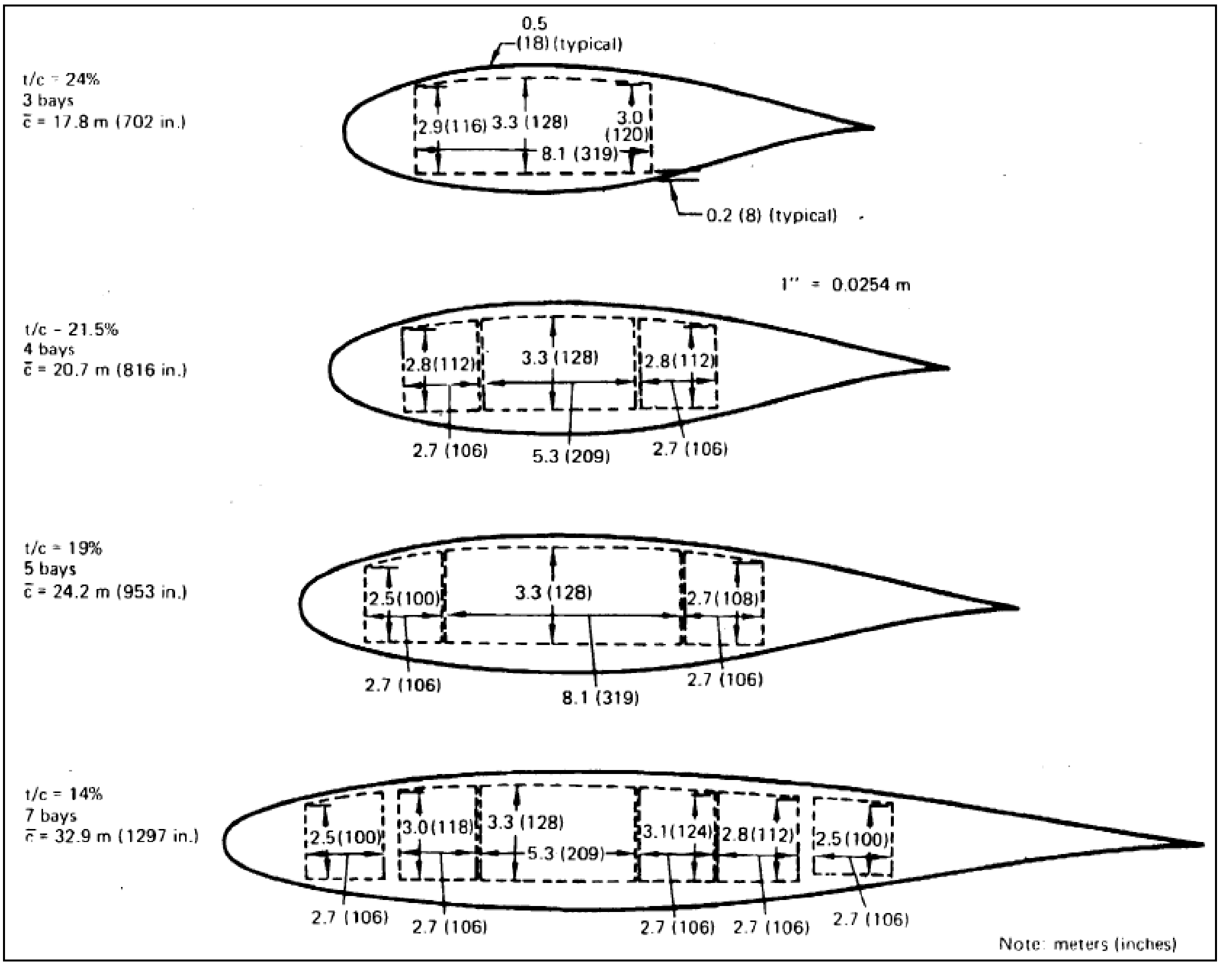


Fig 7.3 DLF Wing Section Utilization (**Boeing 1976**)

In simple terms, BWB aircraft have to be big to be able to transport high items and make use of the benefits of this configuration. For the GF project the main driving number is the height of a Standard ISO Container of 2.6 m or 2.9 m for a 45’ High Cube Container. Based on previous examinations of BWB aircraft, the IFL stated a general absolute minimum payload for BWB aircraft of 50 t.

