LH2 as Alternative Fuel for Aeronautics – Study on Aircraft Concepts

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ABSTRACT

A project under the title "Cryoplane – Liquid Hydrogen Fuelled Aircraft System Analysis", Contract G4RD-CT-1999-00192, has been started within the 5th Framework program of the European Commission in April 2000.

36 partners from industry, research and academia contributed to this project covering aircraft configuration, systems & components, propulsion, safety, environmental compatibility, fuel sources & infrastructure, transition

Total project time was 26 months.

The objectives of the project were to develop a conceptual basis for unlimited applicability, safety, and full environmental compatibility, and to undertake medium/long term scenarios for a smooth transition from kerosene to hydrogen in aviation. This system analysis covers all relevant technical, environmental, societal and strategic aspects providing a sound basis for initiating larger scale activities preparing for the development and introduction of Liquid Hydrogen as an aviation fuel.

The project helped in mastering the necessary technology and provided a comprehensive analysis of the complex interrelated aspects. It looked into the technical feasibility, safety and environmental compatibility of the concept and produced technical solutions and tools. It worked out possible strategies for a smooth transition to the new fuel.

The results of the project confirmed that liquid hydrogen, from the technical side, could be an alternative future fuel. Because of today's high hydrogen production costs and the missing infrastructure it remains not attractive for operation at this time.

This report presents the major results of the assessments made under "WP2 – Aircraft Configurations" and the remarkable messages of the other work packages of the project.

NOMENCLATURE

CMR	Cryoplane Medium Range
CO2	Carbondioxide
A/C	Aircraft
COC	Cash Operation Costs

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DOC	Direct Operating Costs
H2	Hydrogen
H2O	water
LCA	Life Cycle Analysis
LH2	Liquid H2
MTOW	Maximum Take-Off Weight
MWE	Manufacturer's Weight Empty
NOx	Nitrogen Oxide
OWE	Operating Weight Empty
p. a.	per annum
Pax	Passenger
RK	Reference a/c Kerosene
WP	Work Package

INTRODUCTION

Air traffic has enjoyed strong growth over a long time, and it is predicted that such growth will continue at rates of 4 – 5 % p.a. over the next decades. Assuming continuing worldwide economic growth, saturation of air traffic is not yet in sight.

It is generally accepted that the emission of greenhouse gases, most notably of long-living carbon dioxide (CO_2), resulting from industrial activities, cannot be allowed to continue increasing if adverse global climate change is to be avoided.

Air traffic today contributes about 3% to the anthropogenic greenhouse effect. This number may change due to increase of air traffic and the decrease of the major CO2 producers of today.

LH2 could be an alternative to the hydrocarbon fuel like cheap kerosene or any other "designed" hydrocarbon fuel.

It could be a fuel suitable for aircraft to be produced from renewable energy and offering extremely low emissions (zero CO2, very low NOx). It has the potential to eliminate the dependency of aviation upon dwindling crude oil resources and to reduce dramatically, the contribution of aviation to the anthropogenic greenhouse effect. Use of liquid hydrogen hence could allow sustainable growth of aviation at high rates (typically 4-5% per year) with an extreme low impact on the environment.

The project "Cryoplane – Liquid Hydrogen Fuelled Aircraft System Analysis" included the assessment of all aspects relevant to form an overall judgment and defined technical concepts for initializing realization.

The whole project was stuctured into 8 technical work packages.

WP1 (Project Management)

WP2 Aircraft Configuration

WP3 Systems and Components

WP4 Propulsion

WP5 Safety

WP6 Environmental Compatibility

WP7 Fuel Sources and Infrastructure

WP8 Transition Scenarios

WP9 Trade-off: Slush

Overall aircraft configurations have been identified, which meet the requirements of efficient and safe operation in all aircraft categories, from “Business Jets” to “Very Large Long Range Aircraft” (600 and more seats). Their performance has been analyzed and compared to conventional aircraft.

Based on an overall architecture for the fuel system, which was adapted to those tank arrangements required for different aircraft categories, the technical feasibility and availability of suitable components has been assessed.

Detailed analyses of “conventional“ and “unconventional” engines have been done.

Safety aspects specific to aviation have been assessed, coming to the overall conclusion that hydrogen fuelled aircraft certainly will be as safe as conventional aircraft.

Assessments on H2 production (including extensive LCA), infrastructure and ground-handling facilities and procedures were as well part of this exercise.

With respect to environmental compatibility, great benefits have been identified. According to extensive computer simulations, also the contrails produced by hydrogen-fuelled aircraft will contribute less to anthropogenic greenhouse effect compared to the conventional case. (Source: WP 6 of [2])

This report gives an overview of the project.

TECHNICAL WORPACKAGES

According to the introduction WP2 to WP9 are technical work packages. WP1 was only related to project management.

Objective of the WP2

In order to prove the possibility of the use of H2 as an alternative fuel from the aircraft industrial side the exercise of this project was related to the range of aircraft categories, which are in general in commercial operation.

One objective at the beginning of this project was to identify aircraft configurations, which meet the requirements of efficient and safe operation in all aircraft categories, from “Business Jets” to “Very Large Long Range Aircraft”. Their performance and DOC should be analyzed and compared to conventional aircraft.

Based on data coming from the other work packages configurations of the selected aircraft categories have been worked out. Aircraft performances have been calculated and compared with conventional aircraft.

The work on Aircraft configurations WP2 was split into two main groups of tasks; the conventional und unconventional configurations.

