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ARRIVING AT CERTIFIABLE NOVEL AIRLINER USING LIQUID HYDROGEN & EFFICIENCY METRICS

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Abstract

Environmental considerations are focusing attention on exhaust emissions from commercial aircraft and their effect on climate change. In the short term, Synthetic Aviation Fuel (SAF) is being increasingly used. This reduces carbon emissions, a little. For future, the use of liquid hydrogen (LH2) is "promising". However, LH2 has many undesirable characteristics, being cryogenic, low density and potentially explosive near Oxygen. Thus, aircraft design is dominated by the safety and certification issues.

We describe the design of a medium range, LH2 powered airliner of about 160 seats capacity (comparable with Airbus A320 Neo or Boeing 737-8). A few previously publicised configurations are discussed but the preferred one ('Gondola') is a novel twin-fuselage layout with passengers in one fuselage and fuel tanks in the other. This concept has clear advantages in passenger experience, crashworthiness, evacuation, fuel management and ground handling. Additionally, we show Efficiency metrics for LH2 aircraft comparing with Conventional Aircraft. These allow us to predict newer designs with different payload / range specification.

1. Introduction

The high energy content of liquid jet fuel in terms of mass (specific energy) and volume (energy density), has made it a time-honoured choice. Now, Environmental considerations are focusing attention on aircraft with low (or zero) carbon emissions.

In the short term, bio-fuels and / or Synthetic Aviation Fuels (SAF) are being used for moderate and long ranges in conventional aircraft. This will reduce emissions without sacrificing aircraft performance. For long ranges, we can bring in Air to Air Refuelling [1]. Additionally Wake surfing or Formation flying [2] can be exploited for all ranges although it will be more practical for moderate to long ranges. But using SAF emits carbon dioxide and costs remain high.

We can imagine electric batteries as a power source, but they are severely limited at present by the low specific energy capacity per unit weight of battery.

Currently there is growing interest towards Liquid Hydrogen (LH2) powered civil aircraft. Propulsion at a lower risk is perceived by using LH2 turbofan engine. The alternative is to use hydrogen / oxygen fuel-cells, but these are relatively immature in design and service experience, and require high voltage electrical transmission, DC to AC rectification, electric motors and fans / propellers. All these items reduce the overall efficiency of the energy conversion.

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.

2. Previous Experimental Aircraft using LH2 Turbofans

In the mid-1950s, during the US high altitude (reconnaissance-led) research programme, NACA successfully flight-tested a Martin B-57 Canberra, **Fig.1**, equipped with a liquid hydrogen tip-tank supplying one engine of the twin-engine layout [3-5]. The aircraft operated normally in climb, the transition from JP-4 to LH2 occurred at cruise altitude. Gaseous Helium was used in the system to avoid any chance of O2 contamination.

In Russia, TU-155 (modified TU-154), **Fig.2**, was operated as a test bed for alternative fuels [6]. In the civilian context this was the first to use LH2. This aircraft flew in 1988 and made a few successful flights. However, the programme was diverted toward using liquid natural gas [5], prior to project cancellation.

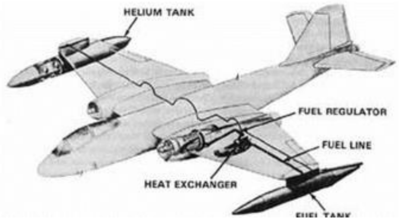

Figure 1 – Martin B-57 Canberra, USA, LH2 trials 1955

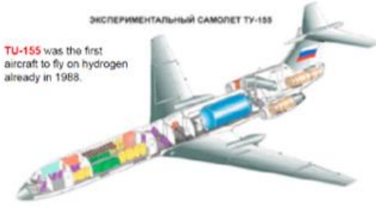

Figure 2 - TU155, LH2 trials, 1988

Overall, the flight experience with LH2 as a source of propulsive power is very limited and there are many knowledge gaps on safety. Whilst LH2 can be a safe, environmentally friendly fuel option, significant work is required on the technology implementation from a mass market perspective.

From Certification viewpoint there are several issues to consider [7]. First a few basics.

3. Hydrogen Properties & Considerations for Use in Aircraft, Tanking

Gaseous hydrogen (GH2) at ambient temperature is a clean burning fuel but has very low density and requires a large volume to store a useful amount of energy and thereby increases aircraft drag.

	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

The attraction of using LH2 is that on equal energy basis, it is 2.8 times lighter than kerosene. However, it requires 4.1 times more volume space than kerosene - far too large to fit inside traditional wing tanks.