7.5.2 Selection of a Conventional Reference Aircraft

In combination with the selection of the BWB configuration, a large comparative conventional aircraft has to be chosen. In this case, it was decided to take the Boeing B777F. It represents a modern and successful cargo aircraft and Airbus possesses broad information on this aircraft resulting from several comparative redesigns.

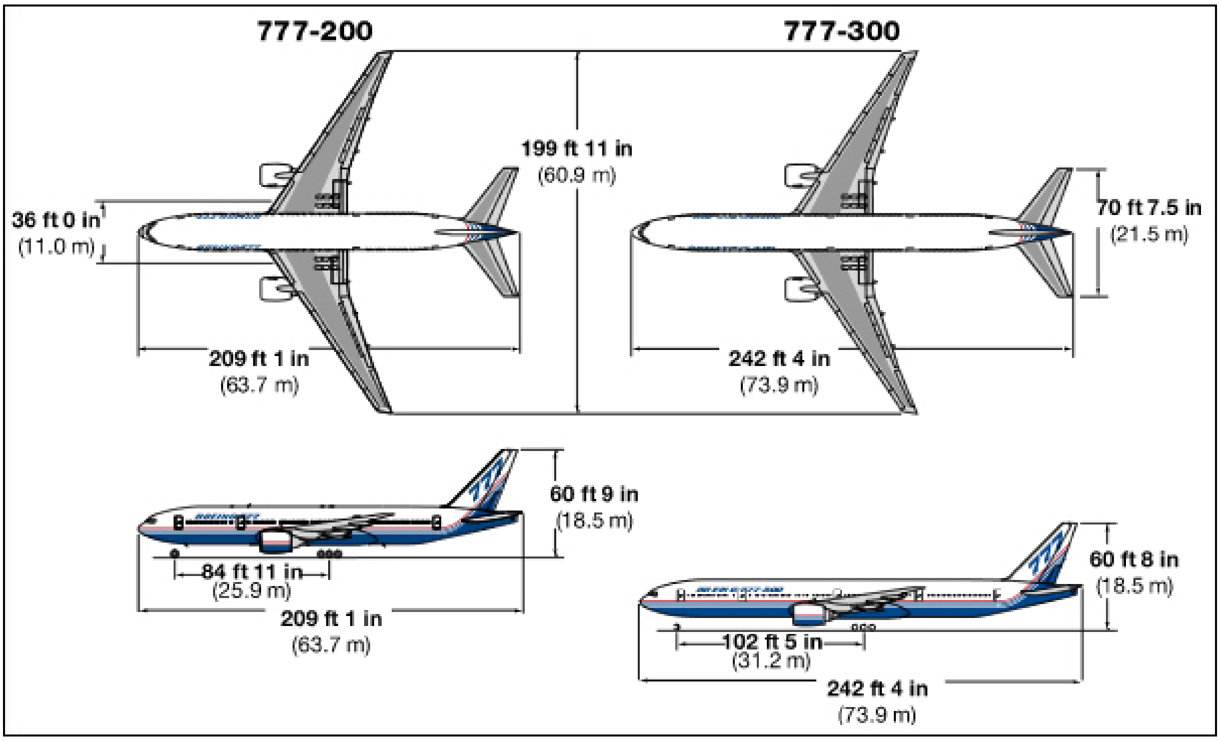


Fig 7.4 777-200/-200ER and 777-300 General Arrangements (**Boeing 2007b**)

8 Next Steps

In general, the next tasks together aim at extending or building up the capabilities and methodologies to investigate all sub-aspects of the Green Freighter aircraft. In particular, these are:

- Estimation of the propeller efficiency,
- Estimation of the mass and required volume for a propeller propulsion system including a gear,
- Determination of the specific masses of a hydrogen fuel system including tank isolation, fuel lines and other system components

Furthermore, the project partners have to define system requirements for the Green Freighter aircraft. Therefore, additional aspects like zero-pilot operation and the resulting effects on the requirements regarding the environmental control-system (ECS) have to be accounted for. Possible effects are no or a trimmed-down ECS.

Finally, all this newly gained knowledge has to be incorporated into PrADO in the form of additional subroutines. These subroutines shall be tested on a previous Airbus hydrogen-powered aircraft which is based on an ATR72 (see Figure 8.1). The results of the PrADO-analyses will be assessed by means of comparison with the Airbus results on this aircraft.

