
ASME Paper Title: Synergistic technology combinations for future commercial aircraft using liquid hydrogen

Authors: Pavlos Rompokos, Andrew Rolt, Devaiah Nalianda, Askin T. Isikveren, Capucine Senné, Tomas Grönstedt, Hamidreza Abedi

ASME Conf Title: ASME Turbo Expo 2020

Volume/Issue: ___Volume 3_________________________ Date of Publication (VOR* Online) _11 January 2021____

ASME Digital Collection URL: https://asmedigitalcollection.asme.org/GT/proceedings/GT2020/84119/Virtual,%20Online/1094642

DOI: https://doi.org/10.1115/GT2020-15694

Proceedings of the ASME 2020
International Mechanical Engineering Congress and Exposition
GT2020
September 21-25, 2020, London, England

GT2020-15694

SYNERGISTIC TECHNOLOGY COMBINATIONS FOR FUTURE COMMERCIAL AIRCRAFT USING LIQUID HYDROGEN

Pavlos Rompokos[1], Andrew Rolt[1], Devaiah Nalianda[1],
Askin T. Isikveren[2], Capucine Senné[2],
Tomas Grönstedt[3], Hamidreza Abedi[3],

[1]Cranfield University, Cranfield, United Kingdom
[2]SAFRAN S.A., Châteaufort, France
[3]Chalmers University of Technology, Göteborg, Sweden

ABSTRACT

Liquid hydrogen (LH_2) has long been seen as a technically feasible fuel for a fully sustainable greener aviation future. The low density of the cryogenic fuel would dictate the redesign of commercial aircraft to accommodate the large tanks, which are unlikely to be integrated within the whole internal volume of the wing.

In the ENABLEH2 project, the morphological aspects of a LH_2 aircraft design are discussed and a methodology for rapid concept comparative assessment is proposed. An exercise is then carried on to down-select short-to-medium range (SMR) and long-range (LR) concepts, able to carry 200 passengers for 3000 nmi and 414 passengers for 7500 nmi respectively.

The down-selection process was split into two phases with the first considering 31 potential airframe architectures and 21 propulsion-system arrangements. The second phase made the final down-selections from a short-list of nine integrated design concepts that were ranked according to 34 criteria, relating to operating cost, revenue, noise and safety. Upon completion of the process, a tube and wing design with the tanks integrated into extended wing roots, and a blended-wing-body design were selected as the best candidates for the SMR and LR applications respectively. Both concepts feature distributed propulsion to maximise synergies from integrating the airframe and propulsion systems.

Keywords: Hydrogen, Alternative Energy Sources, Aeronautical and Aerospace Propulsion Systems, Aerospace Applications

NOMENCLATURE

BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
CASK	Cost per Available Seat-Kilometre
CoG	Centre of Gravity
CU	Cranfield University
EIS	Entry Into Service
ENABLEH2	Enabling cryogenic Hydrogen-based CO_2 free air transport
FL	Flight Level
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LR	Long Range
LSBU	London South Bank University
SFC	Specific Fuel Consumption
SMR	Short to Medium Range
T&W	Tube and Wing
TLAR	Top Level Aircraft Requirements
UAV	Uninhabited Aerial Vehicle

1. INTRODUCTION

Designing commercial aircraft to use liquid hydrogen (LH_2) is one way to substantially reduce their life-cycle CO_2 emissions. The merits of hydrogen as an aviation fuel have long been recognized, but the liquefaction of hydrogen is necessary for all but very short-range aircraft because of the large weight and volume of the tanks needed to store hydrogen as a compressed gas. The handling of a cryogenic fuel adds complexity to aircraft and engine systems and operations, but a cryogenic fuel also presents new opportunities, because its heat-sink capability can be used to increase the efficiency of future propulsion systems.

Considering fuel contents, LH_2 saves about two thirds of fuel mass compared to Jet-A, enabling lighter aircraft, but with fuel tanks approximately four times the volume of Jet-A tanks. This forces aircraft designers to consider modified versions of conventional tube and wing (T&W) configurations with bigger overall volumes that must inevitably increase airframe drag.

Aircraft and airport infrastructure compatibility and costs must also be addressed, as transitioning from one fuel to another dictates some radical changes.

The first steps towards LH_2 powered aircraft were initiated as early as 1955 with the NACA conducting preliminary designs of a subsonic and a supersonic bomber and subsonic and supersonic reconnaissance aircraft [1]. Immediately afterwards, Silverstein led the project where a Martin B-57 Canberra was converted to operate with gaseous hydrogen on one engine. External tanks were mounted under the wingtips and the LH_2 fuel was preheated in a heat exchanger before reaching the engine [2]. Three test flights were successfully completed with the B-57B taking-off with conventional jet fuel, switching to hydrogen at cruise and switching back to kerosene for landing.

NASA funded more studies at Lockheed in the 1970s [3], [4]. Considering potential oil shortages, and future production of hydrogen, methane or synthetic jet fuel from coal, the studies investigated the design of long-range subsonic and supersonic commercial aircraft with these three fuels. However, the studies were discontinued when the price of oil fell.

