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Developing Certifiable Liquid Hydrogen "Gondola" Airliner, Design Innovations & Challenges

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Abstract

Environmental *considerations* are focusing attention towards using LH2 designs for commercial aircraft. But LH2 has unwanted properties, being cryogenic, low density and potentially explosive near Oxygen. Thus, aircraft designs incorporating LH2 must be innovative, with safety / certification issues being paramount. For LH2 designs, low energy density per unit volume and heavy cryogenic tank requirements incur performance penalties compared to kerosene or SAF powered aircraft. Overall, the flight experience with LH2 is very limited, in particular knowledge gaps exist on safety and hence significant work is required on the technology implementation.

Bearing in mind the LH2 Certification & Crashworthiness Issues, the obvious over-arching constraint is that LH2 containment and pipes etc. must be well separated from the passengers (on ground or in air), with emergency evacuation exits not being obstructed. The aircraft structure should be able to survive engine disc-failure or tail scrapes, and the configuration must respect emergency landing regulations including undercarriage collapse or hitting objects on runway. None of the previously publicised. LH2 airliner configurations appear to satisfy the certification / crashworthiness criteria.

We considers the "**Gondola**" concept representing a medium-range, LH2 powered airliner (160 seats capacity, c.f. A320-Neo). A twin-fuselage layout features one fuselage with passengers and the other with fuel tanks. The clear advantages of the concept in passenger experience, crashworthiness, evacuation, fuel management, ground handling are considered including CFD simulations and load computations including further optimisation and balance of the wing planform.

1. Introduction

The awakening of the world to environmental concerns is focusing attention towards using alternate fuels for commercial aircraft. Wright Brothers demonstrated flight 120 years ago and since then, the fuel used has been primarily Kerosene. Environmental and fuel sustainability concerns surfaced about 20 years back and there is just about a quarter of century left to advance technologies towards bringing in reliable aviation using alternative fuels, possibly LH2. Although LH2 combustion is carbon-free, it has low energy density per unit volume and heavy cryogenic tank requirements that incur performance penalties c.f. conventional Kerosene-powered aircraft. LH2 is potentially explosive near Oxygen.

Figure 1 : Aviation Scene to 2050's

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In [1-2], we presented the background early work / philosophy on arriving at the novel **Gondola** configuration. The purpose of this paper is two-fold: (1) to reach out to a wider audience in Europe, reviewing the main features, and (2) to present recent developments in light of the inferences and recommendations from [3]. This helps in advancing the knowledge base on the novel configurations.

1.1 Our Vision for Transportation

Allowing for environmental concerns, the aviation vision for future must alter. Based on [4-5], we propose:

Very short ranges :	Battery Power
Short Ranges :	Battery . Hybrid / Fuel Cells :
To about 400 nm :	Rail travel, Electric Vehicles
To about 2000 – 3000 nm :	LH2
Beyond 3000 nm	SAF
	SAF + Utilize Air to Air Refuelling for long ranges
	SAF +Wake Surfing / Formation Flying

1.2 Using LH2

The properties of using Hydrogen as a fuel are mentioned in **Appendix A1**.

On equal energy basis, cryogenic (-253^0 C) LH2 is 2.8 times lighter than kerosene. However, being less dense, it requires 4.1 times more volume space than kerosene. This brings in the design issue of incorporating / accommodating safe insulated tanking arrangements in aircraft design [3]. There is particular concern about the highly explosive nature of LH2 in contact with oxygen in air.

It follows that aircraft designs incorporating LH2 must be innovative, with safety and certification issues being paramount. For LH2 designs, low energy density / unit volume and heavy cryogenic tank requirements incur performance penalties compared with kerosene or SAF powered aircraft.

2. Previous Flight Experience & Certification Aspects

Overall, the flight experience with LH2 is very limited.

2.1 NACA & Russian Experience

NACA in mid-1950s successfully tested a Martin B-57 Canberra, **Figure 2**. LH2 tank at one wing tip supplied just one engine [6-8]. The aircraft operated normally (using JP4) in climb. The transition to LH2 occurred at cruise altitude. The system needed gaseous Helium to avoid any O2 contamination possibility.

In Russia, TU-155, **Figure 3**, [9] flew successfully with LH2 – just 3 flights. However, the programme was diverted towards using liquid natural gas, prior to project cancellation.