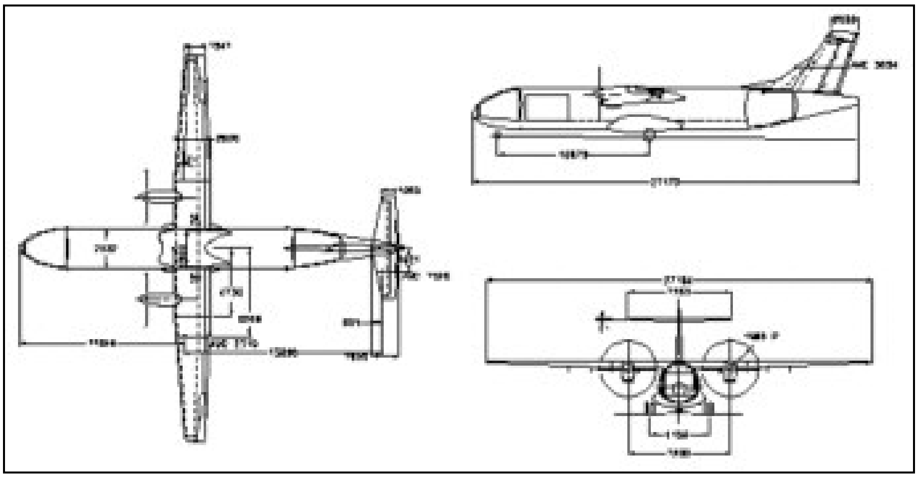


Fig 8.1 Airbus' previous Hydrogen Reference Aircraft

References

ACARE 2003
ADVISORY COUNCIL FOR AERONAUTICS RESEARCH IN EUROPE: *About us/ACARE*, 2003. –
URL: http://www.acare4europe.org/html/about_us1.shtml (2007-07-20)

AC20.30 2006
HAMBURG UNIVERSITY OF APPLIED SCIENCES, AC20.30 PROJECT GROUP: *Student project AC20.30*, 2006. – URL: http://www.ac2030.de/en_umgebung.html (2007-07-26)

Airbus 2006
AIRBUS S.A.S.: *Corporate Information / Global Market Forecast 2006 – 2025*, 2006. –
URL: http://v4.airbus.com/en/corporate/gmf/gmf_doc/5_Air-Cargo-Forecast.pdf
(2007-07-16)

AOA 2006
AIRPORT OPERATORS ASSOCIATION: *Environmental Guidance Manual for Airports*, 2006. –
URL: http://www.aoa.org.uk/publications/SustainableAviation_fullsadoc.pdf (2007-08-02)

ASD 2005
AeroSpace and Defence Industries Association of Europe: *Clean Sky JTI*, 2005. –
URL: http://www.asd-europe.org/Content/Default.asp?PageID=32 (2007-07-24)

airliners.net 2003
LUNDGREN AEROSPACE: *Pakistan International Airlines – PIA Boeing 747-367*, 2003. –
URL: http://www.airliners.net/open.file?id=0332946&size=L (2007-07-25)

airliners.net 2007
LUNDGREN AEROSPACE: *Dan-Air London De Havilland DH-106 Comet 4*, 2007. –
URL: http://www.airliners.net/open.file?id=1195597&size=L&width=1024&height=702&sok=JURER%20%20%28nvepensg_trarevp%20%3D%20%27Qr%20Univyynaq%20QU-106%20Pbzrg%27%29%20%20beqre%20ol%20cubgb_vq%20QRFP&photo_nr=22 (2007-08-03)

allstar 2007
ALLSTAR NETWORK: *Aircraft Engines*, 2007. –
URL: http://www.allstar.fiu.edu/AERO/Propulsion1.htm (2007-07-20)

bobscherer.com 2007
SCHERER, ROBERT: *Beechcraft Starship – NC-51 over Tehachapi Mtns*, 2007. –
URL: http://www.bobscherer.com/Images/Pages/Starship/Starship%20page/star1385%2012x9%20lg.jpg (2007-07-17)

Boeing 1976
BOEING COMMERCIAL AIRPLANE COMPANY, Preliminary Design Department: Technical and economic assessment of span-distributed loading cargo aircraft concepts, Final Report. Seattle : Boeing Commercial Airplane Company, 1976 (NASACR-144963). – Prepared under contract NAS1-13963 for Langley Research Center, National Aeronautics and Space Administration

Boeing 2006
THE BOEING COMPANY: *Boeing Phantom Works to Lead Research on X-48B Blended Wing Body Concept*, 2006. –
URL: http://www.boeing.com/phantom/news/2006/q2/060504b_nr.html (2007-07-26)

