HYDROGEN POWERED FREIGHTER AIRCRAFT – THE FINAL RESULTS OF THE GREEN FREIGHTER PROJECT

K. Seeckt*, W. Heinze, D. Scholz***
*** Hamburg University of Applied Sciences,**
Aero – Aircraft Design and Systems Group, Germany
**** Technische Universität Braunschweig,**
Institute of Aircraft Design and Lightweight Structures, Germany

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Abstract

This paper presents the results of the joint aircraft design project "The Green Freighter" that dealt with the investigation of hydrogen-fueled freighter aircraft. This included conventional as well as blended-wing-body (BWB) aircraft designs. Within the scope of the project the Preliminary Aircraft Design and Optimization program PrADO was extended and applied to analyses of conventional and unconventional freighter aircraft designs. The investigations show that hydrogen as aviation fuel is feasible. Rising energy prices will make air transport more expensive than today, but hydrogen is a potential alternative fuel that keeps air traffic possible even if low-priced kerosene is no longer available. In addition, air traffic could become more environmentally friendly. Hydrogen-fueled regional freighter aircraft have up to 5 % smaller maximum take-off masses and consume about 10 % less energy than the kerosene reference version despite their up to 7 % higher operating empty masses. The installation of large hydrogen tanks using the full fuselage cross section is significantly superior to an installation of removable tanks with smaller diameter. An unmanned freighter can use the cockpit volume for hydrogen storage and further helps to optimize the design. The investigations of the hydrogen-fueled BWB designs show possible savings of about 6.5 % in take-off mass, which is predominantly due to a 66.5 % lower fuel mass. The combination of necessary minimum aircraft size and low fuel mass causes a low wing loading. In effect, the BWB designs cannot make use of their theoretically very high aerodynamic performance during cruise flight.

1 Introduction

Airbus and Boeing project in their actual market forecasts for the next two decades annual growth rates of 4.7 % and 4.9 % for airline traffic and even 5.2 % and 5.4 % for air cargo traffic [1], [2]. Nevertheless aviation faces great future challenges such as global climate change, depleting crude oil resources and a rising worldwide energy demand among others. These facts lead already today to rising energy costs and an increasingly critical public position towards aviation [3], and it is clear that for future aircraft developments these environmental issues and costs will play a larger role than in the past.

1.1 Hydrogen as Aviation Fuel

In the context of future energy supply hydrogen has repeatedly appeared as an interesting alternative to crude oil-based kerosene. The best known examples of earlier investigations of hydrogen as aviation fuel are those of Lockheed and NASA in the 1970s [4], Tupolev in the 1990s [5] and the European Cryoplane project under Airbus leadership [6].

The main advantages of hydrogen compared to kerosene are on the environmental side the very clean combustion including the wide reduction of greenhouse gas emissions and on the political side the increasingly important larger independency from oil-exporting countries. Moreover, the amount of energy per mass of hydrogen is about three times that of kerosene, which would mean significantly lower fuel masses if hydrogen replaced kerosene as fuel. There are also no practical reasons that would inhibit the design or operation of a hydrogen-burning power plant, but hydrogen could even be applied beneficially for e.g. turbine blade cooling. On the other hand hydrogen also has important disadvantages. For example, hydrogen does not exist in pure state in nature but has to be produced under the expense of energy first. This large effort, of course, entails high production costs. Furthermore, hydrogen has a very low density which causes very large fuel tanks. Even in liquid form, hydrogen requires four times the volume that the same energy amount of kerosene needs, and, in addition, hydrogen has to be kept at below 22 K (-251 °C) to stay liquid. Consequently, the hydrogen fuel system of an aircraft would be very heavy due to large tanks and thick thermal insulation.

However, in the light of future energy scenarios and due to its low emissions hydrogen has (again) become an increasingly interesting future alternative to kerosene.

1.2 The Blended Wing Body Configuration

The blended wing body (BWB) configuration promises significant improvements regarding the structural mass and the aerodynamic efficiency of an aircraft compared to the conventional aircraft configuration. This stems from a more even spanwise load distribution and the fact that the fuselage does not only produce drag as in case of conventional aircraft but also adds to the lift. Moreover, the BWB configuration appears especially appropriate for hydrogen applications as it offers a large 'spare' volume at the outer and the rear parts of the fuselage that can be used for hydrogen storage [7]. However, the production of a BWB aircraft would mean enormous changes compared to today's design, production and operation of aircraft. Therefore, there are currently no plans known of any aircraft manufacturer to develop a BWB aircraft. Nevertheless, the interest of aircraft manufacturers and research organizations for the BWB as a possible aircraft configuration in the midterm future stays high. One example of current research activities is the X-48B currently flight tested as an 8.5 % scale model by Boeing, NASA and the US Air Force Research Laboratory (AFRL) [8].

1.3 Freighter Aircraft

As stated in the beginning, global air cargo traffic is growing even faster than airline traffic. Thus, freighter aircraft are in general becoming an increasingly interesting market segment. Moreover, regarding the aforementioned issues of hydrogen as aviation fuel and/or the implementation of the BWB configuration, freighter aircraft appear as the most suitable first practical application. The transport of all air cargo from regional to long-range is limited to a relatively small number of airports. Hence, the required infrastructural changes for the operation of hydrogen-fueled freighter aircraft fleet would be significantly smaller than those for a fleet of passenger aircraft. Also the psychological acceptance of new technologies such as hydrogen propulsion and/or the BWB configuration among others would be greater in case of cargo aircraft without passengers onboard, and valuable experience in the operation of BWB aircraft could be gained before its application to passenger aircraft.