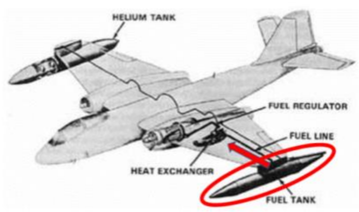

Figure 2 Martin B-57 Canberra, USA LH2 trials, 1955

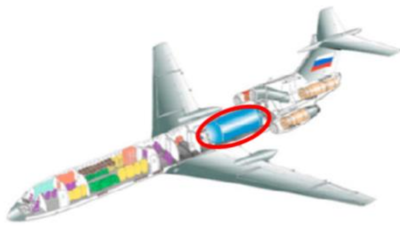

Figure 3 TU-155, Civilian LH2 Trials, 1988 (short period) (3 Flights), converted to Natural Gas usage

Knowledge gaps exist on ensuring safety on ground or in air. Whilst LH2 can be an environmentally friendly fuel option, from a mass market perspective, significant work will be required on the technology implementation.

2.2 Certification Viewpoint.

Spencer's paper [3] has listed several certification and crashworthiness issues as well as constraints that need to be complied with in design of any future LH2 aircraft.

Liquid hydrogen fuel is chosen as a high energy fuel in its highest density form although it still has a low density compared with kerosene. The temperature of the fuel is kept at -253^o C and contact with air could contaminate the

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fuel with solidified nitrogen and oxygen and any other trace elements in the atmosphere. The fuel tanks must be sealed from the atmosphere (no air vents allowed) and pressurised to prevent in-flow. A leak from the fuel tank could cause a cryogenic spill, rapid boiling of the fuel and potentially combining with the atmospheric oxygen to produce an explosive mixture. Thus consideration of crash-worthiness including emergency evacuation must be a major feature of the certification process.

The obvious over-arching constraint is that LH2 containment and pipes etc. must be kept well separated from the passengers on ground and in air. Passenger safety exits must not be obstructed. Also, the structure should survive engine turbine disc-failure which could cause a fuel tank rupture and an ignition source.

The configuration must respect emergency landing regulations: undercarriage collapse or hitting objects on runway. The configuration must survive tail scrapes.

Ground handling procedures must be adhered to ensure quick turnaround and in synergy with the Airport codes of practice e.g. for baggage handling, loading and unloading and most importantly for refuelling on ground.

2.3 Publicised Concepts

NASA and European research projects have yielded several concepts [10-13], as illustrated in **Figure 4**.

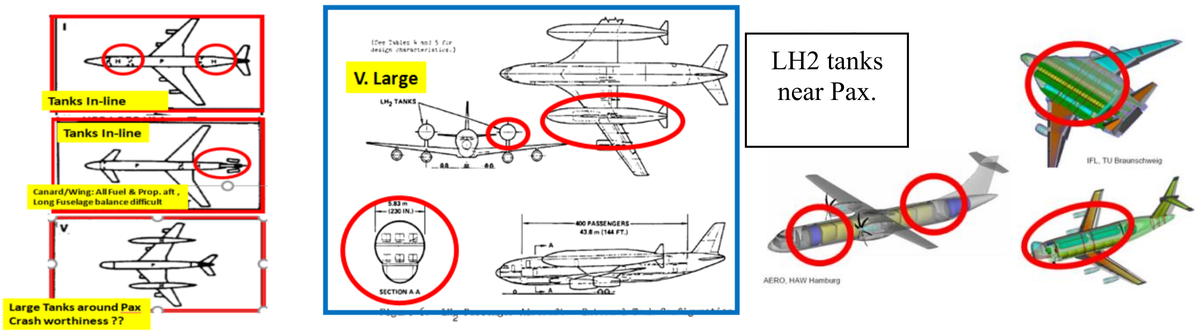
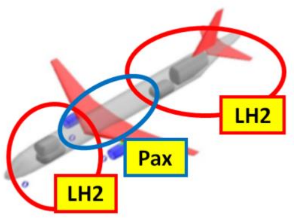


Figure 4: NASA (Brewer) & European LH2 (Cryoplane, HAW, TU Braunschweig) Projects

Some of the configurations have a central payload fuselage containing a LH2 tank, (e.g. Cryoplane [12] with tanks above the passenger cabin) or else a central fuselage and a pair of large LH2 tanks on the wings. The LH2 feed pipes run through passenger cabin.

2.4 Recent Concepts



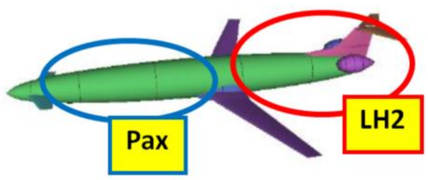


Figure 5 – LH2 Layout proposed, Scholz [11]   Figure 6 – Layout derived from outlines of [13-14]

The concept of **Figure 5** has forward and aft LH2 tanks enclosing the passenger cabin in a long fuselage. The engines remain on the wing. The concepts from [13-14] place the tanks and propulsion at the rear, requiring a lengthened forward cabin fuselage. Such concepts do not meet the certification criteria: crashworthiness. emergency access of passengers. Tank locations ahead, above, alongside or behind cabin are not safe and too near to passengers. There are significant issues in maintaining a safe static margin with respect to CG position for all practical cases of fuel or passenger loadings.