Boeing 2007a
THE BOEING COMPANY: *Current Market Outlook 2007, Freighter Airplanes*, 2007. –
URL: http://www.boeing.com/commercial/cmo/freighter.html (2007-07-16)

Boeing 2007b
THE BOEING COMPANY: *777-200/-200ER and 777-300 General Arrangements*, 2007. –
URL: http://www.boeing.com/commercial/777family/pf/pf_exterior_general.html
(2007-08-07)

Brewer 1991
BREWER, G. Daniel: *Hydrogen Aircraft Technology.* Boca Raton : CRC Press, 1991 –
ISBN 0-8493-5838-8

Chevron 2006
HEMIGHAUS, Greg; BOVAL, Tracy; BOSLEY, Carol; et.al; Chevron Corporation: *Alternative Jet Fuels, Addendum 1 to Aviation Fuels Technical Review (FTR-3/A1)*, 2006. – Corporate literature. URL: http://www.chevronglobalaviation.com/docs/5719_Aviation_Addendum._webpdf.pdf (2007-08-02)

Der Spiegel 2007
WUEST, Christian: Erntedank im Autotank. In: *Der Spiegel*, 2007, no. 8, p. 104-111

DLR 2004
DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT: Leiser Flugverkehr, Zusammenfassender Projekt-Abschlussbericht. Braunschweig : Deutsches Zentrum für Luft- und Raumfahrt, 2004.

EADS 2007
European Aeronautic Defence and Space Company EADS N.V.: *A400M Neue Standards für militärischeTransportflugzeuge, Antrieb*, 2007. –
URL: http://www.eads.net/web/printout/de/1024/content/400003/8/62/41435628.html (2007-07-20)

EKIP Aviation 2004
Aviation Concern EKIP: *EKIP Aviation Concern: 1. Description of Flying Vehicles "EKIP"*, 2004. – URL: http://www.ekip-aviation-concern.com (2007-07-13)

Faaß 2001
FAASS, Reinhard: Cryoplane – Flugzeuge mit Wasserstoffantrieb : presentation. Paper presented at *DGLR-Bezirksgruppe Hamburg: Veranstaltungen und Vorträge*, Hamburg University of Applied Sciences, 2001-12-06. –
URL: http://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2001_12_06_Cryoplane.pdf (2007-07-26)

Farschtschi 2001
FARSCHTSCHI, ALI: *Elektromaschinen in Theorie und Praxis*. Berlin : VDI Verlag, 2001

Flight International 2006a
TURNER, Aimee: Cleaning the Sky. In: *Flight International*, 2006-08-01, p. 36-37

Flight International 2006b
PLISKIN, Michael: Fuel Renewal: The US Air Force tests synthetic fuel on a B-52 as part of foreign fuel reliance reduction drive. In: *Flight International*, 2006-10-04 –
URL: http://www.flightglobal.com/articles/2006/10/04/209576/fuel-renewal-the-us-air-force-tests-synthetic-fuel-on-a-b-52-as-part-of-foreign-fuel-reliance.html (2007-08-02)

Flight International 2006c
LEARMOUNT, David: IATA backs open emissions trade. In: *Flight International*, 2006-12-19

Flight International 2006d
WARWICK, Graham: British blend: UAV X-planes help Boeing with blended wing concept. In: *Flight International*, 2006-05-30 –
URL: http://www.flightglobal.com/articles/2006/05/30/206893/british-blend-uav-x-planes-help-boeing-with-blended-wing.html (2007-07-23)

Flight International 2007a
TURNER, Aimee: ICAO seeks harmonised approach on emissions. In: *Flight International*, 2007-05-29, p. 11

Flight International 2007b
WARWICK, Graham: Boeing's BWB wings way towards air cargo market. In: *Flight International*, 2007-05-22, p. 11

Flight International 2007c
DECKER, Jeffrey: FAA’s ethanol testing confirms power drop. In: *Flight International*, 2007-01-02, p. 19

Flight International 2007d
N. A.: USA pursues the ultimate alternative fuel. In: *Flight International*, 2007-01-02, p. 37

Flight International 2007e
N. A.: Synthetic success. In: *Flight International*, 2007-01-02, p. 17

Flight International 2007f
DECKER, Jeffrey: Fuel for change. In: *Flight International*, 2007-01-16, p. 26-28

Flight International 2007g
NORRIS, Guy: CFM ready for narrowbody leap. In: *Flight International*, 2007-05-15, p. 16