LH2 is denser but needs to be stored at a cryogenic temperature of -253^{o} C in heavily insulated dual-lined tanks. Continuous energy is required to store LH2 without boil-off losses. However, we consider a margin of about 7% of fuel volume to allow for boil-off.

Powered devices such as cryo-coolers are probably not needed. In general, the tank is partially filled with cryogenic LH2 liquid with the void above the fluid occupied by low temperature gas at moderate pressure to minimize boil-off. A typical design case could be an overnight stay at a hot airport (say Dubai). In this case, Ground Support Equipment would be needed to keep the fuel cold and capture any vented hydrogen.

Cryogenic temperatures will cause any contaminants such as air or water vapour to freeze solid and possibly block the fuel pipes and filters. To prevent this, the fuel system should be sealed and pressurized at 1.5 to 2 bar to counter ingress of contaminants, as opposed to the vented tanks used for conventional kerosene fuel which allow the ingress of humid air. This might also permit utilizing the super-critical phase in parts of the fuel system as a measure against boil-off. Some boil-off of LH2 is however unavoidable.

The thick insulated walls of LH2 tanks and the internal pressurization leads to “bulbous”, near-spherical shapes rather than the “flat” wing-box tanks used in conventional aircraft. The optimum shape of a cryogenic tank should have a low ratio of surface area to volume for good insulation and low structural weight, which implies a near-spherical shape.

As fuel is burnt off, the empty space in the tanks (ullage space) should be filled with pressurized Cold gaseous H2. An extra precaution against fuel contamination is to have a separate fuel tank allocated to each engine, thus avoiding a common mode failure such as fuel starvation affecting all engines.

Handling LH2l is hazardous; contact with skin and air must be absolutely avoided. Prolonged storage of cryogenic fuel will lead to fuel loss (boil-off). Provision is needed for the fuel tanks to be separated from the airframe for refuelling off the apron or even off the airport site. Spillages and leakages should not occur near the aircraft. A mix of H2 and O2 leads to unpredictable explosive behaviour.

Tank structural materials may suffer from brittle fracture. Material flaws such as micro-cracks can grow rapidly. Material life is probably less than non-cryogenic parts of the structure and may require frequent replacement. Cryogenic tanks should be designed for easy removal from the airframe. Frost on the outside of the tank is an aerodynamic hazard and may need ground de-icing even when non-cryogenic parts of the airframe are frost-free.

LH2 is Highly flammable (15 times more than JP4 in terms of energy or upsets or sparks!).

4. LH2 Storage Aboard Aircraft – Weights & Previous Configurations

For performance predictions, we need an idea of the system weight required for LH2 usage. In absence of a rigorous approach, we have some starting guidelines based on Space Launch vehicles from [8].

	LH2(kg)	Fuel System Ratio FSR
Shuttle on-board LH2 storage	100	0.25
Ariane fuel tank (LH2)	28,000	0.84
Shuttle external tank (LH2)	230,000	0.83

Notice the differences between the on-board and external tanks. The idea will be to minimize the FSR values and R & D is being conducted at institutes around the World e.g. on an all-composite cryogenic 14 ft fuel tank at NASA Marshall Space Flight Centre. It will be interesting to know the weight parameters.

FSR values used in [8] and [9] are as follows.

	FSR	Fuel kg	Fuel system kg	Total kg	Range km
Ref. 8	4	1190	4750	5940	1220
Ref. 8	1.85	1190	2200	3390	1420
Ref. 9	0.381	6667	2531	9198	near 2000

There is wide disparity here. Scholz's [8] value of 0.381 seems very optimistic.

5. Certification Issues & Recommendations

Spencer [7] paper has listed several certification and crashworthiness issues as well as constraints that need to be complied with in design of any future LH2 aircraft.

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 disc-failure.

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 eg. for baggage handling, loading and unloading and most importantly for refuelling on ground.

6. Previous Proposed Layouts & Certification, Crash-Worthiness Issues

Interest in LH2 aircraft is noted from work by Brewer [11], Scholz [9], Airbus [12] and ATI-FlyZero [13].

A "pot-pouri" of configurations is in **Fig.3**. Most of the configurations have a central payload fuselage containing a LH2 tank, (e.g. Cryoplane [11] with tanks above the passenger cabin) or else a central fuselage and a pair of LH2 tanks on the wings.