3. Need for Radical / Unusual

Bear in mind the Certification and Crashworthiness (C&C) considerations. The primary one is that LH2 containment and pipes etc. must be well always separated from the passengers and crew. Further related issues arise:

- the evacuation exits must not be obstructed
- the aircraft structure should be able to survive engine disc-failure or tail scrapes
- the configuration must respect emergency landing regulations including undercarriage collapse or hitting objects on the runway.

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A certifiable passenger LH2 aircraft will look quite different from a conventional jet fuel aircraft. With modern technologies, there is confidence in developing an unusual innovative LH2 aircraft that broadly matches the A320 in payload capacity and performance.

The “**Gondola**” concept is a twin fuselage configuration. It places the fuel in two separate tanks in the starboard fuselage and the passengers and crew in the port fuselage. The two power-plants are mounted on the centre-section wing. Thus, the fuel tankage and the fuel lines to the power-plants are isolated from the passenger accommodation.

The two fuselages are of different lengths. The port passenger fuselage is longer which gives the pilots a better lateral view from the cockpit. Loading of passengers by stairs or loading bridge is on the port side and baggage loading on the starboard side of the passenger fuselage. Emergency exits would use the four door exits as well as two over-wing exits.

The starboard fuel tank fuselage has a similar diameter to the passenger fuselage but is designed to be detachable so that the fuel tanks can be exchanged for pre-fuelled tanks on the loading apron. To simplify the exchange, the tailplane and fin are mounted on the passenger fuselage only.

There is no CS-25 requirement for an aircraft to be laterally symmetric. From a short literature survey, there are many examples of unusual aircraft developed for special purposes, **Figure 7**. Asymmetric flight has been well demonstrated and it is feasible with twin fuselages. For equal capacity, a twin fuselage aircraft reduces the maximum wing bending moment by about 57% [9], **Figure 8**. This feature can be exploited in **Gondola** design.

An important advantage [9] for the twin is that by virtue of reduced bending moments, high aspect ratios can be used. That implies negating the extra drag of the second fuselage and a more efficient (high L/D) aircraft results.

The certification requirement of LH2 separation from passengers led to seeking inspiration from the unusual radical concepts that have emerged from time-to-time in the rich history of aviation. As illustrated in **Figure 7**.

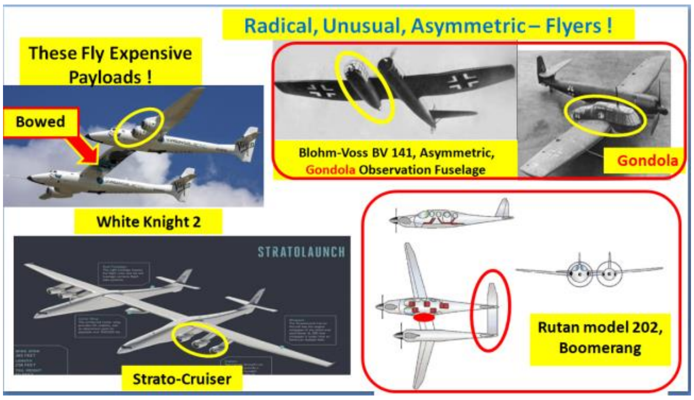

Figure 7: Unusual, Radical Concepts

Of practical interest are multi-fuselage layouts. Houbolt [15], Jenkinson et al [16] and Torenbeek [9] demonstrated that bending moments reduce in twin-fuselage aircraft, **Figure 7**. This compensates for the LH2 fuelled aircraft having a circular section fuel tank concentrated at part span rather than a wing-box fuel tank as in a conventional kerosene powered aircraft that gives a better distribution of relieving bending moment. This implies that higher aspect ratios wings can be incorporated. In LH2 configurations context, the extra profile drag of the second fuselage is offset by the reduced lift dependent drag and a more efficient (high L/D) aircraft results.