Flight International 2007h
NORRIS, Guy: P&W confident geared turbofan concept has the edge over rivals. In: *Flight International*, 2007-05-15, p. 16

Flight International 2007i
TURNER, Aimee: Virgin joins Boeing, GE in biofuels trials. In: *Flight International*, 2007-05-01, p. 7

Flight International 2007j
TURNER, Aimee: Emissions plan faces airline flak. In: *Flight International*, 2007-02-13, p. 4

flightglobal.com 2007
NORRIS, Guy: CFM ready for narrowbody leap, 2007. –
URL: http://www.flightglobal.com/articles/2007/05/15/213832/cfm-ready-for-narrowbody-leap.html (2007-08-08)

Frediani 2005
FREDIANI, A.: The Prandtl Wing. In: TORENBEEK, Egbert (ed.); DECONINCK, H. (ed.): *Innovative Configurations and advanced Concepts for Future Civil Aircraft (Rhode Saint Genèse, Belgium 2005).* Rhode Saint Genèse, Belgium : von Karman Institute for Fluid Dynamics, 2005 (Lecture Series 2005-06) – ISBN 2-930389-62-1

fuelcelltoday 2005
FUEL CELL TODAY: *PEMFC schematic*, 2005. –
URL: http://www.fuelcelltoday.com/FuelCellToday/EducationCentre/EducationCentreExternal/EduCentreDisplay/0,1741,FCImages,00.html?id=6&start=12# (2005-12-21)

GDV 2007
GESAMTVERBAND DER DEUTSCHEN VERSICHERUNGSWIRTSCHAFT E.V., Transport-Informations-Service: *Container types*. –
URL: http://www.tis-gdv.de/tis_e/containe/inhalt2.htm

Granzeier 2007
GRANZEIER, Werner: Varianten der Triebwerksintegration eines Blended Wing Body. In: SCHOLZ, Dieter: Klausur, Flugzeugentwurf, SS 2007. –
URL: http://www.fzt.haw-hamburg.de/pers/Scholz/KlausurFE.html (2007-07-31)

Guynn 2004
GUYNN, Mark D.; FREEH, Joshua E.; OLSON, Erik D.; National Aeronautics and Space Administration: Evaluation of a Hydrogen Fuel Cell Powered Blended-Wing-Body Aircraft Concept for Reduced Noise and Emissions. Hampton : NASA Langley Research Center, 2004 (NASA/TM-2004-212989).

Hirschberg 2005
HIRSCHBERG, Michael J.; Hart, David M.; Beutner, Thomas J.: A Summary of a Half-Century of Oblique Wing Research. In: *45th AIAA Aerospace Sciences Meeting and Exhibit (Reno, 2007)* (AIAA 2007-150). –
URL: http://www.obliqueflyingwing.com/OWhistory.pdf (2007-08-02)

ICAO 2007a
INTERNATIONAL CIVIL AVIATION ORGANIZATION, AIR TRANSPORT BUREAU (ATB): *Environmental (ENV) Unit, CAEP*, 2007. – URL: http://www.icao.int/icao/en/env/caep.htm (2007-08-08)

ICAO 2007b
INTERNATIONAL CIVIL AVIATION ORGANIZATION, AIR TRANSPORT BUREAU (ATB): *Environmental (ENV) Unit, Aircraft Noise*, 2007. –
URL: http://www.icao.int/icao/en/env/noise.htm (2007-08-08)

inauka.ru 2004
OGANEZOVA, Susanna: *A Flying Saucer for the Military: Saratov's flying saucer will be launched in the U.S.A.*, 2004. –
URL: http://www.inauka.ru/english/article41032.html (2007-07-26)

IPCC 1999
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE: Aviation and the Global Atmosphere, Summary for Policymakers. Geneva : Intergovernmental Panel on Climate Change, 1999. - ISBN

IPCC 2007
PACHAURI, R.K.; JALLOW, Bubu; Intergovernmental Panel on Climate Change, Working Group I: Climate Change 2007: The Physical Science Basis : Presentation of Working Group I Contribution to the IPCC Fourth Assessment Report. Nairobi, 2007-02-06 –
URL: http://www.ipcc.ch/present/WMEF_FINAL.ppt

Kresse 2006
KRESSE, Nicolai: VELA – Very Efficient Large Aircraft : presentation. Paper presented at Aeronautics Days Vienna, 2006-06 –
URL: aerodays2006.org/sessions/E_Sessions/E1/E11.pdf (2007-07-20)