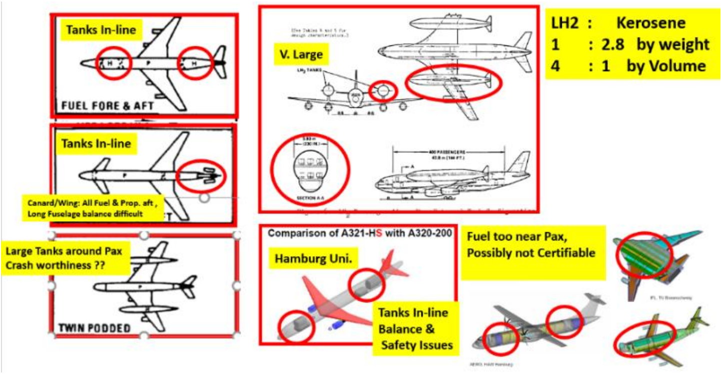

Figure 3 - Familiar Configurations from Brewer’s report, Cryoplane, Work of Scholz. Most Layouts Not Easily Certifiable for Crash- Worthiness

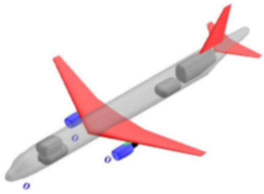

Figure 4 – LH2 Layout proposed, Scholz [9]

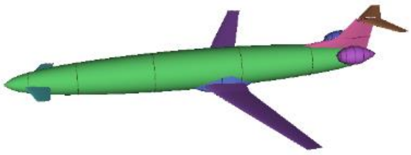

Figure 5 – Layout derived from outlines of [8,13]

Scholz’s concept with LH2 tanks in forward and rear fuselage achieved balance with a lengthened fuselage. The engines were on the wing. The concepts from [8,13] are rather similar along the lines of **Fig.5**. The tanks and propulsion are all at rear and this results in a lengthened forward fuselage to achieve a balance.

From certification viewpoint, we have several observations. Suffice here that none of these fulfil 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 safe static margin for all practical cases of fuel or passenger loadings.

7. A Few Early Attempts for Adequate LH2 Volume

Realizing the size of LH2 fuel tank required and the safety insights, we developed a series of concepts, based loosely on matching the energy capacity of A320 and extending / adapting the previous work. **Fig.6** shows 4 concepts to be described in the paper.

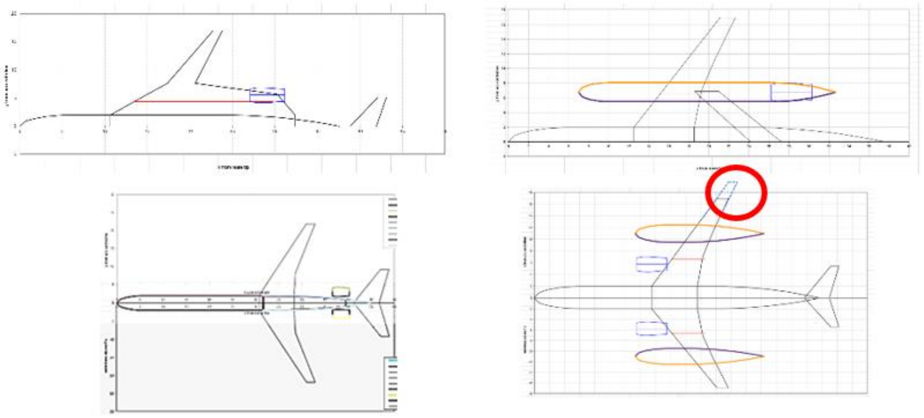

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Figure 6 – A series of Early Concepts Developed for carry Adequate LH2 fuel Volume

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.

8. Unusual Aircraft

There is no CS 25 requirement for an aircraft to be laterally symmetric. From several Wikipedia links, there are many examples of unusual Aircraft developed for special purposes, **Fig.7**. Asymmetric flight has been well demonstrated and it is feasible with twin fuselages. An important advantage 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.