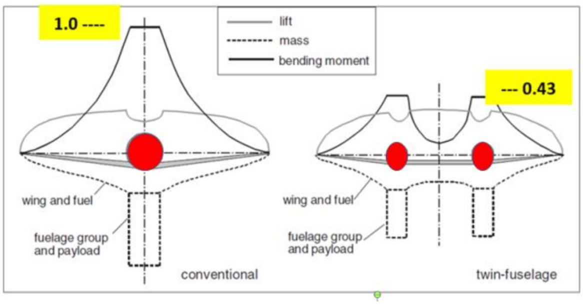

Figure 8: Comparing Single- & Twin-Fuselage Layouts, Spanwise lift, Mass & Bending moment
Interpret: 57% reduction in Wing Root Bending Moment for the Twin – Same Total Payload & Span

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The higher aspect ratios offer the opportunity for application of folding wing tips research ideas [15,16] which enable improved aerodynamic performance via reduced induced drag and minimal increase in loads (and hence weight) due to turbulence and manoeuvres, whilst also enabling airport gate limits to be met.

4. Proposed LH2 Layout

After a series of configuration studies / deliberations [1-2], the following layout emerged and forms the basis for further development.

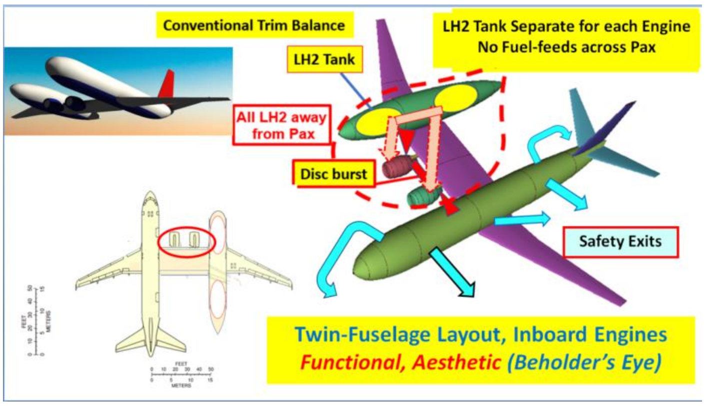

Figure 8: Twin-Fuselage "Gondola" Layout using LH2, Central Engines

Engines with assumed propulsive efficiency of 35% are over the inboard wing panel (total wingspan about 50m). This arrangement fits better in ICAO Type D loading bay (span limit 52m). All fuel and propulsion systems are completely separated from the passenger areas on ground or in air. The fuel fuselage "Gondola" and wing structure act as secondary barriers. This facilitates the application of ignition prevention within these areas and Lower Flammability Level avoidance measures e.g. ventilation. The "Gondola" offers the possibility of designing for deflagration as opposed to detonation of accumulated hydrogen. The dedicated LH2 housing structure lends itself to be crushable structure to protect the LH2 tanks in crash.

The fuel fuselage holds two removable LH2 tanks (one for each power-plant) ahead and behind the centre-section wing box. The part of the fuselage above the wing box does not contain fuel as it lies in the debris zone from an engine turbine disc failure. The two fuel tanks can each be disconnected from the fuselage and be exchanged for refuelled ones. This speeds up the turn-around and dangerous refuelling process is kept away from the loading bay.

The passenger fuselage on the port side has similar access to passenger door and galley servicing as a conventional A320. Baggage bay access is slightly constrained by working between the two fuselages and a special baggage loading ramp may be required.

The dry wing structure should lead to design innovation – may be part-filled with fire-retardant material. Asymmetry allows a degree of freedom in planform design and wing twist etc.

The empennage is on the main fuselage. Its design will require optimising for size and control parameters to off-set the asymmetry and engine failure case. Trim ailerons will balance the aircraft as fuel is used up during flight. Any cross-couplings between longitudinal and lateral responses and motions will imply a fly-by-wire (FBW) solution.

The main landing gear, pivoted on the inner side of the fuselage will retract sideways into the fuselages. The nose wheel is just behind the cockpit on the inner side of the main fuselage and retracts sideways into the belly. The landing gear needs a track of about 9-10m. This may depend on the separation of the fuselages and a wider track may be more appropriate i.e. in the same ballpark as for the larger aircraft. Careful application of wheel and tyre failure models would be needed to ensure that the LH2 tank and fuel systems are not at risk.

We can utilise the folding wing tips technology to fit in the smaller airport loading C type bays (< 36m). Besides the folding tips on the Boeing 777, there is recent Airbus and Bristol University research work with active folding tips [17-18]. Such features lead to a good overall cruise L/D comparable with that for an equivalent single fuselage type.

The cockpit being located ahead of the fuel tank fuselage allows a good all-round view. A remote camera will help for the starboard outer wing.

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The configuration would require an analysis of ditching qualities. Rapid passenger emergency egress would have to consider possible cryogenic and asphyxiation hazards in addition to fire, particularly from the starboard over-wing exits on the port fuselage.