2 The Green Freighter Project

The previous sections show that there's still much research work needed on hydrogen-fueled BWB and conventional aircraft and that freighter aircraft are the most promising first economic applications. These were the reasons to initiate the Green Freighter project that ran from December 2006 until April 2010. Its project partners were the Hamburg University of Applied Sciences (HAW Hamburg), the Institute of Aircraft Design and Lightweight Structures (IFL) of the Technische Universität Braunschweig, Airbus and the engineering office Bishop GmbH – Aeronautical Engineers.

The main technical objective of the Green Freighter project was the investigation of environmentally friendly and cost effective freighter aircraft with unconventional configuration, which led to the following three main areas of activity:

- Extension of the central aircraft design tool PrADO
- Preparation of the preliminary sizing tool PreSTo and its application to conventional aircraft designs
- Application of PrADO to analyses of conventional and unconventional aircraft designs.

2.1 PreSTo

The HAW Hamburg's Aircraft Preliminary Sizing Tool PreSTo is a spreadsheet application for the quick and simplified preliminary sizing and initial conceptual design of conventional transport aircraft [9]. It is made up of Microsoft Excel worksheets each of which treats one particular design step. This modular structure simplifies its application in aeronautical engineering education and its further extension e.g. by student projects. A simplified version is available for download from http://FE.ProfScholz.de.

Some of the design steps that have already been implemented into PreSTo are preliminary sizing, fuselage layout and wing layout including first order design methods for the high-lift system and the tailplane. Statistics sheets provide the user with information on existing jet and propeller aircraft as decision support during data input. Further sheets offer links to the aircraft design programs PrADO (see Section 2.2) and CEASIOM (Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods, [10]) for an in-depth investigation and optimization of the initial PreSTo results. Furthermore, PreSTo features a connection to the CAD software CATIA V5 that enables the visualization of the PreSTo geometry by means of the adaption of a generic CATIA V5 aircraft model.

PreSTo's centerpiece is the preliminary sizing section in which initial aircraft parameters such as its thrust-to-weight ratio (or power-to-mass ratio in the case of propeller-driven aircraft), wing loading and maximum take-off mass are estimated in a quick manner. This makes PreSTo a valuable initial step for the application of more comprehensive aircraft design software such as PrADO – especially in case of the investigation of a completely new aircraft design. Here, PreSTo delivers good initial values (e.g. wing area, required thrust and cruise altitude) for the subsequent optimization with PrADO.

2.2 PrADO

The IFL's Preliminary Aircraft Design and Optimization program PrADO [11], [12] was used in the Green Freighter project as the central tool for the detailed aircraft design analyses. PrADO has a modular structure representing all major aircraft design disciplines. These reach from aircraft geometry description, thermodynamic modeling of the propulsion system, different aerodynamic modules, mass estimation, flight mission simulation and assessment of the aircraft's Direct Operating Costs (DOC) to the Finite Elements "Structural, Aerodynamic and Aeroelastic Sizing Module" SAM [13], [14]. In order to offer a wide range of possible applications, the design modules largely use physical models that are not bound to statistics and specific reference aircraft.

Before the analyses presented in the following sections of this paper could be performed some extensions to PrADO had to be made [7]. The most important ones were

- the 3D-description of liquid hydrogen (LH_2) fuel tanks including aircraft center of gravity travel due to fuel consumption (Figure 1),
- the enhancement of the thermodynamic engine model including the combustion characteristics of hydrogen,
- the development of a turboprop engine model (Figure 2),
- the modification of the flight simulation concerning the use of different fuels and engine types during different flight segments (e.g. hydrogen during take-off and kerosene during cruise), and
- the enhancement of SAM to analyze blended wing body configurations with cryogenic fuel tanks inside the fuselage (Figures 3 and 4).