Tupolev in the 1980s modified a Tu 154 commercial jetliner to the Tu 155, a variant that included an 18 m^3 liquid hydrogen tank and a modified version of one of its NK-88 engine able to run with dual-fuel capabilities for either LH_2 and kerosene or liquefied natural gas (LNG) and kerosene. The first LH_2 powered flight took place on April 1988 and several others followed, however, the project later turned its focus to Liquid Natural Gas (LNG) as a more affordable alternative fuel [5].

Airbus led a project called Cryoplane in the late 1990s. Aircraft concepts covering all categories of commercial aviation were assessed. Other issues such as airport and environmental compatibility, safety and medium/long term scenarios for a smooth transition from kerosene to hydrogen in aviation were also addressed. However, the Cryoplane study considered the transition cost to LH_2 to be prohibitive [6].

The latest demonstration of LH_2 powered flight came from Boeing, with a long-endurance UAV, the Phantom Eye, featuring two large spherical LH_2 tanks installed in the fuselage [7]. Between 2012 and 2014 nine test flights were performed and the aircraft cruised at 54000 ft for 8 hours. Despite the successful demonstration, the project was discontinued and it is unclear whether there will be any long-endurance successor UAVs.

Designing an optimal LH_2 powered aircraft may not be a straightforward conversion of an existing T&W design, even if the latest advancements in airframe and propulsion systems are applied. Synergies from combining these technologies should further reduce fuel burn and strengthen the case for LH_2. This paper describes the methodology applied to qualitatively assess morphologies of short-to-medium range (SMR) and long-range (LR) LH_2 aircraft and the selection of concepts for more detailed study.

2. TOP LEVEL AIRCRAFT REQUIREMENTS

Top-Level Aircraft Requirements (TLARs) enable a viable positioning of the SMR and LR aircraft in the foreseen year-2050 market segments. SMR and LR aircraft mission requirements were chosen based on current commercial aircraft operations and projected growth in capacity of aircraft in the two classes. The two aircraft together may be considered broadly representative of the commercial aviation fleet as a whole. At this stage, to simplify the concept selections, single aircraft designs are proposed, though the relative ease of producing ‘shrink and stretch’ versions of each aircraft design was a factor taken into account in assessing their merits.

The TLARs proposed for the SMR and LR aircraft missions and aircraft design requirements are presented in Table 1. The SMR aircraft may be considered a successor to the Airbus A321neo while the LR aircraft may be considered a successor to the Airbus A350-1000 or to the Boeing 777-9X, scheduled to enter service in early 2022. In order to comply with the Code E airport compatibility limits, i.e. a maximum wingspan of 65 m, the 2050 LR aircraft could feature folding wingtips.

TABLE 1: TLARs for SMR and LR aircraft

General Requirements	**SMR**	**LR**
Range (nmi)	3000	7500
Pax	200 (single class)	414 (two-class)
Typical Payload (t)	21.3	47.6
Max Payload (t)	25	68.7
EIS-year technology	2050	
Airports Compatibility Limits (Wingspan range, m)	Code C (24 – 36)	Code E (52 – 65)
Cruise		
Initial Cruise Altitude (ISA+10)	FL350 (min)	FL330 (min)
Design Cruise Mach Number	M 0.75 (min)	M 0.82 (min)
Max Cruise Altitude	FL410	FL410

3. DOWN-SELECTION OF AIRCRAFT MORPHOLOGY

In Brewer’s study for the long-range subsonic commercial application, nine configurations were initially discussed and their advantages and disadvantages were reviewed against nine criteria [3]. Two T&W designs were considered feasible. The first had a wider fuselage cross-sectional area, featured two passenger decks, and two LH_2 tanks located inside the fuselage, one between the cockpit and the cabin and the other aft of the passenger cabin. The second had two external over-wing-mounted pods, each containing two LH_2 tanks. Both concepts were powered by four underwing-mounted turbofans. After more detail design studies, the first configuration was chosen.

In the Cryoplane study, a brainstorming session was held between Cranfield and Delft Universities, DASA, Dornier, and the former Swedish research organisation FFA. Unconventional aircraft were proposed, as reported by Sefain [8]. 21 novel airframe concepts were considered, including very-large ‘span-loader’ and ‘multi-body’ aircraft, tandem joined or ‘box’ wings, braced wings, deltas, tail-less flying wings, Blended-Wing-Body (BWB) aircraft etc. The pros and cons of each concept were assessed against 26 criteria, with some concepts rejected following discussion. Others were merged to leave six new concepts. These concepts were then scored against nine weighted attributes including relative safety. However, propulsion system choices were not considered.

In the ENABLEH2 study, a more comprehensive approach was adopted, and in each phase a comparative assessment was performed in three steps:

1. A list of criteria was chosen and the weighted importance of each criterion was established.
2. A baseline concept was selected for other concepts to be assessed against using pairwise comparison.
3. Scoring of each criterion followed a geometrical pattern (-9,-3,-1,0,1,3 or 9), with -9 representing a far worse, and +9 a far better, characteristic, compared to the baseline.

The features constituting an aircraft concept (e.g. wing and fuel tank location, propulsion system configurations etc.) would have provided an unmanageable number of potential combinations for assessment. For that reason, the process was broken down into two phases. In the first phase, airframe and propulsion system configurations were assessed separately against a shortlist of criteria. From the outcome of that assessment, five complete SMR aircraft concepts and another four for the LR application were proposed. The second phase scored these nine concepts.