Conventional aircraft configurations have been evaluated for those categories, which were selected before, whereas unconventional categories were worked out in a more general way.

Results

The “Cryoplane - System Analysis” has shown that hydrogen could be a suitable alternative fuel for the future aviation. Nevertheless, due to the missing materials, parts, components and engines further R&D work has to be performed until hydrogen can be used as an aircraft fuel. According to estimations made during this project the earliest implementation of this technology could be expected in 15 to 20 years, under the condition that the research work will continue on a certain level.

From the operating cost point of view hydrogen remains not attractive under the today’s condition, while kerosene is much cheaper than hydrogen and production/infrastructure is completely missing.

Following features have resulted from comprehensive calculation and parametric studies for the above listed range of aircraft categories. Due to the bigger wetted surface the energy consumption would increase by 9% to 14%. The OWE may increase by roughly 23% by having additional tank structure, while the difference of the MTOW will vary between plus 4.4% to minus 14.8% depending on the aircraft configuration and mission. All this will result in an increase of the operating costs by 4% to 5% caused by fuel only.

Various unconventional configurations have been assessed. An advantage of the selected configurations relative to conventional configurations could not be identified.

Detailed analysis of “conventional“ engines has confirmed that a hydrogen engine will be as efficient as a kerosene engine in terms of energy consumption. Substantial improvements in NOx emissions by lean combustion have been quantified on the basis of experimental data. Small but not negligible benefits have been found for unconventional engine configurations, utilizing the liquid hydrogen’s cooling capacity.

A heat exchanger was identified as one novel feature of the fuel supply system. It is needed to heat up the liquid hydrogen to a temperature, which is suitable to the injection into the combustion chamber. Different design principles have been assessed. Result has confirmed the feasibility, but further research is needed for validation of the design itself and its implementation into the power plant.

Requirements and regulations for ground handling and servicing have to be reviewed and adapted. Airworthiness requirements may be amended according to the specific behavior of LH2 and the technical design solutions.

All kind of accidental incidents and results of emergency landings have been identified and analyzed. Technical design solutions and/or possible changes of operating procedures have been identified.

Conservative life cycle analysis, based on the data taken from the detailed analysis of the different production, transportation, storage and consumption methods (oilfield to jet propulsion) of H_2 and kerosene performed and compared. The result showed in any case a lower CO_2 production in case of H_2 use. But the high potential is the production of H_2 by renewable energy.

According to extensive computer simulations, contrails produced by hydrogen-fuelled aircraft will contribute less to anthropogenic greenhouse effect compared to the conventional case. The H_2 fuelled main engines may produce 2,6 times more H_2O as kerosene fuelled engines. H_2O is a greenhouse gas, which will remain only very short time, about half a year, in the upper atmosphere whereas CO_2, which is emitted by a kerosene engine, remains about 100 years in place.

Assessments based on conservative calculations have confirmed that the use of hydrogen would reduce aircraft emissions to a minimum. It needs to be validated that the water emission of hydrogen fuelled aircraft propulsion has low impact to the atmosphere as predicted.

Global scenarios for a soft transition to the new fuel have been quantified and checked for practicality in detail by considering Sweden as the leading region during transition to hydrogen.

WP2 – Aircraft Configuration

General

In order to get comparable data from each configuration assessment, design requirements have been established. The fundamentals have been selected as the basis of 1990 with the technology level of 2010. Design rules describing all necessary features like interior layout, weights, performance etc. have been established. Economical conditions of 2010 have been considered for the calculation of DOCs. Family concepts have been worked out for each configuration (Picture 2). The 200 Seater medium range aircraft has been selected as an example aircraft, for which the basic systems' studies were made.

Conventional Configurations

For a selection of transport aircraft, ranging from regional turboprops to very large, long-range jet aircraft *(Picture 1)*, a comparison has been made between kerosene and LH2 fuelled versions. The tank layout turned out to be the driver for the design on configurations as LH2 requires 4 times more storage volume than kerosene for the same energy content and must be stored under overpressure. This precludes the use of wing tanks. The optimal choice for the tank layout depends on the aircraft category. For seven categories of aircraft, three basic tank layouts are now being proposed. For "Small Regional Aircraft" and "Business Aircraft" tanks are arranged aft of the aft pressure bulkhead only. For "Regional aircraft up to 100 seats" (turboprop as well as jet) and "Short/Medium Range Aircraft" tanks are arranged behind the aft pressure bulkhead and on top of the fuselage. For "Long Range Aircraft" and "Very Large Long Range Aircraft" (VLLR) tanks are proposed aft of the rear pressure bulkhead and between the cabin and the cockpit. Although these solutions seem to be so diverse as to be conflicting, they are in line with each other as will be explained in the following.

Small Regional Aircraft and Business Aircraft

The simplest solution, the tank behind the aft pressure bulkhead, is only feasible from a center of gravity location consideration when the fuel weight fraction is small. Hence it is applicable only to the "Small Regional Aircraft". However, this concept was used for the "Business Aircraft" as well, for lack of an alternative. To reduce the impact of the single tank on the center of gravity, a wider fuselage was adapted than usual. An exploratory study revealed yet an excessive center of gravity travel, probably requiring a combination of fly-by-wire and a very large horizontal tail, or operational restrictions to the center of gravity. As a result, the aircraft will suffer from increased trim drag and reduced maximum lift.