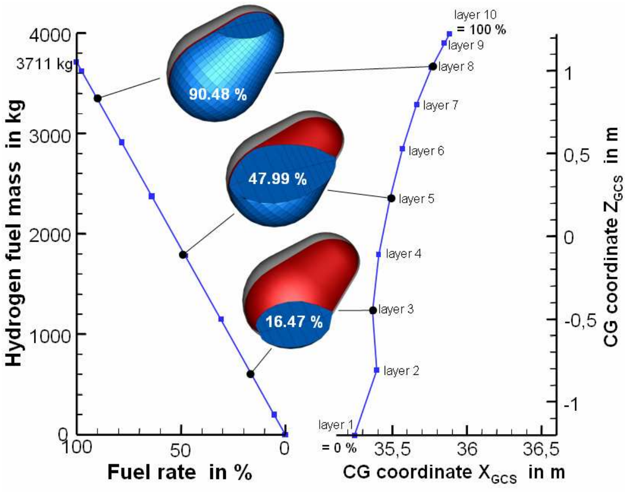

Fig. 1. PrADO Cryogenic Fuel Tank Model

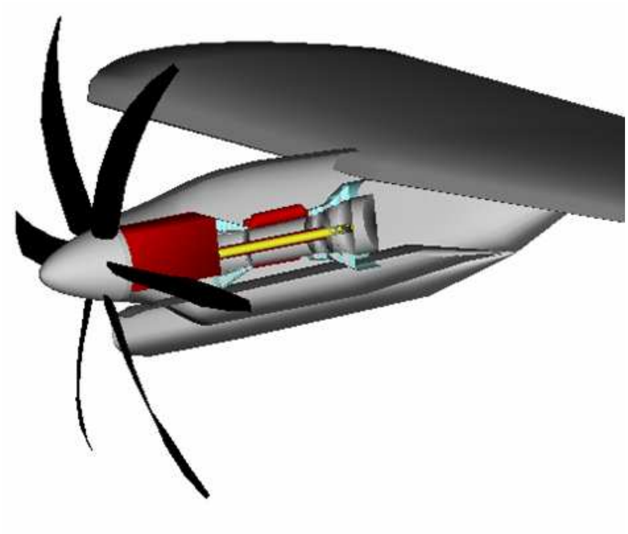

Fig. 2. PrADO Turboprop Engine Model

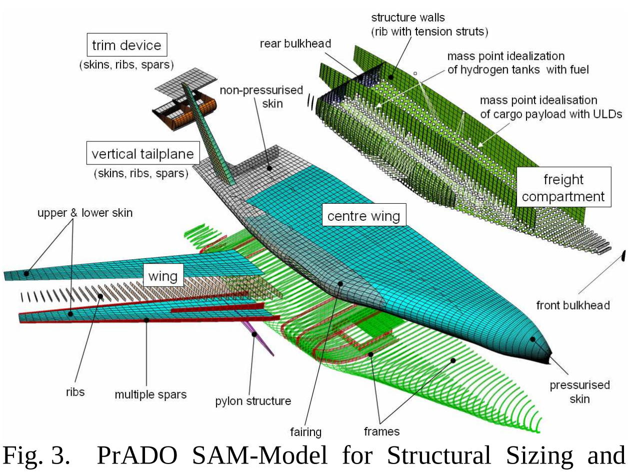

Fig. 3. PrADO SAM-Model for Structural Sizing and Mass Calculation

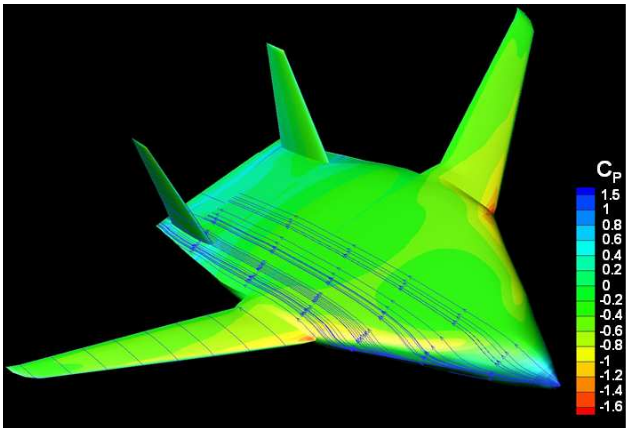

Fig. 4. Pressure Distribution on the Unmanned BWB Aircraft Design for SAM Aerodynamic Load Determination (Panel Code HISSS)

2.3 Reference Aircraft

Prior to the selection of specific reference aircraft it was decided that the aircraft sizes of interest for the Green Freighter project are

a) regional freighters and
b) large long-range freighters.

Regional freighters were selected as this is the most probable market segment for the first application of hydrogen as fuel in air transport. The conversion of an existing aircraft into a hydrogen demonstrator aircraft and the production of a dedicated hydrogen freighter would technically be comparatively manageable and cause relatively low costs. The ATR 72 full freighter version was selected as the regional reference aircraft due to its importance in that aircraft size range and good availability of data on this aircraft. The ATR 72 features a conventional high-wing configuration and a turboprop propulsion system. Its length and wing span are both 27 m, and the aircraft features a maximum payload of 8.1 t.

The Boeing B777F with a maximum payload of 108 t was selected as the long-range reference aircraft. Previous aircraft design studies at the IFL showed that BWB aircraft must feature a certain minimum size in order to become competitive or even advantageous compared to conventional aircraft [15]. The Boeing B777F was expected to be of the minimum size for a reasonable comparison, and, moreover, it is a modern representative of long-range freighter aircraft.

3 Regional Freighters with Conventional Configuration

The following investigations of regional freighter aircraft were performed by HAW Hamburg. This article concentrates on the investigations performed with PrADO – the results of the preliminary sizing activities using PreSTo are presented in [9]. In the course of the Green Freighter project the following regional freighter versions were investigated; the aircraft as well as their order of evolution are shown in Figure 5:

- RF00-KP[a] (based on real ATR 72 full freighter version; reference version)
- RF10-KJ (jet version)
- RF20-HP (initial hydrogen version)
- RF21-HP-UNM (unmanned)
- RF22-HP-EXT (external tanks)
- RF23-HP-STR (stretched fuselage)
- RF30-HP-FCS (full cross section tanks)

All hydrogen powered aircraft descend from version RF20-HP in which the aircraft fuselage was kept the same as that of the reference version RF00-KP. In this version the required fuel storage volume was subtracted from the available cargo compartment volume. Consequently, this design violated the cargo capacity requirement (see Table 1) but delivered a good basis for first investigations of the hydrogen propulsion system. The results of the comparative investigations of the versions RF00-KP, RF10-KJ and RF20-HP are presented in [3] and [16]. The basic conclusion from these investigations for the future work was that jets are significantly inferior to propeller-driven versions. Thus, in the following steps only propeller aircraft were studied. The models of version RF22-HP-EXT with external hydrogen tanks under the wings and the unmanned version RF21-HP-UNM show the wider spectrum of possibilities. An unmanned aircraft design has the potential to further improve the design as the former cockpit area can be used for hydrogen storage. This reduces or avoids the need for a fuselage stretch. Moreover, several aircraft systems, such as the environmental control system (ECS), that are essential when humans are onboard can be scaled down or omitted [17]. In the following the versions RF00-KP, RF23-HP-STR and RF30-HP-FCS are presented in more detail.