3.1 Assessment criteria

The list of criteria was agreed upon in a dedicated workshop hosted by Cranfield University with participants from SAFRAN Group, GKN Aerospace, Chalmers University and London South Bank University. A total of 26 were chosen and were distributed under three major categories, cost per available seat-kilometre (CASK), revenue and noise. CASK is divided into fuel-related costs and other costs, fuel-related cost was then further subdivided to thrust requirements and propulsion system SFC. Another eight safety criteria were established to assess safety aspects separately. It is to be noted that the safety criteria address the relative difficulty in ensuring a safe configuration, as it was considered that every concept assessed had the potential to be a safe design. The criteria were weighted separately by the participating organisations and the results were averaged to minimise subjectivity. The exercise was performed twice to obtain different weightings for the SMR and LR applications. The results are presented in Table 2, where, from top to bottom, the upper-level categories, their subdivisions and the full list of the criteria, including the safety-related ones, are shown. The percentages refer to overall weighted importance. It is worth mentioning that in general there was close agreement between the weightings each organisation proposed, since for all criteria an average deviation of just 5.5% was observed for both the SMR and LR applications.

TABLE 2: List and corresponding weightings of the criteria selected for SMR and LR concept assessment

Criteria					**Overall averaged weightings**	
					SMR	**LR**
Top Level Categories				**CASK**	46.7%	50.0%
				Revenue	30.0%	30.0%
				Noise	23.3%	20.0%
				Breakdown of CASK		
CASK				Asessed Non-fuel Costs	17.1%	13.3%
				Overall Fuel Burn	29.6%	36.7%
				Breakdown of Fuel Burn		
	Fuel Burn			Overall Drag and Thrust Requirement	13.8%	15.3%
				Overall SFC	15.8%	21.4%
				Breakdown of Thrust Requirement		
		Thrust		Overall L/D	7.8%	10.2%
				Overall OWE	6.0%	5.1%
CASK	**Fuel Burn**	**Thrust requirement**	**L/D**	Aspect Ratio and winglets *	3.1%	3.7%
				Surface Area *	2.6%	3.1%
				Fuselage Fineness Ratio *	1.2%	1.4%
				Trim Drag to maintain pitch, stability *	0.9%	2.0%
			Operating Weight Empty	Airframe structural efficiency *	1.9%	1.6%
				Total propulsion system weight	1.6%	1.3%
				Wing Bending Moment relief	0.8%	0.7%
				CoG Location	0.6%	0.5%
				Fuel Tanks Capacity and Efficiency *	0.7%	0.6%
				Undercarriage length	0.4%	0.4%
		Propulsion system SFC		Propulsive efficiency **	4.6%	4.8%
				Core thermal efficiency **	4.5%	5.8%
				Transfer efficiency **	4.0%	5.8%
				Nacelle Drag **	1.3%	2.6%
				Benefit from BLI systems **	1.4%	2.4%
	Other Costs			Shrink and Stretch Capability *	7.1%	5.6%
				Complexity	6.1%	5.0%
				Maintainability	3.9%	2.8%
Revenue				Comfort	7.4%	10.5%
				Aesthetics	6.7%	5.0%
				Safety Perception *	9.2%	7.0%
				Cargo capacity *	6.7%	7.5%
Noise				Ducted Fans or Open Rotors **	7.4%	7.0%
				Noise Shielding	7.0%	6.0%
				Inlet distortion related noise	3.9%	2.0%
				Airframe noise	5.1%	5.0%
Safety				Engine Location **	8%	8%
				Fuel tank location *	14%	13%
				Ditching Capability	10%	13%
				Systems Redundancy **	13%	17%
				Fuelling Capability	13%	9%
				Emergency Egress *	21%	21%
				Crew access to all areas	10%	10%
				Stability & Control	11%	11%

3.2 Initial assessment

The attributes that constituted a concept were broken down into six major categories as presented in Table 3. Almost any concept can be expressed as a combination of one characteristic from each of these categories. The empennage and wingtip design, as well as the choice of the potential power transmission systems from the main engines to any secondary propulsors, were not included at this level, as they could be considered at a later stage of the concept design. Using pairwise comparison, 31 airframe configurations (combinations of fuselage cross-section, tank type and location, and wing design) were assessed against baseline concepts featuring a circular cross-sectional area, low wings and external tanks mounted above the passenger cabin. Similarly, for the propulsion system configuration, 21 concepts were assessed (as combinations of engine type, engine location and boundary layer propulsors) against the selected baseline featuring underwing-mounted turbofans. The airframe and propulsion system concepts are shown in Fig. A1 and Fig. A2 in the appendix. The assessments were performed for both SMR and LR applications, only for the shortlisted criteria in Table 2 (marked * for airframe, and ** for propulsion system) according to their corresponding SMR and LR overall weightings.