Liebeck 2005
LIEBECK, Robert H.: Design of the Blended-Wing-Body Subsonic Transport. In: TORENBEEK, Egbert (ed.); DECONINCK, H. (ed.): *Innovative Configurations and advanced Concepts for Future Civil Aircraft (Rhode Saint Genèse, Belgium 2005).* Rhode Saint Genèse, Belgium : von Karman Institute for Fluid Dynamics, 2005 (Lecture Series 2005-06) –
ISBN 2-930389-62-1

Muissus 2007
MUISSUS, Sebastian: GEFF – WP3 – Energy Carrier : presentation. Paper presented at Green Freighter progress meeting, Hamburg, 2007-06-26

NASA 1980
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, Dryden Flight Research Center: *Dryden Flight Research Center ECN 15846 Photographed 1980 AD-1*, 1980. –
URL: http://www.dfrc.nasa.gov/Gallery/Photo/AD-1/Small/ECN-15846.jpg (2007-07-24)

Palaszewski 1997
PALASZEWSKI, Bryan; NASA, Lewis Research Center: Gelled Liquid Hydrogen: A White Paper. Cleveland, OH : NASA Lewis Research Center, 1997. –
URL: http://sbir.grc.nasa.gov/launch/GELLED.htm (2007-06-04)

piaggioaero.com 2007
PIAGGIO AERO INDUSTRIES S.P.A.: *P.180 Ferrari's Livery*, 2007. –
URL: http://www.piaggioaero.com/en/media/33_list_gallery_details/galleryapp_194.php (2007-07-17)

Raymer 2006
RAYMER, Daniel P.: *Aircraft Design: A Conceptual Approach*. 4th Ed. Reston : AIAA, 2006 – ISBN 1-56347-829-3

Rivoire 2007
RIVOIRE, Vincent: Propulsion Integration Challenges : presentation. Paper presented at *DGLR-Bezirksgruppe Hamburg: Veranstaltungen und Vorträge*, Hamburg University of Applied Sciences, 2007-07-05 –
URL: http://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2007_07_05_Propulsion_Integration.pdf

Schmidt 2006
SCHMIDT, M. André: The AC20.30 Blended Wing Body Configuration: Development & Current Status 2006 : Presentation, paper presented at *25th Congress of the International Council of the Aeronautical Sciences / ICAS Congress 2006*, Hamburg, 2006-09-05 –
URL: www.ac2030.de/dok_medien/ICAS2006.pdf (2007-07-26)

Schmitt 2007
SCHMITT, Dieter: Future Partnerships for Airbus and Universities : Presentation, paper presented at *8th European Workshop on Aircraft Design Education / (EWADE 2007)*, Samara, 2007-06 –
URL: http://www.fzt.haw-hamburg.de/pers/Scholz/ewade/2007/EWADE2007_Schmitt_AirbusAndUniversities.pdf (2007-08-02)

Scholz 2006
SCHOLZ, Dieter: *Grüner Frachter – Vorhabensbeschreibung*. Hamburg, University of Applied Sciences, Department of Automotive and Aeronautical Engineering, project description, 2006

Seeckt 2006
SEECKT, Kolja: *Performance assessment of part-electric General Aviation aircraft*. Hamburg, University of Applied Sciences, Department of Automotive and Aeronautical Engineering, diploma thesis, 2006

Szodruch 2006
SZODRUCH, Joachim: Die Zukunft der Luftfahrt – Die europäische Vision 2020 : Presentation, paper presented in Bonn, 2006-05-30 –
URL: http://www.dglr.de/literatur/publikationen/DGLR_Szodruch_Vision2020.pdf (2007-07-20)

Thramer 2004
THRAMER, Bernd: *Rumpf – Aspekte beim Flugzeugentwurf*. Hamburg, University of Applied Sciences, Department of Automotive and Aeronautical Engineering, Aircraft Design Lecture Notes, 2004. – URL: http://www.fzt.haw-hamburg.de/pers/Scholz/skriptFEs/Rumpf.pdf (2007-07-31; password required)

Torenbeek 2005
TORENBEEK, Egbert (ed.); DECONINCK, H. (ed.): *Innovative Configurations and advanced Concepts for Future Civil Aircraft (Rhode Saint Genèse, Belgium 2005).* Rhode Saint Genèse, Belgium : von Karman Institute for Fluid Dynamics, 2005 (Lecture Series 2005-06) – ISBN 2-930389-62-1