3.1 Aircraft Design Investigations

As first step the reference PrADO RF00-KP model was set up, based on the original ATR 72's operational characteristics (see Table 1). These values also represent the top-level aircraft requirements (TLARs) posed to all derivative versions.

Tab. 1. Regional Freighters – Top-Level Aircraft Requirements [18], [19]

Parameter	Value
Maximum Payload	8093 kg
Design Range (@ max. Payload)	500 NM
Cargo compartment capacity	7 LD3 containers
Cruise Mach Number	0.41
Distance to Alternate Airport	87 NM
Loiter Time	45 min

The requirement for a storage capability of seven LD3 containers led to a cargo compartment length of about 14.5 m. As external tanks should be avoided, the fuselage was stretched to be able to store the hydrogen in two tanks: one forward and one aft of the cargo compartment. Due to the installation of the forward hydrogen tank that would obstruct the large cargo door in its initial position the door positions had to be switched so that the large cargo door was now located aft of the wing.

The masses of the hydrogen tank structure and insulation were estimated using the method given in the German Aerospace Handbook (LTH, [20]) and data given in Brewer [21]. The insulation was assumed to be a 12 cm thick layer of non-vacuum insulating foam. The tank masses also include the mass for the hydrogen system of 100 kg per tank, thus 200 kg in total. This value has been achieved by means of an upscale of the hydrogen system of the Dornier Do 328 hydrogen demonstrator aircraft design

[a] RF: Regional Freighter
K: Kerosene
H: Hydrogen
P: Propeller
J: Jet

from the Cryoplane project [22]. The hydrogen tank dimensions and tank masses used for versions RF23-HP-STR and RF30-HP-FCS are listed in Table 2.

Tab. 2. Hydrogen tank dimensions and masses

Parameter	RF23-HP-STR		RF30-HP-FCS	
Length [m]	Forward: Aft:	2 3.1	Forward: Aft:	1.2 2.8
Diameter [m]	Forward: Aft:	1.75 1.85	Forward: Aft:	2.3 2.2
Tank mass* [kg]	Forward: Aft:	246 302	Forward: Aft:	266 303

* Including tank structure, insulation and 100 kg of system components (pumps, pipes, etc.)

In case of version RF23-HP-STR the tank diameter was limited by the sizes of the cargo compartment and large cargo door to enable tank removal and replacement for maintenance. Version RF30-HP-FCS uses the full available fuselage cross section, which leads to the fact that the hydrogen tanks of this version could not be removed from the aircraft for inspection and/or replacement. Consequently the tanks must be accessible for inspection on the aircraft and issues such as hydrogen embrittlement must not be critical. The tank masses of version RF30-HP-FCS are larger than those of version RF23-HP-STR due to the larger tank diameters and/or structurally disadvantageous tank shapes.

3.2 Results

Table 3 shows the resulting aircraft parameters of versions RF00-KP, RF23-HP-STR and RF30-HP-FCS. The original aircraft parameters of the ATR 72 full freighter version are well represented by the reference model RF00-KP. The resulting hydrogen aircraft masses show that the empty mass penalties due to the installation of hydrogen tanks and its snowball effects such as a higher mass of the stretched fuselage could be widely reduced by the tank installation of version RF30-HP-FCS. The smaller fuselage stretch more than balances its higher tank masses. Thus, making use the complete available fuselage cross section is strongly advisable to reduce the empty mass increases caused by the installation of hydrogen