TABLE 3: Attributes for SMR and LR aircraft

Airframe	Fuselage cross-section		1. Circular 2. Side-by-side double-bubble 3. Double decks 4. BWB - single deck
	Tank Location	Internal	1. None 2. Rear of cabin 3. Front and rear of cabin 4. Top (and maybe rear) of cabin 5. Middle (between forward and aft cabins) 6. Below cabin
		External	1. None 2. Above fuselage 3. Under-wing 4. Over-wing 5. Between joined wing 6. Conformal
	Wing design		1. Low 2. High 3. Mid 4. Joined (tandem wings)
Propulsion system	Engine Type		1. Turbofan 2. Open Rotor 3. Turboshaft (turbo-generator)
	Engine Location		1. Under-wing ducted 2. Over-wing ducted 3. Aside aft fuselage ducted 4. Over aft fuselage / tail 5. Buried or Semi-buried
	BLI propulsors		1. None 2. Aft fuselage open rotor 3. Aft fuselage single ducted 4. Above wing or BWB ducted fans 5. Aft of wing external tanks ducted 6. Aft of wing external tanks open rotor

In the initial assessment, the safety-related criteria were not scored as discussed at the beginning of this section, but instead, every concept was assessed on safety grounds and marked with a pass or a fail. The only concepts that failed this first safety assessment were the propulsion system configurations 12 and 19 in Figure A2, as it was argued that twin turbofans or open rotors mounted above the aft fuselage would be more likely susceptible to cross-engine-debris impact. For the airframe design, the configurations that scored the highest were the twin fuselage concepts both for SMR and LR, for their potential high aspect ratio wings as well as their shrink and stretch capability and increased cargo capacity. Similarly the BWB configuration scored highly as well in the aerodynamic performance related criteria for the LR application, but not so well for the revenue related ones.

Propulsion system configurations that featured BLI fans scored relatively higher than the ones that did not, mainly due to higher propulsive efficiency and low noise. The open rotors were also considered high with respect propulsive efficiency, but they were marked low in terms of noise, especially for the heavier LR applications. Overall the first phase provided an overview of the many potential configurations that could be selected for the final concept down-selection, however, the potential synergies between propulsion system and airframe designs were not yet captured.

3.3 Shortlisted configurations

From the feedback gained from the first phase, nine shortlisted SMR and LR configurations were proposed and these are presented in this section.

Cobalt Blue 2 SMR: Concept proposed by Safran, is a T&W variant that features a mid-wing, the roots of which are extended to form a trapezoidal area to create the volume required to fit in elliptical LH_2 tanks between the passenger cabin above and the cargo bay below. A single Turbofan, mounted on the tail, or buried at the aft end of the fuselage with an S-duct intake, provides some amount of thrust and could potentially produce some electrical power. In conjunction with the turbofan, fuel cells are provided for powering a set of electric fans in a partial hybrid-electric distributed propulsion configuration. The fans ingest the boundary layer developed on the extended wing surface and have the capability of orientation change to provide active flow control. A wide fuselage cross-section allows for a 2-2-2 seating arrangement (for fast boarding and emergency egress) and a cargo area capable for accommodating LD3-45 containers. The concept is presented in Fig. 1.

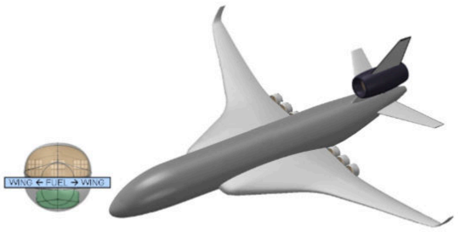


FIGURE 1: Cobalt Blue 2 SMR

SMR CU1: Concept proposed by Cranfield University, features a twin fuselage with two turbofans, mounted aside the aft fuselages, powering two open rotors that aim to re-energise the boundary layer developed on each fuselage. The concept is based on the Airbus A319 with passengers seated in both fuselages and the last seat rows were removed to make space for internal LH_2 tanks. In this way all hydrogen systems are placed away from the passenger cabin. Electrical power transmission is proposed though the “pi-shaped” empennage, with each turbofan powering the opposite open rotor to minimise asymmetric thrust in case of an engine failure. Faster boarding might be possible through a "T-shaped" bridge in-between the fuselages and 12 emergency exits (6 per fuselage) are considered for faster emergency egress. To gain the full benefit of the structurally-efficient higher-aspect-ratio wings, folding wingtips will be needed to comply with the Code-C 36 m wingspan limit. The main-gear wheel-span limit is 9 m, so may need to be offset from the fuselage centrelines together with the nose-wheels. The concept is presented on the left side of Fig. 2.

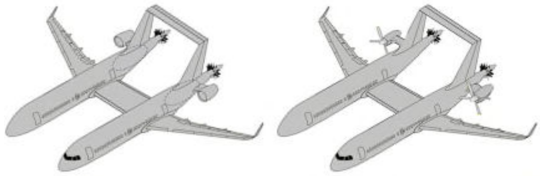


FIGURE 2: Left, SMR CU1. Right SMR Chalmers

SMR CU2: Proposed by Cranfield, SMR CU2 is a single-hull concept with a 'T' tail and aft-fuselage pusher open rotors with a third electrically-driven BLI open rotor on the fuselage centreline. Alternatively, the third open rotor could be mechanically driven from the main engines using rotorcraft transmission technology instead of using a superconducting turboelectric system. Like the CU1 concept, all the hydrogen systems are located aft of the passenger cabin, minimising some risks. A larger fuselage diameter and a Boeing 767-type 2-3-2 (or Airbus A300-type 2-4-2) twin-aisle seating arrangement may be needed to avoid an excessively-long 200 passenger aircraft. Improved engine and aircraft fuel-efficiency for year 2050 reduces LH_2 requirements, making a single hydrogen tank aft of the passenger cabin possible, provided the centre of pressure can be adjusted in flight with relatively little trim drag penalty. The open rotor noise sources are not shielded so external noise is a major concern for the CU2 concept. The open rotor engines might be replaced by turbofans, and the BLI open rotors might be off-loaded on take-off and on approach, relative to the turbofans, to minimise noise. The BLI systems give the greatest fuel-burn benefit in cruise. The concept is presented in Fig. 3.

