20th ISPE International Conference on Concurrent Engineering
C. Bil et al. (Eds.)

doi:10.3233/978-1-61499-302-5-391

Conceptual Design of Sustainable Liquid Methane Fuelled Passenger Aircraft

M. Burston[1], T. Conroy[2], L. Spiteri[2], M. Spiteri[2], C. Bil[3] and G. E. Dorrington[3]
RMIT University, Melbourne, Victoria, 3083, Australia

Abstract. Motivated by concerns over rising costs of Jet-A fuel and the current limitations of "drop-in" fuel substitutes, it is proposed that biomethane (or Bio-LNG) provides a promising sustainable aviation fuel. This paper discusses some technical considerations for converting a jet airliner to biomethane fuel. Following consideration of aircraft configuration alternatives and performance issues, a conceptual design is presented where cryogenic methane is stored in both an insulated wing-box and under-wing pods. It is concluded that the weight penalty of such a cryogenic fuel system would be relatively modest, hence the range and payload capability of existing Jet-A aircraft can be matched.

Keywords: Liquefied Natural Gas, Biomethane, Biofuel, Air Transportation

Introduction

In 2012, the aviation sector consumed $209 billion (US) of Jet-A (Avtur) fuel [1], emitting 634 million tonnes of CO_2 into the atmosphere [2]. In the next 20 years, it is predicted that the annual demand for commercial airline passenger transport will grow from 5.1% to 12.8% revenue passenger-km [3]. However, IATA and ACARE have set challenging targets for the reduction of carbon emissions by 2050. To meet these targets, net carbon-emissions per seat-km must be substantially reduced, without imposing any significant increase in Direct Operating Cost (DOC).

1. Future Aviation Fuel Options

1.1. Drop in Fuels

To achieve carbon-emission targets many "drop-in" biofuels have been proposed [4-6], however current production rates and market prices limit their near-future use as a blend with Jet-A [7]. Drop-in biofuel production requires large areas of land and extensive use of fertilizer, pesticide and water, etc., and is therefore not capable of supporting the global aviation fleet [5, 8]. Furthermore, the cost of existing drop-in biofuels is significantly higher than Jet-A fuel [9]. Another option as a drop-in solution involves the use of synthetic Jet-A or "Syn-Jet" made from natural gas through the

[1] Undergraduate, Bachelor of Engineering (Aerospace)
[2] Undergraduate, Bachelor of Engineering (Aerospace) and Business (Management)
[3] Academic staff member, School of Aerospace, Mechanical and Manufacturing Engineering, contact for correspondence: graham.dorrington@rmit.edu.au

Fischer-Tropsch (FT) process [10]. However, the FT process does not result in any net CO_2 emission reduction. Synthetic fuels are therefore not considered a viable solution for sustainable aviation [11].

1.2. Liquefied Natural Gas (LNG), Biomethane and Bio-LNG

IATA data shows that the global price of Jet-A fuel has risen substantially in recent years [12], essentially following the fluctuating price of crude oil. Meanwhile, US Energy Information Administration (EIA) data suggests that the US import price of Liquefied Natural Gas (LNG) has become decoupled from crude oil [13] and is presently only about 20% of the Jet-A price on an equal energy basis (**Figure 1**).

LNG consists of more than 90% liquid methane (LCH_4), but also includes small fractions of liquid ethane, propane, nitrogen and other impurities. The obvious disadvantage is that LNG is a cryogen and storage tanks need to be thermally insulated [14], since LCH_4 boils at 111-126 K at 1-3 bar [14, 15]. In order to operate LNG fuelled aircraft, a global infrastructure change to supply and store LNG at airports is required. Despite to the high infrastructure costs, LNG aircraft operations could offer a profitable and prudent investment due to the abundance of low cost LNG fuel [16].

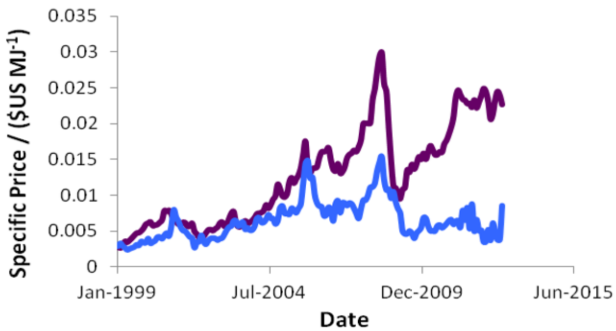


Figure 1. Jet-A Fuel Price (upper) vs. LNG Price (lower). Data sourced from the US EIA [13].

Stoichiometric fuel-air combustion equations show that a 20% reduction in CO_2 emission may be achieved using LNG instead of Jet-A (for the same heat release). To achieve further reductions, liquid biomethane would have to be blended with LNG, to create "Bio-LNG". Biomethane is produced from biogas and potentially reduces net CO_2 emissions by up to 97% relative to petroleum fuels [17], in line with the "EU Flightpath 2050" objectives for CO_2 emissions and sustainable biomass fuel derivation [18, 19]. Biomethane is a relatively energy efficient biofuel per hectare of land available and is already used in the automotive and maritime sectors [19]. For example, liquid biomethane is already used safely in airports to fuel passenger buses [20].

1.3. Previous Proposals for LNG Aircraft

The use of LNG in aviation has been considered by Beech, Lockheed and Tupolev. In 1980, Beech successfully flew a Beech Sundowner aircraft on LCH_4 [21]. Lockheed performed a major LCH_4 aircraft study in 1980 [22] and Tupolev flew a Tu-156 test aircraft on LNG in 1986 [23] .