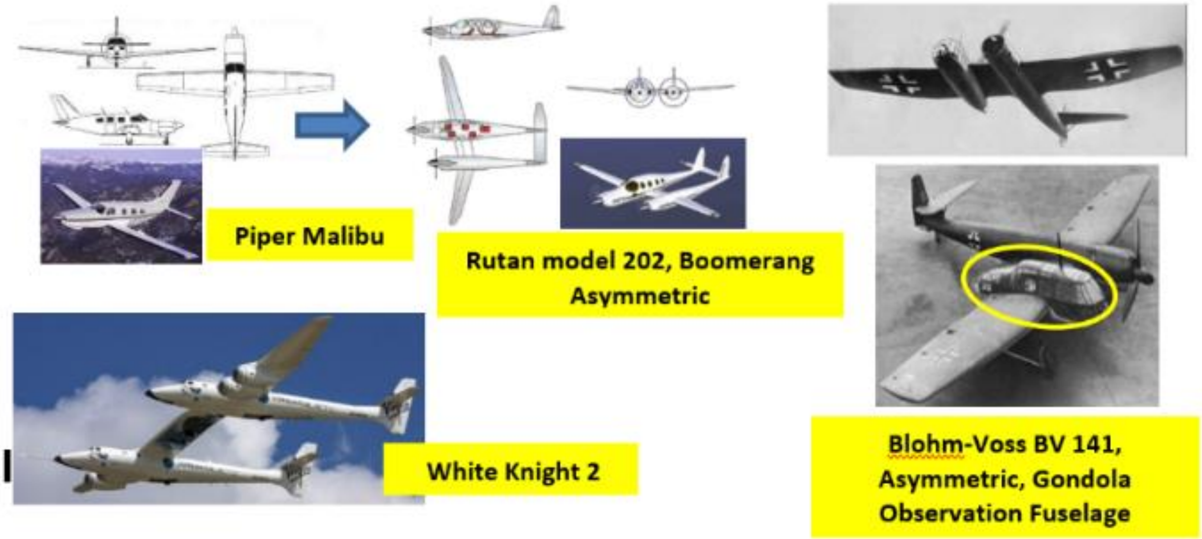

Figure 7 – Unusual and Asymmetric Flying Configurations

9. Twin Fuselage “Gondola”

We propose twin-fuselage “Gondola” configuration, **Fig.8** with the passengers in one fuselage (port) and the fuel in the other (starboard). The fuel tank fuselage is a little shorter but has the same cross-section.

Figure 8 - Twin-Fuselage Layout using LH2, Central Engines

Engines 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 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 and 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 as on military aircraft.

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 [13-14]. Such features lead to a good overall cruise L/D comparable with that for an equivalent single fuselage type.

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

Such a 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.

As a footnote, history shows that disruptive propulsive technology drives a 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.

10. Selected Analyses

Limited analyses on this configuration are presented in an earlier paper [15]. Here we consider an important facet of Bending Moments estimation and verification.

Figure 9 shows the aerodynamic spanwise lift and drag loadings and Bending Moment to help with Aeroelastic analysis. Note that the twin with span of about 50 m has similar bending moment as that for A320. This in line with previous work on twin fuselage configurations.

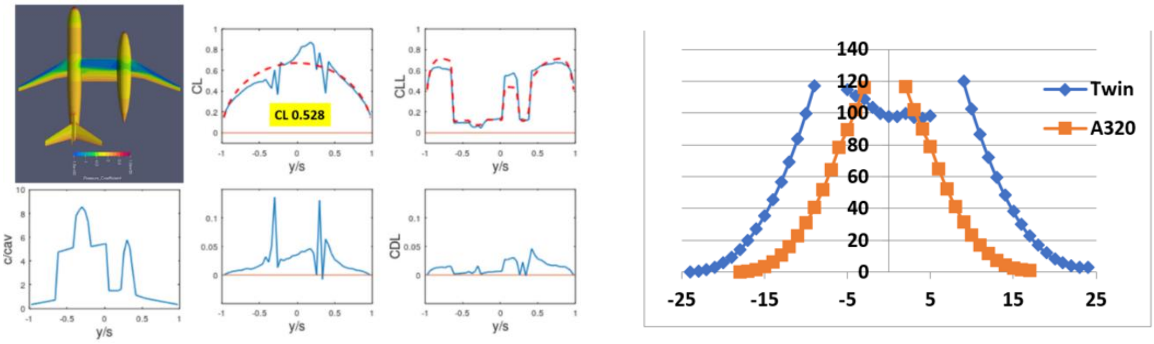

Figure 9 - Wing + Fuselage + Tank + Empennage, Flow AoA 1°, Cp Distributions, Spanwise Loadings

11. Performance Relationship to Previous Work on Efficiency Metrics

In [1 & 17], Efficiency parameters for Civil Aircraft have been described. These were based on correlating data from a large number of civil aircraft. Useful aspect was that we could predict the performance of a new aircraft for a given range, based on non-dimensional parameter Z thus extending the Breguet Equation Terminology.