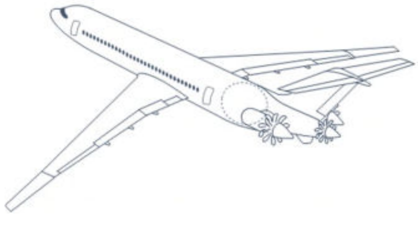


FIGURE 3: SMR CU 2

SMR Chalmers 1: Concept proposed by Chalmers University, based on an earlier Cryoplane study configuration with one LH_2 tank in the tail and others located above the passenger cabin. It has two conventional under-wing mounted turbofans and consequently has relatively-long fuel lines running through or around the passenger cabin. With tanks above the cabin, the tail-tank could be quite small in this SMR aircraft, so a single-aisle fuselage with 3-3 seating may still be possible. The concept aircraft is shown in Figure 4.

FIGURE 4: SMR Chalmers 1

SMR Chalmers 2: Proposed by Chalmers University and shown on the right side of Fig. 2, is a variant on the CU1 concept that is re-optimised for lower cruise speeds. It has simpler and less-expensive single-rotation turboprops and laminar-flow wings. The design should reduce fuel burn, but it will not meet the cruise speed requirement set in Table 1.

LR CU BWB: Fig. 5 shows the BWB concept from CU, which is a stretch of the original NASA N3-X airframe, as discussed by Felder in [9], in order to increase the area of the passenger deck and provide extra under-floor volume for the LH_2 tanks. This concept features turbo-electric distributed propulsion potentially with two turbofans semi-buried under the wing roots that also power an array of electric fans on top of the fuselage (the NASA N3-X featured turboshaft engines mounted at the wing tips). The electric fans reenergize the boundary layer developed over the fuselage and increase the propulsive efficiency of the propulsion system. The buried engines and the position of the fans also provide shielding to external noise and the passenger cabin. The LH_2 tanks would be located below and/or behind the pressurized cabin, stacked as close as possible to the CoG. The passenger cabin is divided into four bays, each with a 3-3 abreast seating arrangement for the economy class and 2-2 for business class. Because the BWB pressure hull has a flattened cross-section there are structural partitions between some of the seats, but these would not present continuous solid walls. This aircraft is estimated to be 10-15% longer than the N3-X, and in order to address stability and control issues due to shifting of the CoG, modifications could be considered such as adding canards and folding wingtips outboard of tail-fin winglets.

FIGURE 5: LR CU BWB (3-D model adapted from [10])

LR GKN1: Concept shown in Fig. 6 similar to Chalmers 1, but with larger tanks above the passenger cabin. Unlike earlier NASA and Cryoplane LR aircraft designs there is only a single passenger deck with seating similar to the Boeing 777-9X [6], [11]. This has two aisles and a 3-4-3 seating arrangement in the economy section. To reduce drag, there is potential for some area-ruling of the fuselage cross-section between the fore and aft tanks. The tanks are separated by a gap to minimise exposure to debris from a potential uncontained engine failure.

FIGURE 6: LR GKN 1

LR CU2: Another concept proposed by Cranfield has a horizontal double-bubble fuselage cross-section, as shown in Fig. 7, and two underwing mounted turbofans. Like the BWB proposal it has a structural partition in the passenger cabin, dividing the 12-abreast economy seating into two halves each with 3-3 seating. This enables the LH_2 tanks to be located at the forward and aft ends of the fuselage while maintaining access between the cockpit and the passenger cabin. The structurally-efficient double-bubble arrangement has lower drag than a circular fuselage of the same width and gives a broader wingspan for the same wing root bending moment. Also, compared with a BWB airframe, it is more-easily shortened or lengthened to create a family of aircraft.

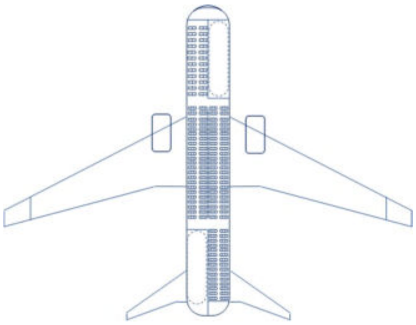


FIGURE 7: LR CU 2

LR GKN2: The last concept is shown in Fig. 8, was proposed by GKN and Chalmers and is a conventional T&W configuration with two external over wing-mounted pods each containing two LH_2 tanks. A space between the tanks in each pod avoids total loss of LH_2 in case of debris impact from a potential uncontained engine failure. The wing bending moment relief provided by the mass of these pods added to that of the under-wing engines could facilitate increased wingspan with folding wingtips to meet the 65 m limit.