Regional 100-Seater Aircraft

For larger fuel fractions and thus range, the fuel in the aft tank must be balanced by a more forward tank. For the "Regional aircraft up to 100 seats" (turbo-prop and turbo-jet) and "Short/Medium Range Aircraft" the fuselage diameter is too small to enable a catwalk parallel to and beside the forward tank, to serve as the cockpit-cabin connection. This forces the tank on top of the fuselage, thereby creating a weight and profile drag penalty. Special attention must be paid to disk burst, as this might lead to an explosion of the LH2 in the top tank. Therefore a dry bay may be created. As a consequence, this configuration is less efficient as the other solutions. It is expected that the top tank does not pose a threat to the passengers in case of fire, as the LH2 will boil off, evaporate and rise upwards.

Short and Medium Range Aircraft

Picture 2 shows the aircraft and family designs, which was based on market requirements

1st Step: Basic version 185 passengers (dual class) 4000 nm design range

2nd Step: Stretch version 218 passengers (dual class) 3300 nm design range

3rd Step: Second step with developed MTOW for 4000 nm design range

4th Step (option only): 1st step with reduced MTOW and engine thrust reduction,

The design philosophy for fuselage assumed the requirements for the fuselage cross section of the 6-abreast single aisle design. This type of cross section is well balanced in terms of comfort / flexibility and freight. On the Cryogene fuselage the top of the cross section is flattened off in the pressurized cylindrical section for reason of tank integration at minimum wetted area.

The first approach a/c CMR-200 -driven by hydrogen fuel - is based on a high wing design for reason of the following considerations:

- use of the box volume - being available anyway – as part of the overall integrated fuel system and as a benefit from this
- close coupled tank without fuel piping in the pressurized cabin.

As a side condition it is assumed that the wing fuel volume should not be under 30% of the total, because it is estimated that otherwise the volume / system ratio would be out of balance.

The condition to provide 30% of the total fuel volume in the wing defines a very large area (233 m^2).

Calculation of the drag polar showed that this configuration has a penalty of 17,5% compared with the conventional aircraft.

To improve the situation, the Cryoplane configuration - in a second approach - was redefined. In principle, the low wing (170 m^2) of the kerosene aircraft (RK-200) was combined with the fuselage of the initial Cryoplane aircraft (CMR-200). However, as it makes no sense to carry LH2 fuel in the small wing (volume/system unbalance) the tail cone of the fuselage was reshaped to provide the additional volume required for total fuel.

The second-approach configuration of the CMR1-200 a/c, driven by hydrogen fuel, is based on a low wing design and is characterised by a close coupled wing tank on top of the fuselage, by a tail tank and by the absence of fuel piping in the pressurized cabin.

This configuration showed a penalty on the drag polar of 3,5 % against the conventional A/C.

The weight comparison led to following results:

MWE/pax

- Cryoplane a/c: longer fuselage, higher wing weight, additional fuselage tank structure, LH2 tanks 29% higher MWE vs kerosene version

MTOW/pax

- Cryoplane a/c: ~60% lower fuel weight compensates the higher structural weight and leads to 3.3% lower MTOW vs kerosene version at design range (4000 nm)

(Propulsion+Fuel) /pax

- Cryoplane a/c: Same Propulsion weight, ~60% lower fuel weight 46% lower (propulsion+fuel ratio) vs kerosene version

(Propulsion+Fuel+Tanks) /pax

- Cryoplane a/c: Same Propulsion weight, ~70% lower fuel weight, additional tank structure 23% lower (Propulsion+Tanks+Fuel) ratio vs. kerosene version,

For the payload range the design point is the same on both versions 185 pax / 4000 nm. However, the hydrogen aircraft is extremely sensitive to payload variations and exchanging payload for LH2 fuel has a severe effect on range. In consequence of this, the payload – range flexibility on an individual LH2 aircraft is fairly limited, in particular, as for this type of aircraft the fuel volume is not defined by stretched versions. This is specific to the actual LH2 configuration – fuel tanks on top of the fuselage –, because fuel volume increases automatically when the fuselage is lengthened.

Contrary to this, the fuel volume on a conventional kerosene aircraft is defined by the requirements of stretched family members, but – of course – it can be used also for payload/range flexibility on the basic version, if required.

Again, the design point is the same on both versions 218 pax, 4000 nm Payload – range effects, of course, are the same as described under the basic versions. It is worth mentioning, however, that the CMR1-300 has available some extra fuel volume from its stretch, whereas the fuel volume on the RK-300 was already designed into the basic version.

Economics – Fuel Price Assumption: As hydrogen-fuelled aircraft are in an early stage of development there is quite a number of years ahead until this type of aircraft could enter service.

It may be that there will be various reasons to develop the LH2 technology for aeronautical use, like political initiatives in order to protect the environment locally and or globally, increase of kerosene price. As this analysis should not depend on vague speculations, political initiatives have not been taken into consideration.

Therefore, an estimate of future price trends on LH2 / kerosene fuel was established and this was made the reference for basic COC / DOC trends of LH2 and kerosene aircraft. When comparing the cross over points of the fuel cost curves and the COC curves it is found that the year of cross over is identical – for all practical purposes (2037 / 2038).

It may be assumed, therefore, that in terms of economic performance the H2 version CMR1–200 is almost identical to the reference kerosene aircraft RK–200.

As it is assumed that the aircraft price is dependent on the aircraft OWE, and as the H2-variant is some 26% heavier than the kerosene version the cross over point of the DOC curves – relative to fuel and COC - move two years farther into the future (2040).