We write Breguet Range equation in non-dimensional Efficiency parameter form as [1, 16]:

$Z = R/X = \ln [W1/(W1-WFB)]$

with X, the Range parameter defined as

$X = V/sfc . L/D = H . \eta . L/D.$

R is range assuming incidence, airspeed and specific fuel consumption is constant
sfc is specific fuel consumption
L/D is lift/drag ratio
W_i is initial aircraft weight, start of cruise
W_f is the weight of fuel consumed in the cruise
H is the calorific value of the fuel (energy per unit mass)
η is the efficiency of the powerplant in converting fuel energy to thrust energy

The Payload Range Efficiency PRE then follows from:

*PRE = Payload * Range / Fuel used   (nm, usually for convenience)*

In non-dimensional terms, PRE/X is a convenient non-dimensional parameter to be plotted against Z

Figure 10 shows the various weight factors as function of range using the design points of several aircraft. Note that as Range increases, Payload decreases and fuel ratio increases (at a faster rate).

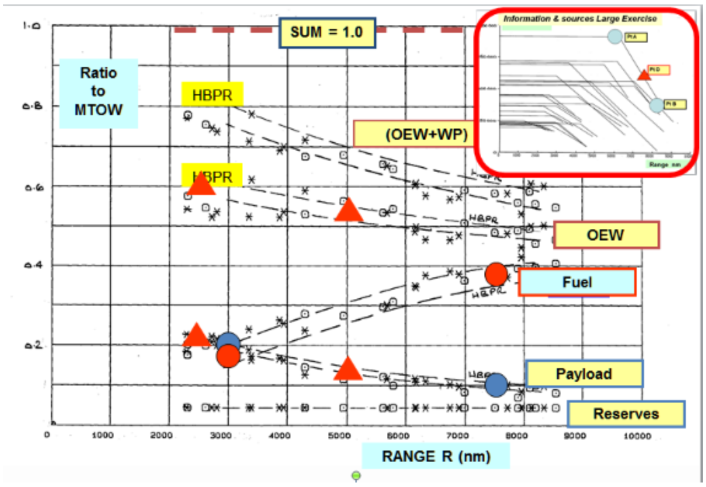

Figure 10 - Design Point D, OEW, Fuel & Payload Ratios vs Range

Figure 11 shows PRE/X the weight factors as function of range parameter Z. Note that peak of the Point- A PRE/X curve is near Z= 0.13. Point-D curve is is always lower than the Point-D curve [17]. This is useful graph for estimating / relating efficiency of many types of aircraft flying over different ranges.

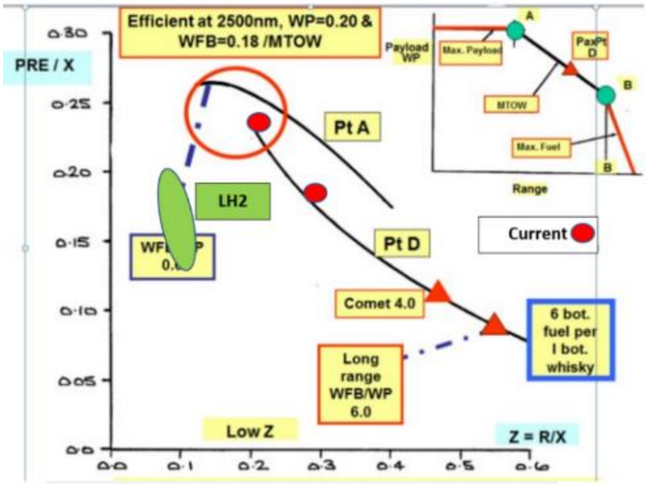

Figure 11 - PRE/X vs Z = R/X, Point A & Point D of the Payload Range Diagram. Note the Green (Elliptic) Area is for equivalent LH2 aircraft operating at Point D.

It is interesting now to see how the LH2 aircraft stack up against conventional aircraft in terms of the efficiency parameters. We use two different classes (moderate /the flong range types based on A320 & A330) of aircraft. The A320 specification is: 150 pax over 2950 nm, MTOW 78 tonnes, L/D about 18, Mach 0.78 cruise at 35,000 ft, sfc 0.584. The A330 specification is based on 330 pax over 4973 nm, MTOW 230 tonnes, L/D about 20, Mach 0.82 at 35000 ft, sfc 0.53.

We can assume that L/D is similar for the conventional and the LH2 twin (with extra span and weight etc. as outlined previously), we can set up a way of predicting configurations for other ranges

We note that the fuel volumes required for the LH2 aircraft will be higher. Thus, the A320-twin requires 130-140 cubic metres and the A330-twin about 700 cubic metres.