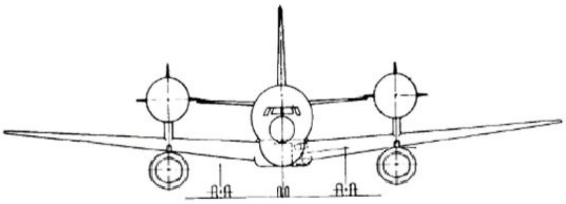


FIGURE 8: LR GKN2 (schematic adopted from [3])

4. DOWN-SELECTION RESULTS

The final scoring was undertaken by ten people from Safran, CU and Chalmers, with two more from LSBU only scoring the relative safety of the concepts. The baseline concepts chosen for each design to be scored against were the Cobalt Blue 2 and the LR CU1, for the SMR and LR assessments respectively, as these were originally considered to be the most promising designs. In each assessment, the score for each criterion ($score_i$) was multiplied by the corresponding weighting ($weighting_i$) and the overall score derived as the sum of all these weighted scores, as shown in Eq. 1. (The results are multiplied by 100 for ease of comparison). Following the same practice when establishing the criteria weightings, the overall scores from each participant were averaged to provide the final result. The results are presented according to the overall score, and the score without the revenue criteria, but with relative safety scores always shown separately.

$$Score_{overall} = \sum^{\#criteria} 100 * weighting_i * score_i \qquad \textbf{Eq. 1}$$

4.1 SMR concepts assessment

The original pairwise comparisons gave the baseline configuration scores of zero for all criteria, but to present the results more neutrally, the average weighted score from the individual assessments in each case was subtracted for from the original scores for each of the concepts. Table 4 presents these normalised scores for the different assessments together with the original scores beside them in brackets.

In terms of overall weighted score, Cobalt Blue 2 came highest. Its CASK-related assessment slightly lagged the other concepts, but it came first with regards to revenue (shrink and stretch capability, passenger perception and comfort) and noise (since the single main engine and BLI fans were considered quieter than any other configurations). That was reflected in the overall weighted score without revenue, where only the SMR Chalmers 1 concept was assessed as better. The SMR CU2 scored remarkably well with regards the CASK criteria and more specifically on propulsive efficiency due to the open rotors, however, when considering noise it was marked-down compared to the other candidates. The relatively low overall weighted score of SMR CU1 comes mainly from the revenue related factors due to its unconventional design. Finally, with regards to safety, the rest of the concepts scored better than the baseline, as locating the fuel and propulsion systems behind and away from the passenger cabin, was positively appreciated.

TABLE 4: SMR assessment results

SMR concept	Overall weighted score	Excluding revenue factors	Weighted Safety score
Cobalt Blue 2	29 (0)	12 (0)	-38 (0)
SMR CU1	-23 (-52)	-15 (-26)	16 (54)
SMR CU2	10 (-19)	3 (-9)	38 (77)
SMR Chalmers1	19 (-10)	27 (15)	-33 (5)
SMR Chalmers2	-35 (-64)	-27 (-39)	17 (55)

4.2 LR concepts assessment

In the same manner as the SMR assessment, the average score was subtracted from the LR scores to provide comparable overall scores and the results are presented in terms of overall score and the score without revenue related criteria, with safety assessed separately. Like Table 4, Table 5 presents normalised scores together with the original scores in brackets.

TABLE 5: LR assessment results

LR concept	Overall weighted score	Excluding revenue factors	Weighted Safety score
LR CU BWB	46 (0)	35 (0)	-8 (0)
LR GKN 1	-5 (-51)	-7 (-42)	18 (26)
LR CU 2	-16 (-61)	-14 (-49)	-33 (-28)
LR GKN2	-25 (-70)	-14 (-49)	24 (32)

The CU BWB concept scored significantly better in the fuel burn, noise and revenue related categories than the rest of the concepts did, however, its shrink and stretch capability, as well as ease of maintainability, were questioned. Safety-wise, the rest of the designs scored better, as emergency egress from the baseline configuration was considered less efficient, an issue also identified and addressed by Liebeck in [12]. After the CU BWB, the LR GKN1 scored second best, both in terms of the overall score and the score without revenue related criteria, since its more-conventional design was considered to be more easily maintained and more easily stretched or shrunk to create a family of aircraft. However, the location of the fuel tanks on the LR CU2 concept had a negative impact on the scoring, both in relation to revenue-related safety perception and relative safety criteria.

5. CONCLUSIONS AND NEXT STEPS

This paper has reported on the first part of the ENABLEH2 Technology Evaluator work package, which will make a critical technology appraisal of LH_2 aircraft designs. This study has presented the methodology followed for the comparative assessment of different aircraft concepts having LH_2 fuel. In the final phase, seven shortlisted concepts were compared against two baseline configurations and scored according to 34 criteria. A T&W aircraft with extended wing roots (Cobalt Blue 2) was selected for the SMR application and a BWB design (CU BWB) was selected for the LR application. These concepts are “maximum synergy” designs and considered best candidates for the more-detailed assessments using the Techno-economic and Environmental Risk Assessment (TERA) evaluation platform developed in previous EU programmes. The multi-objective, multi-disciplinary assessments and trade-off studies are now under way and the safety concerns raised by the assessment are being addressed. In addition to the maximum synergy concepts, two “more conventional” aircraft concepts, similar to the SMR Chalmers 1 and the LR GKN 1, will be modelled. These can help to quantify the additional benefits afforded to the Cobalt Blue 2 and CU BWB aircraft by having more advanced and integrated propulsion systems taking advantage of the cooling potential of the LH_2 fuel.