As a footnote, history shows that disruptive propulsive technology drives diverse and evolving airframe technology. Ultimately the optimum airframe configuration emerges, and the once disruptive propulsion technology becomes the refined norm. One may anticipate the same for LH2 aircraft!

5. Analyses

Limited analyses on this configuration are presented in earlier papers [1-2]. Here we pick up on weight and bending moments from the point of view of structure development.

5.1 Weights & Bending Moments

The weight estimates suggest a component breakdown for the twin cf A320 class as depicted in **Figure 9**.

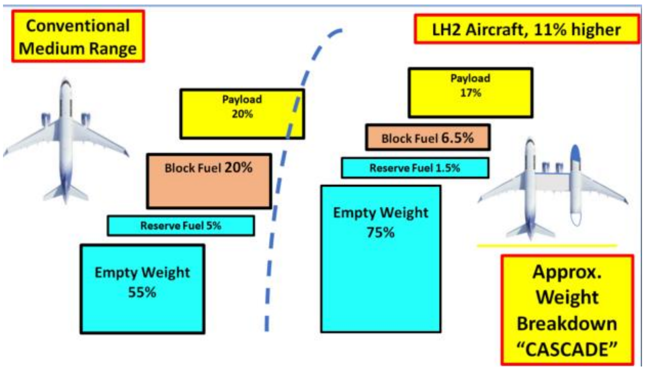
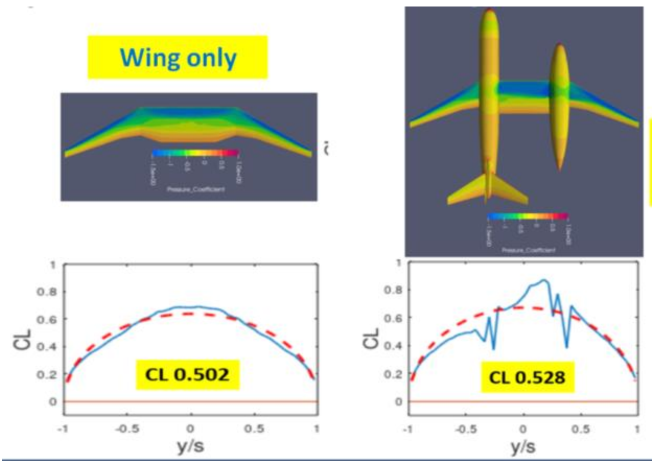


Figure 9: Preliminary Weight Breakdown Cascade, Comparing with a Conventional (Kerosene - JP4) Aircraft

Interesting figures emerge:

- MTOW of the LH2 aircraft is about 14% higher than that for an equivalent conventional fuel aircraft (e.g. A320) (9% higher than A320Neo)
- The empty weight ratio of the LH2 aircraft is some 20% higher than OEW of the (37% more than A320Neo) A notable implication is that landing weight of LH2 aircraft is about 93% of MTOW cf. A320 about 80%).

Figures 10-11 show the span-wise lift, drag loadings and Bending Moment distributions to help with Aeroelastic analysis. Note that the twin with span of about 50 m has similar maximum bending moment as that for A320. This is in line with previous work on twin fuselage configurations.



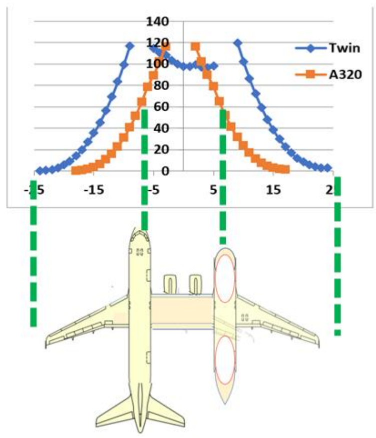


Figure.10: Aerodynamic Spanwise Lift Loadings **Figure 11: Bending Moment Distribution along Wing-span**

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5.2 Planform, Asymmetry & Engine Location Variations

Following on from the disc-burst arguments, a *matrix* of 6 layouts has been explored. The variations include 10° inner wing sweep and changes in engine locations. The fuel tanks are slightly smaller with assumption of futuristic 41% propulsive efficiency as used in work of ATI-FlyZero project [19].