Torenbeek 2005a
TORENBEEK, Egbert: *Introductory Overview of Innovative Civil Transport Aircraft Configurations*. In: TORENBEEK, Egbert (ed.); DECONINCK, H. (ed.): *Innovative Configurations and advanced Concepts for Future Civil Aircraft (Rhode Saint Genèse, Belgium 2005).* Rhode Saint Genèse, Belgium : von Karman Institute for Fluid Dynamics, 2005 (Lecture Series 2005-06) – ISBN 2-930389-62-1

Tradeway 2007
URL: http://www.tradeway.com.au/aircspecs.cfm#1 (2007-07-23)

Tupolev 2007
PSC TUPOLEV: *Development of Cryogenic Fuel Aircraft*, 2007. –
URL: http://www.tupolev.ru/English/Show.asp?SectionID=82&Page=1 (2007-07-27)

von Heeremann 2007
VON HEEREMANN, Raphael: The Myth of CO_2 in the Airline Industry : presentation. Paper presented at *Royal Aeronautical Society Hamburg Branch*, Hamburg, 2007-06-14 –
URL: http://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2007_06_14_CO2.pdf (2007-08-02)

Westenberger 2003
WESTENBERGER, Andreas: Cryoplane – Hydrogen Aircraft : presentation. Paper presented at H2 Expo, Hamburg, 2003-10-11 –
URL: http://www.h2hh.de/downloads/Westenberger.pdf (2007-07-26)

Wikipedia 2007
URL: http://en.wikipedia.org/wiki/Containerization (2007-07-24)
URL: http://en.wikipedia.org/wiki/Contra-rotating (2007-07-11)
URL: http://en.wikipedia.org/wiki/Delta_wing (2007-07-18)
URL: http://en.wikipedia.org/wiki/Fischer-Tropsch_process (2007-07-09)
URL: http://en.wikipedia.org/wiki/Flying_wing (2007-07-23)
URL: http://en.wikipedia.org/wiki/Fuel_cell (2007-08-07)
URL: http://en.wikipedia.org/wiki/Image:Concorde_on_Bristol.jpg (2007-07-18)
URL: http://en.wikipedia.org/wiki/Image:NORTHROP_B-2.png (2007-07-23)
URL: http://en.wikipedia.org/wiki/Image:Saab_Draken.jpg (2007-07-18)
URL: http://en.wikipedia.org/wiki/Image:Turbofan_operation.png (2007-07-20)
URL: http://en.wikipedia.org/wiki/Image:Turbojet_operation-_axial_flow.png (2007-07-20)
URL: http://en.wikipedia.org/wiki/Image:Turboprop_operation.png (2007-07-20)
URL: http://en.wikipedia.org/wiki/Jet_engine (2007-07-11)
URL: http://en.wikipedia.org/wiki/Oblique_flying_wing (2007-07-24)
URL: http://en.wikipedia.org/wiki/Propeller_engine (2007-07-11)
URL: http://en.wikipedia.org/wiki/Propfan (2007-07-11)
URL: http://en.wikipedia.org/wiki/Silane (2007-07-23)
URL: http://en.wikipedia.org/wiki/Solar_radiation (2007-07-27)

Zandstra 2007
ZANDSTRA, Sijmen: *The Economic Performance of the Green Freighter*. Delft, Technical University, Faculty of Aerospace Engineering, master thesis literature research report, 2007

260sepilots.org 2006
WWW.260SEPILOTS.ORG: *N725AS: Katmai with BRS airframe parachute*, 2006. –
URL: http://www.260sepilots.org/gallery/N725AS/aaf (2007-07-17)

Appendix A

Physicochemical Properties of liquid and gaseous Fuels

Table A.1 Physicochemical Properties of gaseous Fuels (**Muissus 2007**)