ACKNOWLEDGEMENTS

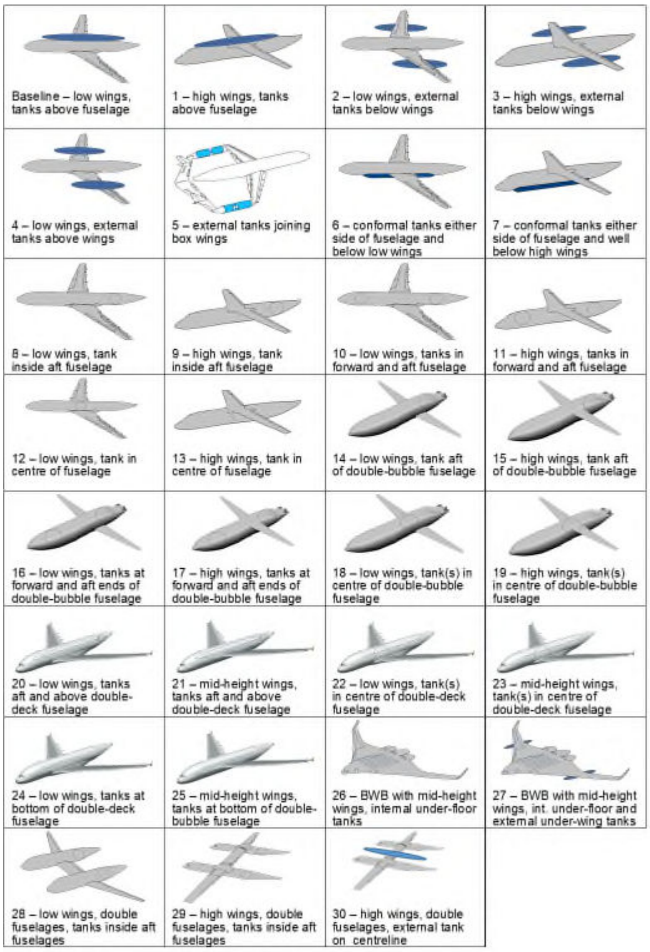
The ENABLEH2 project is in receipt of funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 769241. The authors would also like to express their gratitude to James Tidd, Lida Sykara and Riccardo Mazzeo for their contribution of Figures 4, 5 and 6 respectively.

REFERENCES

1. Silverstein, A.; Hall, E.W. *Liquid Hydrogen as a Jet Fuel for High Altitude Aircraft*; Cleveland, Ohio, 1955;
2. NACA Research on Hydrogen for High-Altitude Aircraft Available online: https://history.nasa.gov/SP-4404/ch6-4.htm (accessed on Nov 5, 2019).
3. Brewer, G.D.; Morris, R.E.; Lange, R.H. *Study of the Application of Hydrogen Fuel To Long-Range Subsonic Transport Aircraft, Volume 1*; 1975;
4. Brewer, G.D.; Morris, R.E.; Lange, R.H. *Study of the Application of Hydrogen Fuel To Long-Range Subsonic Transport Aircraft, Volume 2*; 1975;
5. Sosounov, V.; Orlov, V. Experimental turbofan using liquid hydrogen and liquid natural gas as fuel. In Proceedings of the AIAA/SAE/ASME/ASEE 26th Joint Propulsion conference; Orlando, Florida, USA, 1990.
6. Airbus Deutschland GmbH Cryoplane Final Technical Report: Liquid Hydrogen Fuelled Aircraft-System Analysis. **2003**, 1–80.
7. Mills, G.L.; Buchholtz, B.W.; Olsen, A. Design, fabrication and testing of a liquid hydrogen fuel tank for a long duration aircraft. *AIP Conf. Proc.* **2012**, *1434*,

773–780.
8. Sefain, M. Hydrogen Aircraft Concepts & Ground Support, Cranfield University, 2005.
9. Felder, J.; Kim, H.; Brown, G.; Chu, J. An Examination of the Effect of Boundary Layer Ingestion on Turboelectric Distributed Propulsion Systems. In Proceedings of the 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition; Orlando, Florida, 2011; pp. 1–26.
10. Moore, M. OpenVSP: NASA N3-X Concept Available online: hangar.openvsp.org/vspfiles/59 (accessed on Aug 25, 2019).
11. Brewer, D. *Hydrogen Aircraft Technology*; CRC Press, 1990;
12. Liebeck, R.H. Design of the Blended Wing Body Subsonic Transport. *J. Aircr.* **2004**, *41*, 10–25.