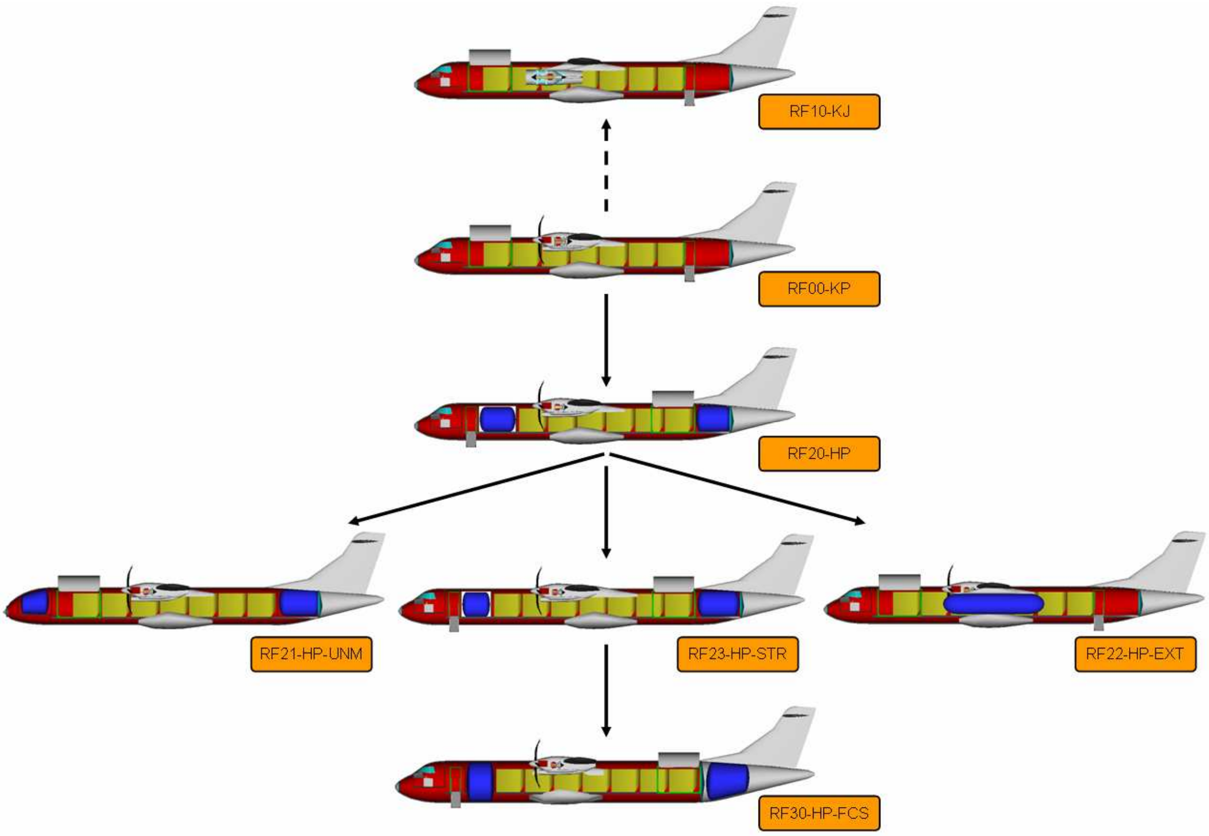

Fig. 5. Regional freighter versions overview

tanks and its snowball effects and to counterbalance overall disadvantages caused by the mentioned maintenance implications.

Tab. 3. Aircraft Parameters of Versions RF00-KP, RF23-HP-STR and RF30-HP-FCS

Parameter	Original ATR 72 [18]	RF00-KP	RF23-HP-STR	RF30-HP-FCS
Operating empty mass [t]	11.9	11.8	12.6	12.0
Max. take-off mass [t]	22	21.9	21.3	20.7
Fuel consumption [kg]	2000	1974	619	615
Energy consumption [GJ]	85.6	84.5	76.0	75.5

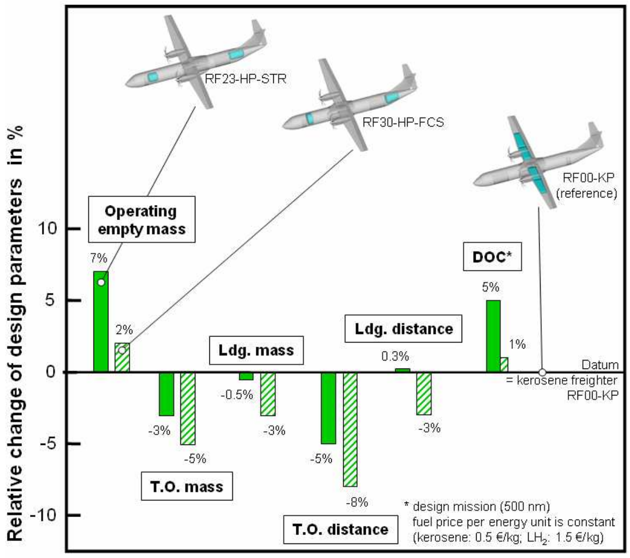

Fig. 6. Relative Comparison of Hydrogen Aircraft Versions and Reference Kerosene Aircraft

It would even be possible to enlarge the fuselage cross section in order to further minimize the fuselage length increase. With respect to a possible use of the determined fuselage and fuselage cross section also for passenger aircraft a greater fuselage diameter, especially a wider fuselage, also fits to current trends in aircraft cabin design to provide the passenger with more space and consequently comfort (see e.g. Airbus A350XWB).

Figure 6 depicts a comparison of the main aircraft parameters of version RF23-HP-STR and RF30-HP-FCS relative to version RF00-KP and the original ATR 72 full freighter version.

The hydrogen versions show 3 % to 5 % lower maximum take-off masses despite their 2 % to 7 % higher operating empty masses, which is due to the significantly lower fuel mass. The fact that also the maximum landing masses of the hydrogen versions are 0.3 % to 3 % lower than that of the reference aircraft even though their operating empty masses are higher results from the original ATR 72's high ratio of maximum landing to maximum take-off mass of 0.97. So, this aircraft can land with almost full (kerosene) fuel load. The lower take-off and landing masses of the hydrogen versions lead to 5 % to 8 % shorter take-off and 0 % to 3 % shorter landing distances.

Table 4 shows the DOC of the hydrogen versions in relation to the kerosene version RF00-KP. It can be seen that the DOC-penalties of the hydrogen versions of 1 % to 5 % result mainly from their higher empty masses to which the aircraft prices are estimated proportionally. Their lower energy consumptions at today's fuel price for kerosene of 0.5 €/kg and an energy-equivalent price for hydrogen of 1.5 €/kg reduce this penalty to some extent.