An energy (block – fuel) comparison came to the result that the energy used by the H2 version on one hand and the kerosene version increases by 6% to 10% on the H2 side, depending on the mission range and on the member of the family considered.

The LH2 aircraft takes off at a higher weight than the kerosene version on short ranges. However, the difference between the two is decreasing as stage length is increasing, and at design range the LH2 MTOW is even slightly below that of the kerosene aircraft.

This results from the effect that the mission-weights of both versions come closer to each other at longer ranges in consequence of that the LH2 fuel is less heavy than kerosene.

Long Range Aircraft and Very Long Range Aircraft

For the "Long Range Aircraft" and "Very Large Long Range Aircraft" the tank can be placed in the front and aft part of the fuselage. The very large long-range aircraft is very similar to the one shown, except a three-deck layout in order to remain within the 80x80x80 box.

Further Discussion

Finally a check on the various solutions, an extensive parametric study was performed on the allowable combinations of fuselage cross-section, passenger capacity and design range. It appeared that all designs confirm their validity.

All aircraft designs have been compared to check their consistency. The tank layouts have already been discussed. The design weights show a remarkable trend of almost constant OWE versus MTOW fraction of 0.68, i.e. independent of aircraft category or size *(Picture 10)*.

The consistency in operational cost penalty to be paid for the improvement in emissions has been investigated. Considering the fact that no technology jump is required for implementation of LH2, aircraft prices have been estimated on basis of empty weight only and no additional development costs have been incurred. The production price of LH2 was assumed to come down from a high factor 5 more expensive than kerosene now to equal in 2037, based on the same energy content. The energy consumption increase of LH2 aircraft is dependent on aircraft category due to the efficiency of the various tank layouts.

All these considerations combined lead for a 1000 nm mission to a 25 % higher DOC now, decreasing to a break-even point in 2040. Obviously, this outcome is heavily dependent on fuel price development of both fuel types.

Unconventional Configurations

A score of configurations has been screened on their suitability for LH2 application. It surfaced very soon that none exhibits those characteristics that met the requirement of carrying volume. Only one configuration, "the twin boom", was promising. As a comparison, the blended wing body (BWB) was studied as well in the of Medium Range Aircraft category. In the end it appeared that none is superior to the conventional configuration. For the twin boom configuration the large external tanks, leading to high profile and interference drag.

At the end it turned out that all for all unconventional configurations, selected for this study, no advantage against the conventional configurations was obvious.

General conclusions

Various tank layouts appeared to be optimal depending on aircraft category. Crucial element is balancing of the aircraft's center of gravity. Due to the large and heavy tanks, aircraft empty weight will go up by some 25% compared to kerosene aircraft. However, due to the light LH2 maximum take-off weights will go down. As a consequence of the bulky tanks the energy consumption increases as well, resulting in a 25 % increase in DOC as of today for a 1000 nm mission. When LH2 production cost drops to the level of kerosene price, DOC's for LH2 and kerosene fuelled aircraft may reach a crossover point at about 2040.

REFERENCES

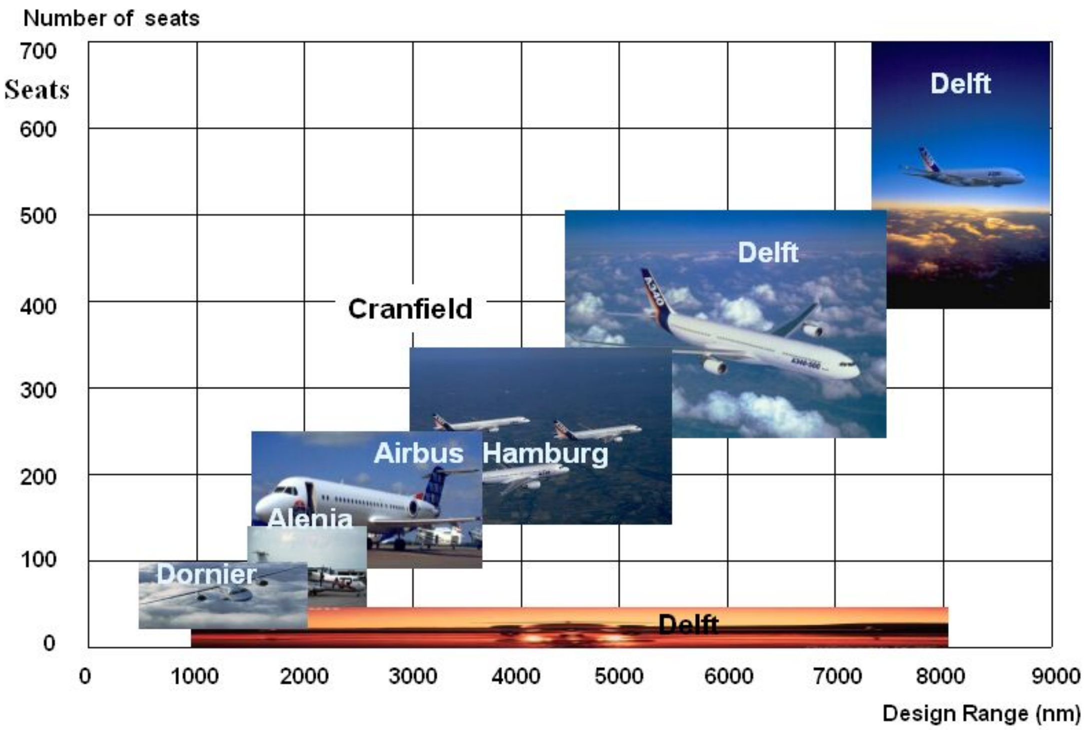
[1] "Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE)", Part B, Proposal No. GRD1-1999-10014. 14th June 1999. 5th Framework Program of the European Communities Contract No. G4RD-CT-2000-00192.