Values of gaseous, conventional and alternative fuels											
	chem. Formula	density at 0°C and		main constituents	boiling temperature at 1013mbar	calorific value		ignition temperature	theoretical need of air	ignition limits	
Units	-	kg/m³		Weight-%	°C	MJ/kg	MJ/m³	°C	kg/kg	volume % gas in air	
		min.	max.			fuel	fuel-air-mixture for lambda=1,2			lower	upper
liquid gas		2,25			-30	46,1	3,11	400	15,5	1,5	15
town gas		0,56	0,61	50H, 8CO, $30CH_4$	-210	ca. 30	ca. 2,73	560	10	4	40
natural gas		ca.	0,83	76C, 24H	-162	47,7					
water gas		0,71		50H, 38CO		15,1	2,8	600	4,3	6	72
blast furnace gas		1,28		28CO, 59N, 12C	-170	3,2	2,17	600	0,75	ca. 30	ca. 75
sewage gas				$46CH_4$, $54CO_2$		27,2	3,62				
carbon monoxide		1,25		100CO	-191	10,05	3,22	605	2,5	12,5	75
methane		0,72		75C, 25H	-162	50	2,88	650	17,2	5	15
acethylene	C_2H_2	1,17		93C, 7H	-81	48,1	3,66	305	13,25	1,5	80
ethane	C_2H_6	1,36		80C, 20H	-88	47,5		515	17,3	3	14
ethene	C_2H_4	1,26		86C, 14H	-102	47,1		425	14,7	2,75	34
propane	C_3H_8	2		82C, 18H	-43	46,3	3,09	470	15,6	1,9	9,5
propene	C_3H_6	1,92		86C, 14H	-47	45,8		450	14,7	2	11
butane	C_4H_{10}	2,7		83C, 17H	-10	45,6	3,11	365	15,4	1,5	8,5
butene	C_4H_8	2,5		86C, 14H	-5	45,2			14,8	1,7	9
hydrogen		0,09		100H	-253	120	2,81	560	34	4	77
disilane	Si_2H_6										
methane hydrate	CH_4 x 5,75 H_2O										

Table A.2 Physicochemical Properties of liquid Fuels (**Muissus 2007**)

Values of liquid conventional and alternative fuels																		
		chem. Formula	density		main constituents	boiling temperature		enthalpy of evaporation		calorific value		ignition temperature	theoretical need of air	ignition limits		RON[1)]	CaN[2)]	
		-	kg/l		Weight-%	°C		kJ/kg		MJ/kg		°C	kg/kg	olume %, gas in ai				
			min.	max.		min.	max.	min.	max.	min.	max.			untere	obere		min.	max.
motor fuels	normal		0,715	0,732	86C, 14H	25	215	377	502	42,7		300	14,8	0,6	8	92	14	
	super		0,73	0,78	86C, 14H	25	215	419		43,5		400	14,7			98	8	
aviation fuels			0,72		85C, 15H	40	180			43,5		500		0,7	0,8			
kerosene	Jet A1		0,77	0,83	87C, 13H	170	260			43		250	14,5	0,6	7,5		40	55
diesel	Normal		0,815	0,855	86C, 13H	180	360	ca.	250	42,5		250	14,5	0,6	6,5			
crude oil			0,7	1	80-83C, 10-14	25	360	222	352	39,8	46,1	220	14,3	0,6	0,65			
heavy oil			0,95		86C, 13H	175	450			40	41		13,7				34	44
pentane		C_5H_{12}	0,63		83C, 17H	36		352		45,4		285	15,4	1,4	7,8			
hexane		C_6H_{14}	0,66		84C, 16H	69		331		44,7		240	15,2	1,2	7,4			
n-heptane		C_7H_{16}	0,68		84C, 16H	98		310		44,4		220	15,2	1,1	6,4			
iso-octane		C_8H_6	0,69		84C, 16H	99		297		44,6		410	15,2	1	6			
benzene		C_6H_6	0,88		92C, 8H	80		394		40,2		550	13,3	1,2	8	98	10	
toluene		C_7H_8	0,87		91C, 9H	110		364		40,8		530	13,4	1,2	7			
xylene		C_8H_{11}	0,88		91C, 9H	144		339		40,8		460	13,7	1	7,6			
aether			0,72		64C, 14H, 22O	35		377		34,3		170	7,7	1,7	36			
acetone			0,79		62C, 10H, 28O	56		523		28,5		540	9,4	2,5	13			
ethyl alcohol		C_2H_5OH	0,79		52C, 13H, 35O	78		904		26,8		420	9	3,5	15	> 100	8	
methanol		CH_3OH	0,79		38C, 12H, 50O	65		1110		19,7		450	6,4	5,5	26	> 110	3	
brown caol creosote			0,85	0,9	84C, 11H	200	360			40,2	41,9		13,5					
mineral coal creosote			1	1,1	89C, 7H	170	330			36,4	38,5							
ammonia		NH_3														110		
silane	trisilane	Si_3H_8				53												
	tetrasilane	Si_4H_{10}				108												
bio diesel			0,878		77C, 12H, 11O	182	338						13,8				48	65

1) research octane number
2) cetane number