Tab. 4. Direct Operating Costs of Versions RF23-HP-STR and RF30-HP-FCS in Relation to RF00-KP

DOC Element	Relative DOC	
	RF23-HP-STR	RF30-HP-FCS
Aircraft Price	+ 8 %	+ 2.5 %
Fuel	- 5 %	- 5.5 %
Crew	0 %	0 %
Maintenance	+ 4 %	+ 1 %
Fees	- 0.5 %	- 1 %
Total DOC	+ 5 %	+ 1 %

Possibilities for supplementary mass reductions are the use of hydrogen tanks that are an integral part of the fuselage structure and an alternative entry to the cockpit that avoids the entrance area between the cockpit and the forward hydrogen tank. Areas of further research and improvement potential are

- the integration of the environmental impact into the current DOC assessment method,

- the integration of the extra inspection and maintenance effort into the DOC assessment
- the integration of an automatic hydrogen tank and system mass estimation method into PrADO and
- a more in-depth structural sizing as the beam model used during the current investigations does not take into account the crashworthiness requirements for hydrogen tanks or the cutout for the large cargo door in the structurally loaded rear part of the fuselage.

4 Long-Range Freighters with Conventional and Blended Wing Body Configuration

The following investigations were performed by the IFL. As previously stated, the Boeing B777F was chosen to be the long-range reference aircraft and consequently defines the common TLARs collected in Table 5.

Tab. 5. Long-Range Freighters – Top-Level Aircraft Requirements

Parameter	Value
Maximum Payload	108571 kg*
Design Range (@ max. Payload)	4779 NM
Cargo Volume	667 m³
Cruise Mach Number	0.84
Distance to Alternate Airport	200 NM
Loiter Time	30 min

* Including 5741 kg container mass

4.1 Long-Range Freighters with Conventional Configuration

Prior to the development of the BWB freighter aircraft designs the Boeing B777F was modeled and analyzed as benchmark test for the design and analysis methods applied. Table 6 contains the main PrADO-results in comparison to the respective data given by Boeing [23].

Tab. 6. Long-Range Freighters – Conventional Aircraft Results

Parameter	Boeing Data	PrADO Result	Deviation
Operating Empty Mass	139539 kg	139534 kg	-0.004 %
Fuel Mass	97050 kg	90242 kg	-7.54 %
Max. Take-Off Mass	345160 kg	338347 kg	-2.01 %
Cruise Glide Ratio	Not Disclosed	19.6	-

The PrADO re-design delivers a very good correlation with the real aircraft's operating empty and maximum take-off mass of 2 % deviation. The larger deviations of 7.5 % in fuel mass are firstly the result of a simplified flight simulation in which flight segments such as the ground rolls during take off and landing are not taken into consideration. Secondly, the engine analysis was performed under the assumption that there is no energy and bleed air extracted from the engine. According to experience, this may lead to up to 5 % deviation in specific fuel consumption for conventional passenger transport aircraft but would probably be somewhat less for freighter aircraft.

For a complete assessment of the following hydrogen powered BWB versions an additional hydrogen-fueled freighter aircraft with conventional configuration was designed (see Figure 7). This aircraft features a large spherical liquid hydrogen tank behind the cargo compartment. In order to keep the maximum aircraft length of 80 m additional hydrogen tanks were placed above and below the main deck, and the cargo pallets were positioned in three longitudinal rows. The resulting fuselage cross section was 8.5 m wide and 8.2 m high. This optimized conventional hydrogen freighter has a take-off mass of 314 t which is 7.2 % lower than that of the conventional kerosene freighter. For the reference mission of 4779 NM it consumes 32.6 t of hydrogen.

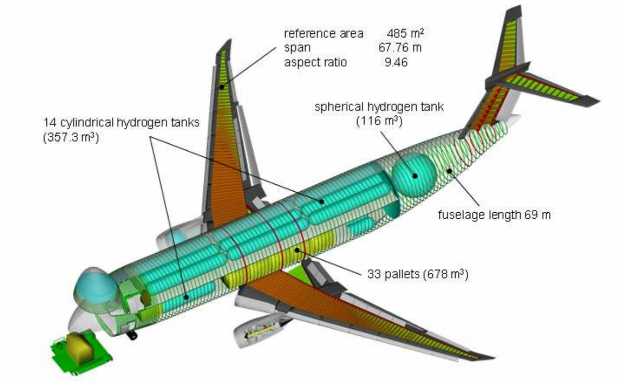

Fig. 7. Optimized Conventional Hydrogen Freighter

4.2 Long-Range Freighters with Blended Wing Body Configuration

The initial comparative BWB design was a downsized version of the so-called VELA3 (Very Efficient Large Aircraft) configuration [24]. The aircraft was scaled down so that it was just capable of storing the required cargo volume and fitted into the 80 m x 80 m box of maximum allowable aircraft size at the airport. The required amount of liquid hydrogen was placed in tanks with a small diameter of maximal 1.5 m which led to a total number of 50 hydrogen tanks. The reasons for this decision are a good usage of the available rectangular storage compartments and the possibility to easily remove and replace the tanks through the cargo doors for maintenance. A comparison of these two aircraft is shown in Figure 8.

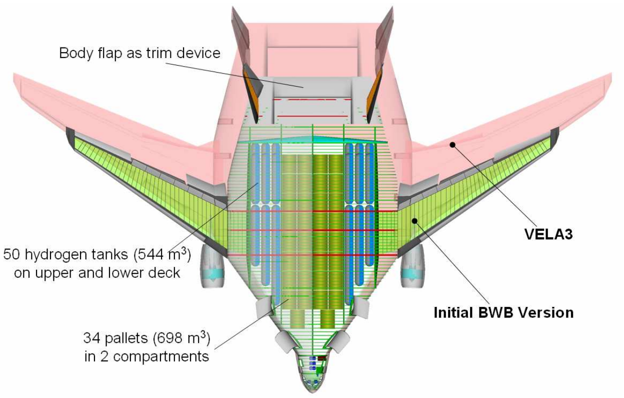

Fig. 8. PrADO Model of Initial BWB Version in Comparison to VELA3 Configuration

The first analyses of the initial BWB aircraft showed a 1.8 % higher maximum take-off mass than the kerosene reference aircraft resulting from a bad glide ratio of less than 17. The reason for that is the low lift coefficient during cruise caused by the low wing loading due to the extremely large wing and the low hydrogen fuel mass. Moreover, this aircraft was not naturally stable during cruise flight.