[2] Westenberger, A., "Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE)", Final Technical Report, Revision 1.

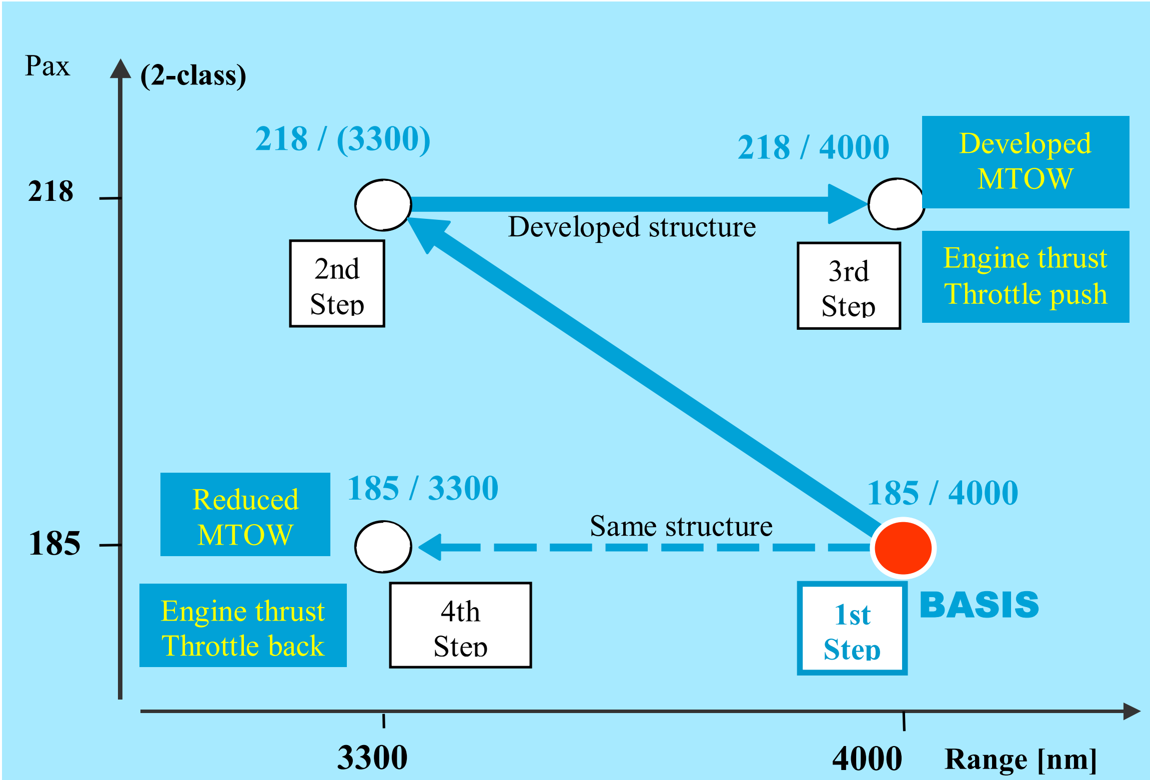
[3] Prenzel, E., "Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE)", TFR2.2.4, Aircraft Configuration - Short/Medium Range Aircraft, Revision 1, 30.09.01.

[4] Slingerland, R., "Liquid Hydrogen Fuelled Aircraft – System Analysis (CRYOPLANE)", WFR2, Aircraft Configuration, Revision 1, 18.o7.02.

Figures

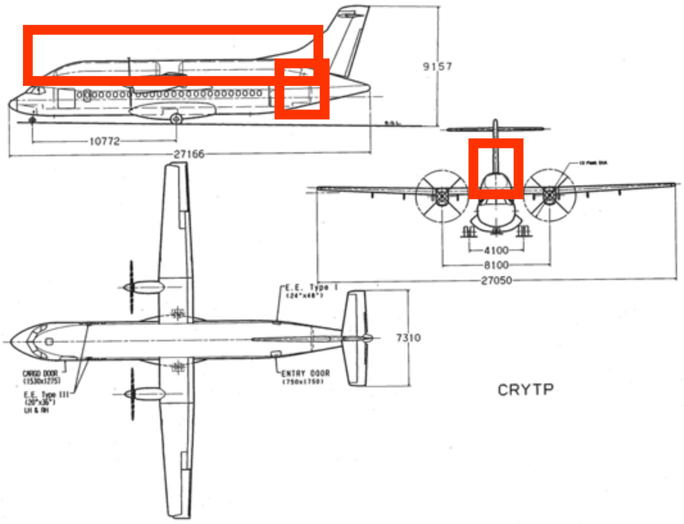


Picture 1: Range of Aircraft Categories, which have been subject of this Project. Dornier, Alenia, Airbus Deutschland, Cranfield and TU Delft have been the partners within this work package)