We can now derive the rest of the parameters and present them in non-dimensional manner as in Figure 12. Not that the Zero fuel weight ratio is always higher for LH2 aircraft. The corresponding PRE/X values are in Fig.11 (green area).

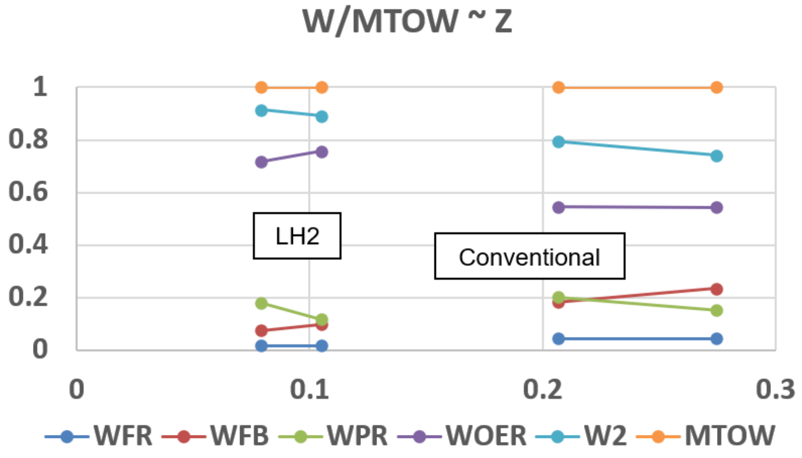

Figure 12 - OEW, Fuel & Payload Ratios vs Range, 2 Classes of Aircraft

In turn, Figure 12 allows us to derive dimensional relationships for fuel tankage and MTOW as function of range. See Figure 13. Note that for a given range, the LH2 aircraft will be increasingly heavier than a conventional aircraft. This relationship suggests that achieving long ranges with LH2 aircraft is more difficult even though LH2 is a lighter fuel.

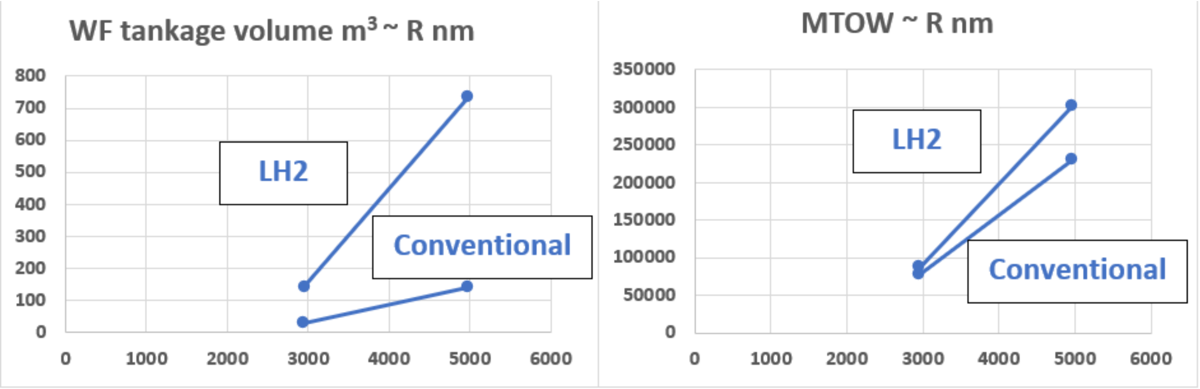

Figure 13 – Fuel Tankage Volume & MTOW (kg) vs Range, 2 cases

12. Major Inferences & Concluding Remarks

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”.

The fuel tanks are isolated from the passengers. We adopt a twin fuselage layout with fuel tanks in the starboard fuselage and payload in the port fuselage. This reduces the risk from fire and fuel spillage.

- Two LH2 tanks are provided, one for each 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 which would freeze solid at cryogenic temperatures.
- 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.
- Some loss of hydrogen will eventually occur due to boil-off. Procedures should be stipulated for safe venting of hydrogen gas.
- 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.
- Ground access and loading are similar to the A320. The port fuselage is same as that for the A320. The aircraft meets ICAO ground handling requirements..
- Landing Weights are 5 to !0% 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.

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In view of political / public urgency being placed, there is an interesting quote from Feynman [17]: “*For a successful technology, reality must take precedence over public relations, for nature cannot be fooled”.*

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