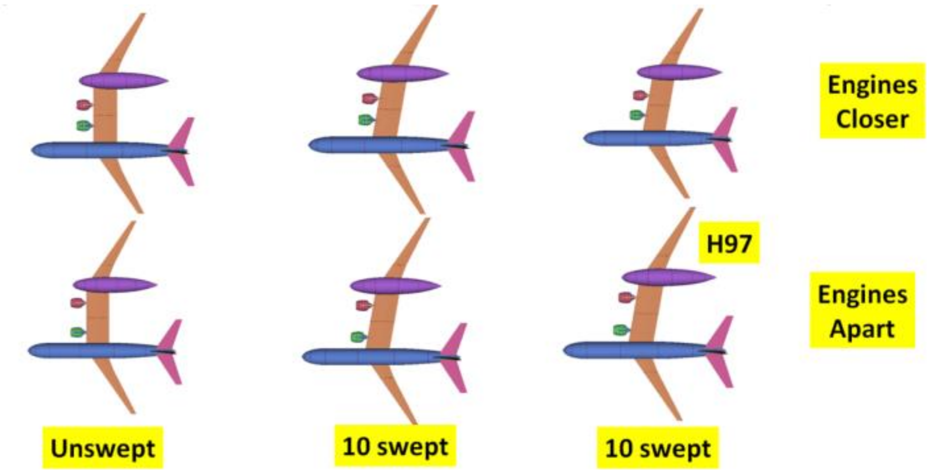

Figure 12: Configuration Matrix Exploring Propulsion Locations & Asymmetry Aspects

For the particular H97 labelled layout, chordwise Cp distributions and spanwise loadings are shown in **Figure 13**. These give an air of respectability and suggest that an optimum aerodynamic design should be achievable without undue difficulties.

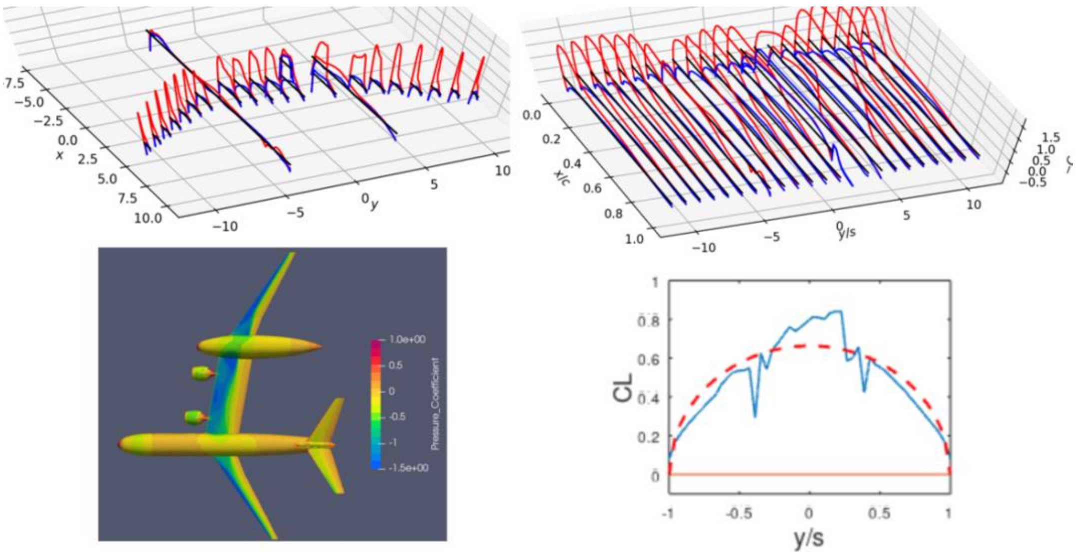

Figure 13: Config. H97, Mach 0.75, CL=0.528, Chordwise Cp distributions and spanwise Loadings

Further detailed work on this aspect can be accomplished in due course.

5.3 Asymmetry Considerations, Sideslip

This becomes an important aspect to quantify.

Figure 14 shows the effect of sideslip variation (-4°, 0°, 4°) at Mach 0.75. The differences in body shapes and izes introduce yawing and rolling moment differences.

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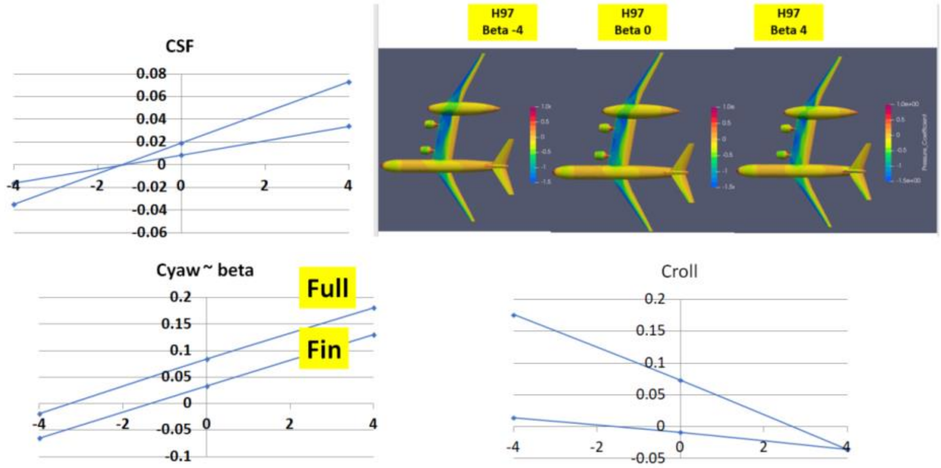