A decrease of the outer wing incidence angle by 3° reduced the trim drag caused by the deflection of the body flap. Another positive aspect was a new lift distribution that reduced the outer wing structural loads and caused a mass reduction of 5.2 t or nearly 15 % of the wing mass. The stability characteristics were improved by a slight rearward movement of 1 m of the outer wing combined with a forward movement of 0.4 m of the payload package.

The next optimization step was the decrease of the outer wing area with the aim to increase the wing loading. The problem here was the significantly higher landing mass of the hydrogen freighter compared to a kerosene fueled aircraft that resulted from the lower hydrogen fuel mass share in take-off mass. This determined the thrust requirement (minimum missed approach climb gradient with one engine inoperative) and reduced the possible area reduction due to the landing field length requirement. The design calculations caused a slight reduction of the reference area (1448 m² to 1336 m² or -7.7 %) combined with an increase of the initial cruise altitude from 11.6 km to 12.5 km. Due to the climb angle requirement that depends on the number of engines, the final manned BWB version featured four instead of two engines. This measure itself led to a further 5 % reduction of the operating empty mass and – as snowball effects – to 3 % smaller fuel and take-off masses.

Based on this final manned BWB aircraft version an unmanned version was set up and analyzed in the final step. In this version the additional mass of the required larger avionics system was estimated as 185 kg. Moreover, the nose part of the fuselage was modified to be more triangular and featured a large up swinging cargo door. Figure 9 shows both BWB versions.

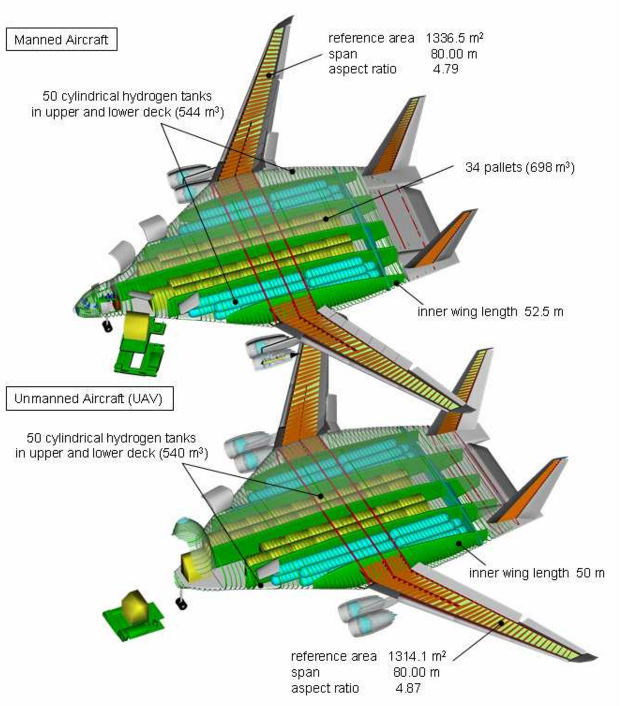

Fig. 9. Optimized Hydrogen Fueled BWB Configurations Designed for the Reference Mission of the Kerosene-Powered Freighter

4.3 Results

Figures 10 and 11 show comparisons of the main aircraft parameters of the hydrogen aircraft versions to the kerosene reference aircraft.

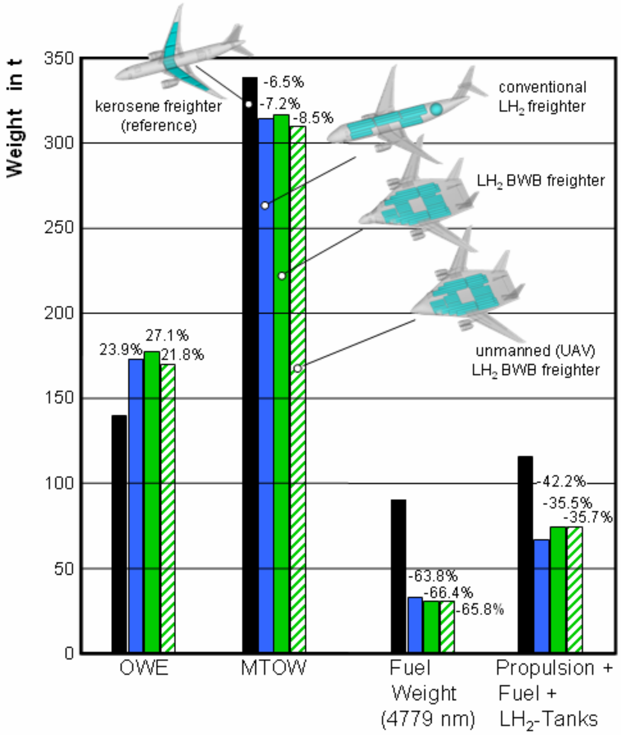

Fig. 10. Mass Comparison of Hydrogen Aircraft Versions and Reference Kerosene Aircraft