APPENDIX



Baseline – low wings, tanks above fuselage

1 – high wings, tanks above fuselage

2 – low wings, external tanks below wings

3 – high wings, external tanks below wings

4 – low wings, external tanks above wings

5 – external tanks joining box wings

6 – conformal tanks either side of fuselage and below low wings

7 – conformal tanks either side of fuselage and well below high wings

8 – low wings, tank inside aft fuselage

9 – high wings, tank inside aft fuselage

10 – low wings, tanks in forward and aft fuselage

11 – high wings, tanks in forward and aft fuselage

12 – low wings, tank in centre of fuselage

13 – high wings, tank in centre of fuselage

14 – low wings, tank aft of double-bubble fuselage

15 – high wings, tank aft of double-bubble fuselage

16 – low wings, tanks at forward and aft ends of double-bubble fuselage

17 – high wings, tanks at forward and aft ends of double-bubble fuselage

18 – low wings, tank(s) in centre of double-bubble fuselage

19 – high wings, tank(s) in centre of double-bubble fuselage

20 – low wings, tanks aft and above double-deck fuselage

21 – mid-height wings, tanks aft and above double-deck fuselage

22 – low wings, tank(s) in centre of double-deck fuselage

23 – mid-height wings, tank(s) in centre of double-deck fuselage

24 – low wings, tanks at bottom of double-deck fuselage

25 – mid-height wings, tanks at bottom of double-bubble fuselage

26 – BWB with mid-height wings, internal under-floor tanks

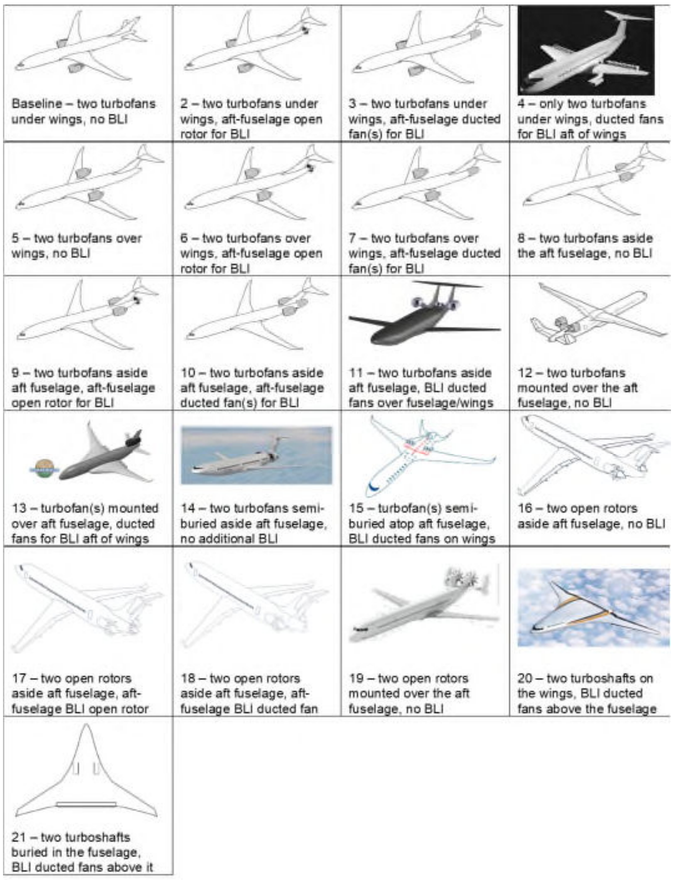
27 – BWB with mid-height wings, int. under-floor and external under-wing tanks

28 – low wings, double fuselages, tanks inside aft fuselages

29 – high wings, double fuselages, tanks inside aft fuselages

30 – high wings, double fuselages, external tank on centreline

FIGURE A1: Airframe configurations assessed in the first phase of the down-selection



Baseline – two turbofans under wings, no BLI

2 – two turbofans under wings, aft-fuselage open rotor for BLI

3 – two turbofans under wings, aft-fuselage ducted fan(s) for BLI

4 – only two turbofans under wings, ducted fans for BLI aft of wings

5 – two turbofans over wings, no BLI

6 – two turbofans over wings, aft-fuselage open rotor for BLI

7 – two turbofans over wings, aft-fuselage ducted fan(s) for BLI

8 – two turbofans aside the aft fuselage, no BLI

9 – two turbofans aside aft fuselage, aft-fuselage open rotor for BLI

10 – two turbofans aside aft fuselage, aft-fuselage ducted fan(s) for BLI

11 – two turbofans aside aft fuselage, BLI ducted fans over fuselage/wings

12 – two turbofans mounted over the aft fuselage, no BLI

13 – turbofan(s) mounted over aft fuselage, ducted fans for BLI aft of wings

14 – two turbofans semi-buried aside aft fuselage, no additional BLI

15 – turbofan(s) semi-buried atop aft fuselage, BLI ducted fans on wings

16 – two open rotors aside aft fuselage, no BLI

17 – two open rotors aside aft fuselage, aft-fuselage BLI open rotor

18 – two open rotors aside aft fuselage, aft-fuselage BLI ducted fan

19 – two open rotors mounted over the aft fuselage, no BLI

20 – two turboshafts on the wings, BLI ducted fans above the fuselage

21 – two turboshafts buried in the fuselage, BLI ducted fans above it

FIGURE A2: Propulsion systems configuration assessed in the first phase of the down-selection

2021-01-11

Synergistic technology combinations for future commercial aircraft using liquid hydrogen

Rompokos, Pavlos

American Society of Mechanical Engineers

Rompokos P, Rolt A, Nalianda D, et al., (2021) Synergistic technology combinations for future commercial aircraft using liquid hydrogen. In: ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition, 21-25 September, Virtual Event. Paper number GT2020-15694

https://doi.org/10.1115/GT2020-15694