Figure 14: Asymmetry Considerations & Component Contributions

Often, on single engine propeller aircraft, to reduce the torque and yaw effects, an idea has been to introduce small off-set of the vertical stabilizer. This idea finds an application here. **Figure 15** shows an example of how the fin produces positive yawing moment to cancel the "natural" asymmetry yawing moment of the twin layout. The rolling moment balance can be achieved with wing twist and aileron deflections. This aspect will be subject of future studies.

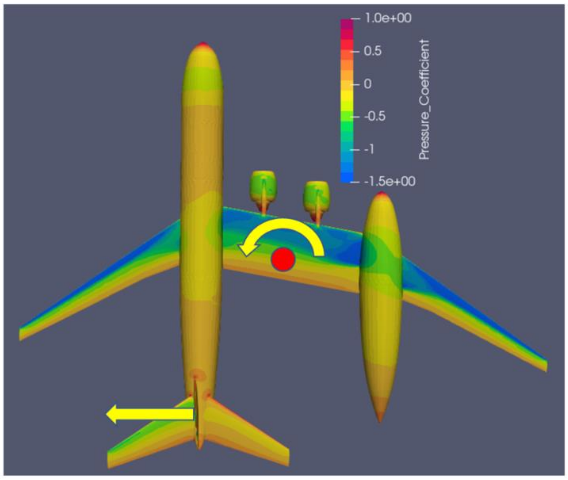

Figure 15: Cancellation of Yawing moment with Fin off-set

6. Efficiency Metrics Extended for LH2 aircraft

In previous papers [4, 20], we have described the derivation of "near-universal" non-dimensional Efficiency metrics, that condense the weight information of passenger jet (civil) airliners. The metrics e.g., PRE/X vs R/X allow prediction of future aircraft performance, **Figure 16**.

Because of reduced weight/energy (bulky) properties of LH2 (cf conventional Kerosene), the LH2 trend remains lower. The peak of PRE/X may not be as good as that for Kerosene aircraft. Further work is needed to establish such trends in greater detail.

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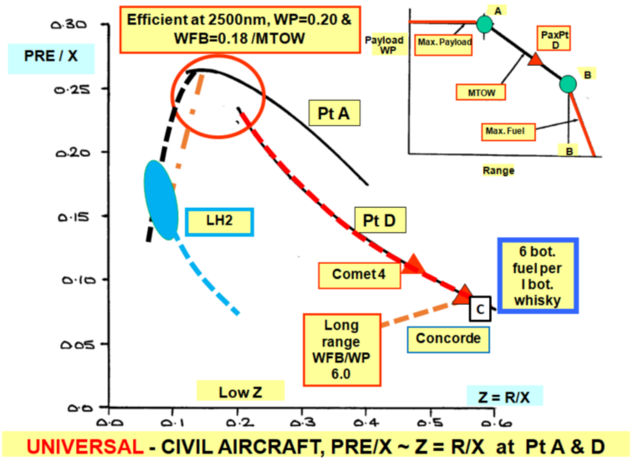

Figure 16: Non-Dimensional Efficiency Metrics

7. Future Tasks

Figure 17 shows that ideas of this paper could be adapted towards smaller A220 version. In the longer term, we can build up on Dr RT Jones legacy, using oblique wings with twin fuselages [21]. The empennage will be different.