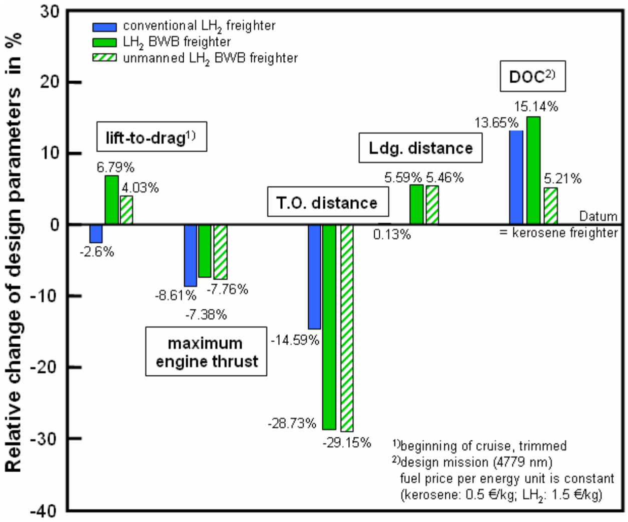

Fig. 11. Relative Comparison of Hydrogen Aircraft Versions and Reference Kerosene Aircraft

Primarily the design analyses indicate significant technical advantages of the hydrogen aircraft. The hydrogen versions show 6.5 % to 8.5 % lower take-off masses. These values are mainly due to the 63.8 % to 66.4 % lower fuel masses that more than compensate the additional masses for the hydrogen tanks. In consequence, the required take-off field lengths result as between 14 % and 28 % shorter. However, the mass benefits are not sufficient to also cause economic benefits. Even under the optimistic assumption that both fuels are equivalently expensive with respect to their energy content the hydrogen freighters have up to 15 % higher DOC. This stems from their higher aircraft prices that are directly proportional to their higher operating empty masses.

The final hydrogen-fueled BWB aircraft does not show considerable superiority over the conventional aircraft designs but is only an equivalent solution, although there are clear technical advantages noticeable:

- The cruise glide ratio is 8 % higher than that of the conventional aircraft (aerodynamic advantage).
- Despite a 50 % larger wetted area of the inner wing the complete structural mass of the hydrogen BWB is only about 21 % larger than that of the conventional hydrogen aircraft (structural advantage).

However, due to the low wing loading the BWB is not able to achieve its full maximum glide ratio of about 23. In case of the unmanned version this disadvantage is even higher (1.5 % higher fuel demand). No longer necessary aircraft systems such as the emergency oxygen system or the environmental control system lead to a small total advantage of 2.2 % less take-off mass of the unmanned version. Remarkably, the DOC of the unmanned version are 8.6 % lower than those of the manned BWB due to the elimination of the crew costs. In comparison to the kerosene reference version the DOC disadvantage is reduced to 5.2 %.

5 Conclusions

The results of the Green Freighter project show that hydrogen as aviation fuel is feasible from an aircraft design point of view. This conclusion is supported by previous aircraft design studies [4], [5], [6], [21] and experts from other disciplines, e.g. [25], [26]. Rising energy prices will make air transport more expensive than today, but hydrogen is a potential alternative fuel that keeps air traffic possible even if low-priced kerosene is no longer available. In addition, air traffic could become more environmentally friendly. Freighter aircraft and especially regional freighters lend themselves as demonstrator aircraft and first production-models of aircraft with hydrogen propulsion. In first instance, the high energy density of hydrogen and the resulting lower fuel mass lead to a larger mass advantage compared to kerosene-fueled aircraft than can be achieved by conventional means such as the use of lightweight materials. Hence, the challenge in hydrogen aircraft design is to make use of this natural advantage and to use up of it as little as possible for additional masses of tanks, insulation and systems. In this context one essential task is the optimized installation of tanks. Unmanned designs announce further mass improvements as in these designs the former cockpit volume can be used for the installation of hydrogen tanks.

The regional hydrogen aircraft versions have 2 % to 7 % higher operating empty masses than the kerosene fueled reference aircraft, but 0.5 % to 5 % smaller maximum take-off and landing masses due to their significantly smaller fuel masses. In consequence, they consume about 10 % less energy than the kerosene version. In future scenarios with rising costs for energy this is expected to become an increasing economic benefit. At today's kerosene price and an energy-equivalent hydrogen price the hydrogen aircraft have 1 % to 5 % higher DOC. The installation of liquid hydrogen tanks that extend over the full available fuselage cross section is significantly superior to removable tanks with smaller diameter and leads to a 5 % smaller operating empty mass and about 4 % less DOC.

The operation of BWB aircraft is principally feasible. Possible first applications could be military freighters (as it is e.g. intended for the X-48B). The conducted design analyses show a mass saving potential of 6.5 % to 8.5 % for an unmanned hydrogen-fueled BWB freighter aircraft in comparison to the conventional reference aircraft Boeing B777F at a reference mission of 4779 NM with 108 t of payload. Nevertheless, the BWB aircraft show no clear superiority over a hydrogen-fueled freighter aircraft in conventional configuration. The main reason for that is the low wing loading, which is a consequence of the necessary minimum size of the BWB and the low hydrogen fuel mass. In consequence, the BWB cannot take advantage of its aerodynamic advantages during cruise flight. This disadvantage, however, would lose its significance if BWB aircraft were designed for even larger payloads of more than 150 t. This gives room for continuing studies during which also BWB configurations with fewer larger tanks (that could also be placed outside the pressurized cabin) could be investigated.

Further Information

For further information please visit the Green Freighter website http://GF.ProfScholz.de or contact Mr. Seeckt by email under kolja.seeckt@haw-hamburg.de.

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