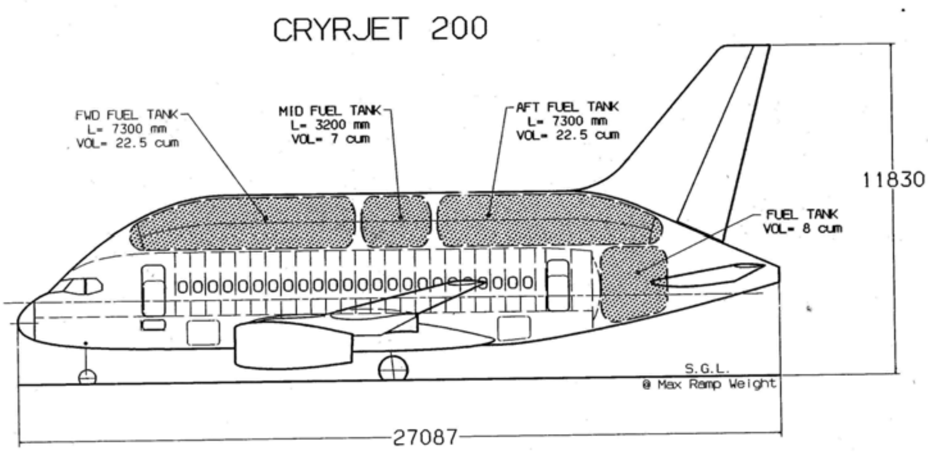


Picture 2: Family Concept for S/M range Aircraft

Picture 3: Small Regional Aircraft.