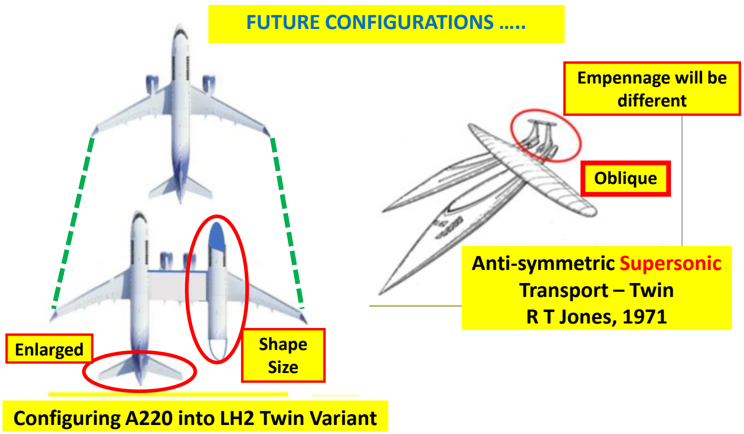

Figure 17: Future Tasks, Transonic & Supersonics

8. Major Inferences & Conclusions

Liquid hydrogen fuel is a highly energetic, low-density fuel that can be burnt in modified turbofan engines. However, if mishandled, the fuel can be very dangerous due to its cryogenic and explosive properties. To achieve a safe and certifiable passenger airliner, several design features are introduced in the twin-fuselage “**Gondola**”.

LH2 Containment

- The fuel tanks are isolated from the passengers in the twin fuselage layout. The fuel tanks are in the starboard fuselage and the payload is in the port fuselage. This reduces the risk to passengers from fire and fuel spillage.
- Each tank supplies one engine, to reduce the risk of fuel contamination and all-engines failure.
- The fuel tanks are sealed and pressurised to prevent the ingress of “contaminants” such as air that would freeze solid at cryogenic temperatures. The nose cap of the tank fuselage has a crushable structure to absorb bird strikes and a heater mat for de-icing on ground or in air.
- The fuel tanks can be detached from the airframe to enable refuelling at a specialized facility away from the apron. This enables a swift turn-around, reduces the risk of spillage and permits the tanks to be replaced (structural life may be low).
- The tanks have a thick layer of heat insulation including a double wall structure. The tanks have a large diameter and short length to reduce surface area and heat gains.

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- Some loss of hydrogen will eventually occur due to boil-off. Procedures should be stipulated for safe venting.

Configuration

- Ground access and loading are like the A320. The port fuselage is same as that for the A320. The aircraft meets ICAO ground handling requirements.
- Landing Weights are 5 to 10% lower than Take-off Weight; refined high-lift system needed.
- The fuel tank fuselage increases profile drag but the larger wingspan balances this by reducing lift dependent drag. Overall cruise L/D is of the same order as for the A320.
- The longitudinal variation of the aircraft CG, due to payload and fuel variations, is similar to that for A320. However, the lateral CG variation is more significant and requires trimming ailerons for lateral balance.
- Future development could take the form of a longer passenger fuselage (greater payload) or longer fuel tanks (greater range). Overall, very long range LH2 aircraft is more difficult.

General

In view of political / public urgency being placed, there is an interesting quote from Feynman [22]: "*For a successful technology, reality must take precedence over public relations, for nature cannot be fooled".*

In terms of Aviation and environment concerns, we can't stand still. In this paper, we have presented a work programme on certifiable LH2 aircraft: **Gondola**. Let us team up to continue developing this with proper International cooperation and backing.

Appendix A1 Some Facts & Figures about Hydrogen as Fuel

A1.1 Gaseous & Liquid Hydrogen compared with Kerosene (JP4)

Gaseous hydrogen (GH2) at ambient conditions is a clean burning fuel but it has very low density and requires a large volume (bulky) to store a useful amount of energy. For usage in aircraft, the bulky implications imply increasing drag. So properties of Liquid Hydrogen (LH2) must be considered.

	JP4	LH2	GH2	Ratio LH2/JP4	Ratio JP4/LH2
Specific Energy MJ/kg	43	120	120	2.8	0.358
Density kg /m3	808	71	42	0.088	11.4
Energy Density GJ/m3	34.7	8.5	5	0.25	4.1
Storage Temp	ambient	-253° C			
Storage Pressure, bar	?	1.5-2			

A1.2 Alternatives Fuels & Realistic Power Assessments

Battery electric –	Max 400kW (RR Spirit of Innovation aircraft)
GH2 Electric –	600kW (Daily Telegraph 20-1-2019, 19 pax, 300 miles)
LH2 Electric –	> 1 MW (many challenges)
LH2 Turbojet –	2MW (estimated) B57 (test flights in cruise 1957)*
Hybrid Electric Fan -	2MW ambition E-FanX demonstrator (project cancelled)
Kerosene Turbofan –	9MW (Single Aisle bench mark)
LH2 Turbofan –	9MW (feasible with caveats e.g. ignition & contrails)

Note:

1 hp is the work done at rate of 550 $ftlbfs^{-1}$, 550 fts^{-1} = 375 mph, Power (hp) = Thrust (lbf) x speed (mph)/375 mph. 1 hp = 745.7 W @375 mph

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