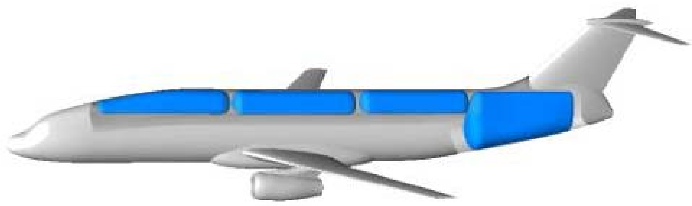


Picture 4: Regional Turboprop Aircraft

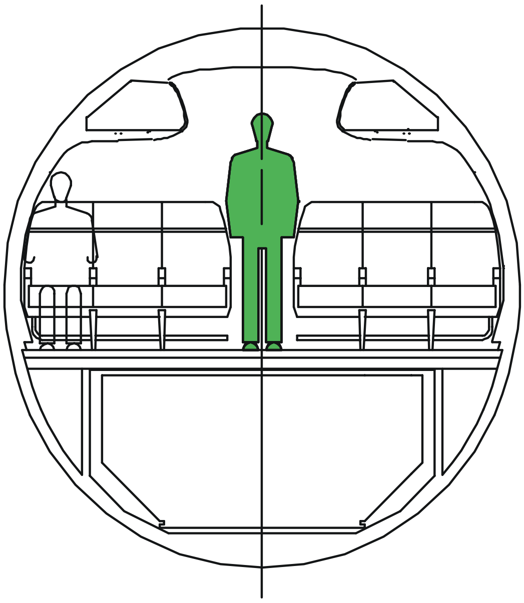


Picture 5: Regional Jet Aircraft

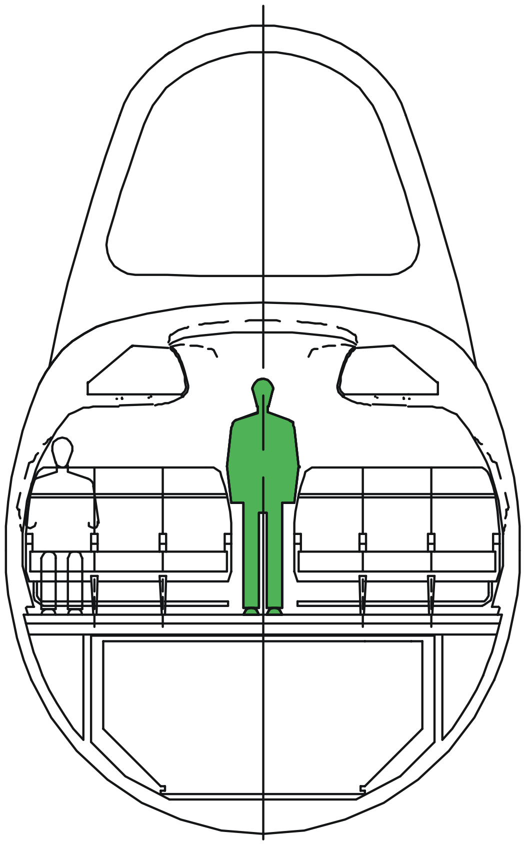
Picture 6: S/M Range A/C First proposal



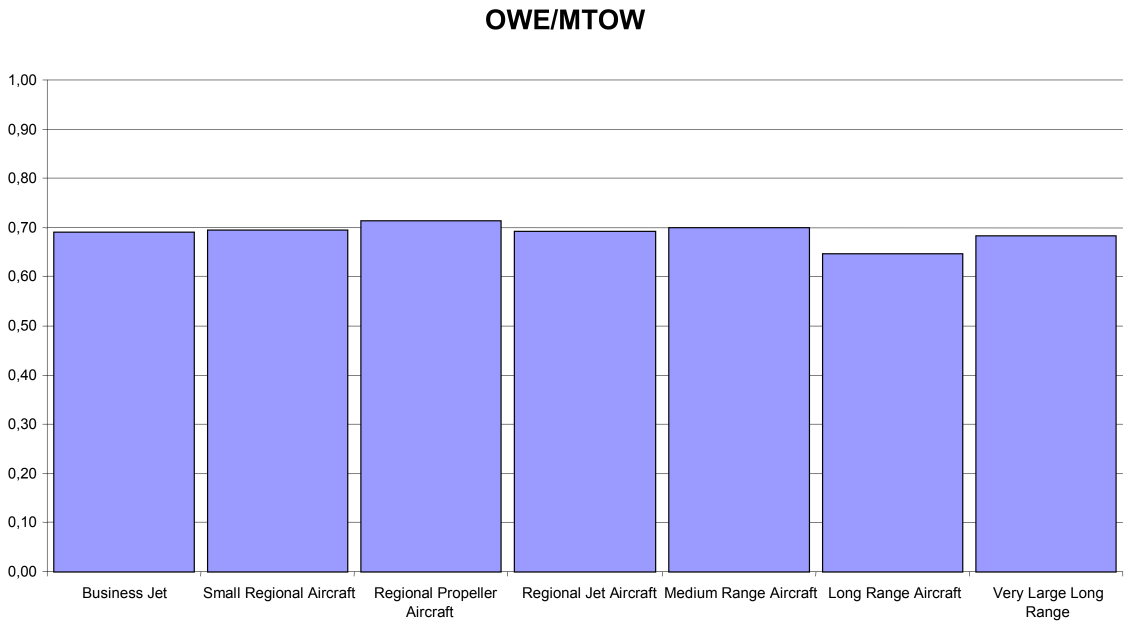
Picture 7: Revised configuration



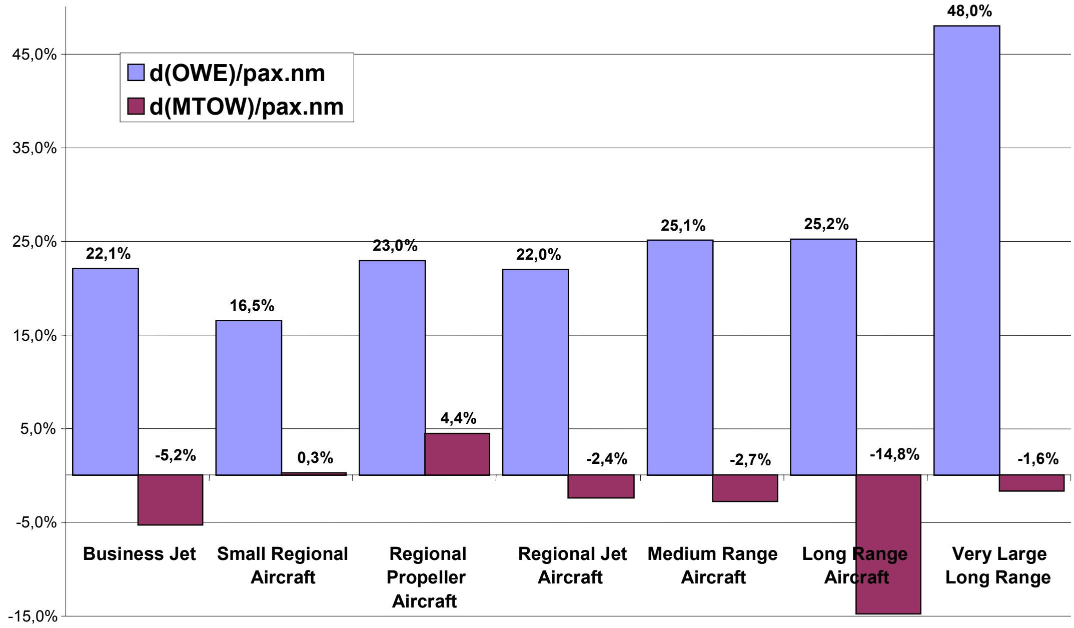
Picture 8: Cross section R-200



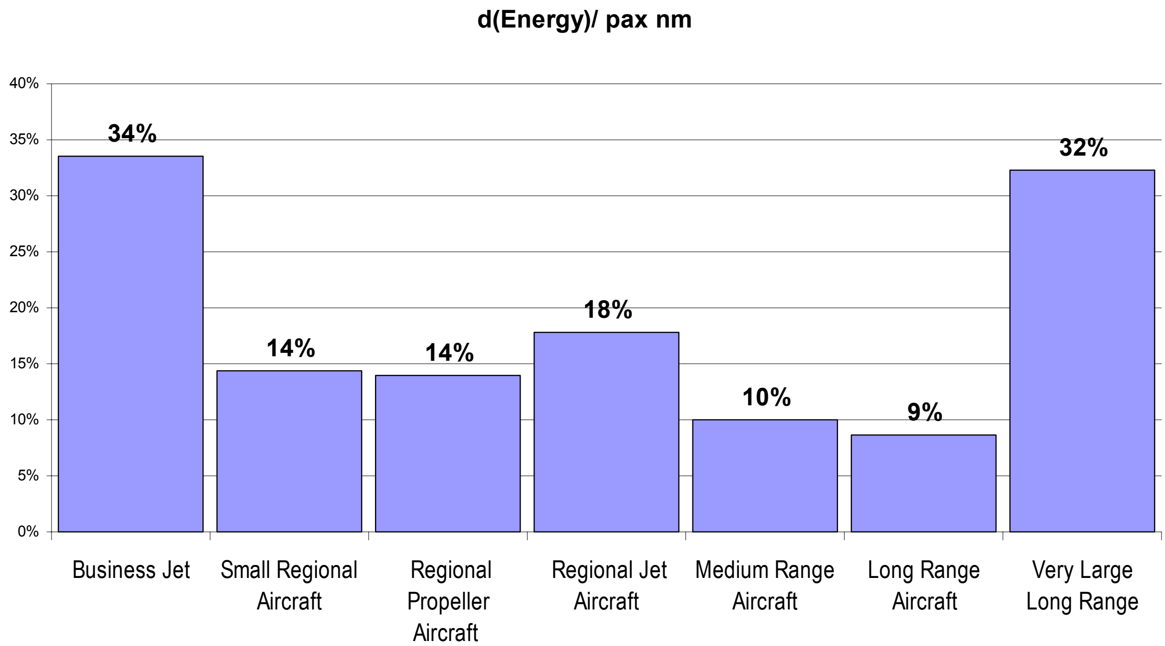
Picture 9: Cross section of RCK(1)-200



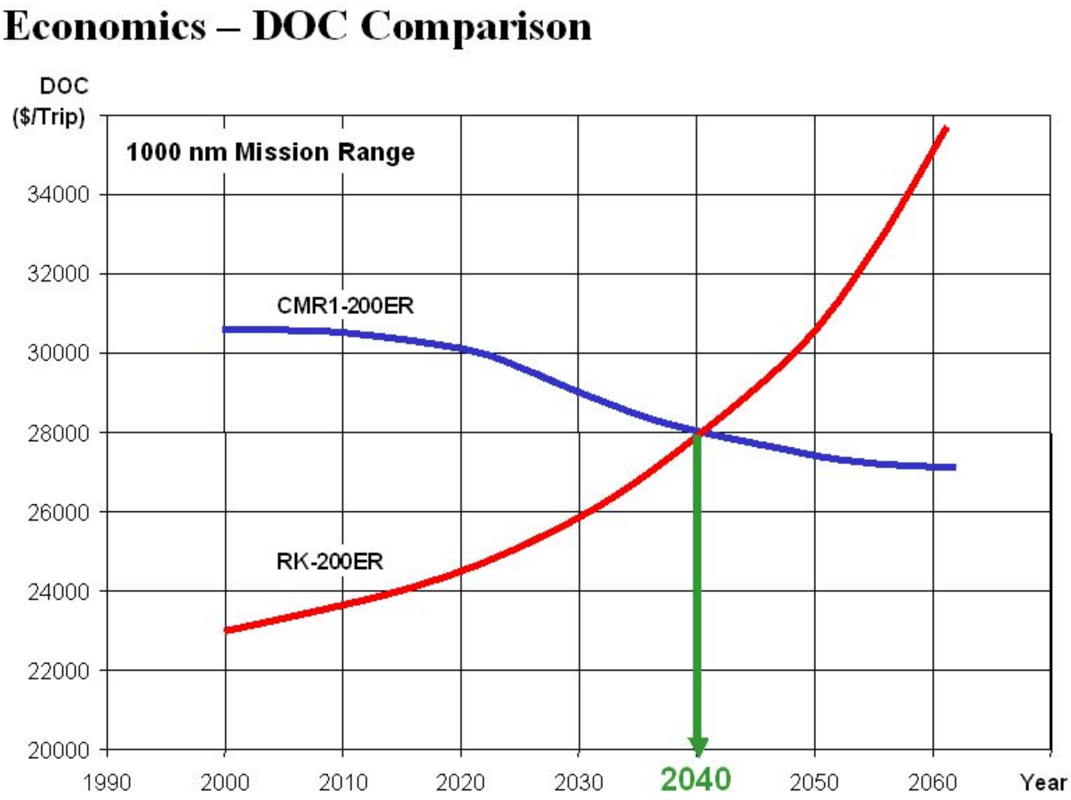
Picture 10: Fraction of OWE/MTOW.



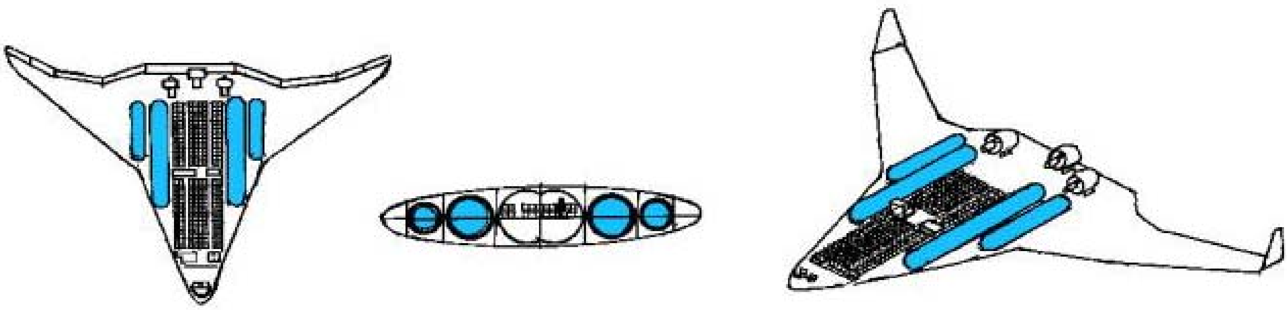
Picture 11: Dependencies between operating weight empty and max. take off weight, when H2 is applied on the Aircraft.



Picture 12: Change of energy consumption for H2 fuelled aircraft.



Picture 13: Calculated beak even point in case of RK-200ER and CMR-200ER



Picture 14: Blended Wing Body