More recently, interest in LNG in aviation has gained renewed interest: Greitzer [24] proposes LNG as a future fuel in the NASA "SUGAR N+4" research initiative and Kawai presents compelling arguments for a dual fuel (LNG plus Jet-A) Blended Wing Body (BWB) aircraft [25]. It is interesting to note that Kawai was influenced by Gibbs et al. [26] who submitted a proposal for an LNG fuelled aircraft to the 2011 Airbus "Fly-Your-Ideas" competition (see acknowledgements).

2. System Requirements and Performance

2.1. System Requirements

The following top-level system requirement targets were set:

1) The LNG fuelled aircraft shall offer Airbus A320-A350 sized aircraft, at least a 20% reduction in net CO_2 emission per seat-km.
2) The Bio-LNG fuelled aircraft shall offer Airbus A320-A350 sized aircraft, at least a 50% reduction in net CO_2 emission per seat-km.
3) The payload and range of the (Bio-) LNG aircraft shall not be inferior to that of an equivalent-sized Jet-A fuelled aircraft.
4) Operating safety levels shall exceed those of Jet-A aircraft
5) LNG shall be supplied at all airports, such that the delivery price is sufficient to bring-out a DOC reduction compared to the equivalent-sized Jet-A aircraft, allowing for the development costs of the LNG aircraft.

2.2. System Architecture

A system overview is presented for Bio-LNG fuelled aircraft in **Figure 2**. The shaded subsystems represent the primary subsystems that were considered during the design process.

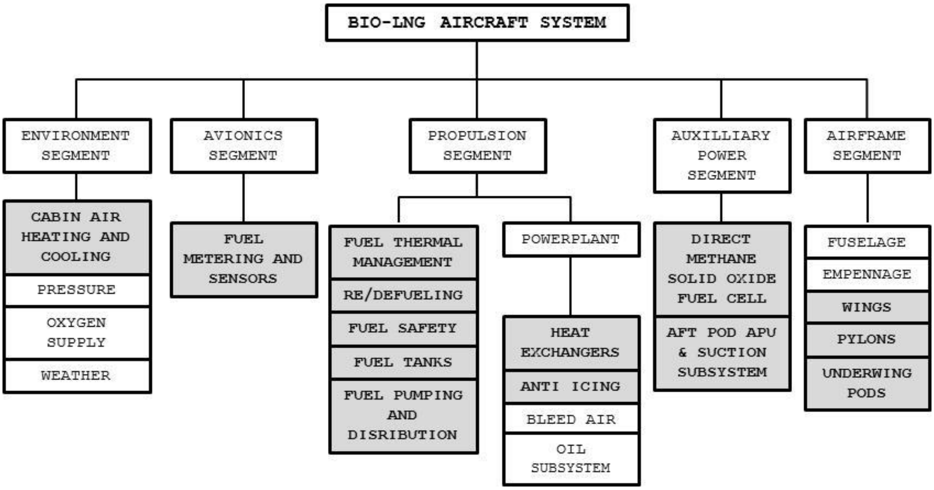


Figure 2. System architecture for the Bio-LNG aircraft

2.3. Range and Payload

The performance of the Bio-LNG fuelled aircraft was investigated using Airbus A320 and A350-900 baselines [27]. A comparison of the range-payload characteristics of Jet-A and Bio-LNG variants with equal gross take-off weight is provided in **Figure 3**. To achieve this performance it was found that the cruise lift-to-drag (L/D) value of the modified aircraft cannot fall below approximately 7% of the Jet-A equivalent while the dry mass penalty of LNG subsystem changes must be less than about 2 tonnes (A320 case), assuming a specific fuel consumption gain of about 10% (section 3.2).

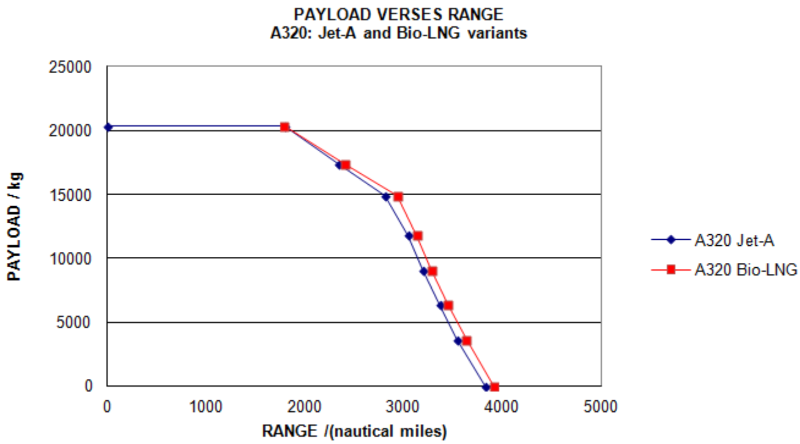


Figure 3. Range and Payload for different A320 fuel configurations, GTOW, 73.5 tonnes.

3. Aircraft Configuration and Subsystems

3.1. Configurations Options and Evaluation Methods

Previous studies of cryogenic fuel aircraft have placed fuel tanks primarily within the fuselage [21, 22, 24, 26, 28-30]. However, such configurations have disadvantages. In particular, placing fuel tanks within the fuselage compromises useful space and requires high load factor mountings, i.e., there is a weight penalty [24]. Also any leakage of CH_4 vapour inside the fuselage could result in the accumulation of an explosive mixture (Section 4.3). Early in this design study, it was therefore decided to store Bio-LNG within the wing-box, also noting the advantage of distributed span-loading. However, to match Jet-A on an equivalent energy content basis, the wing-box volume of existing aircraft would have to be increased by about 45%, hence under-wing mounted fuel pods are proposed (Section 3.3).

Although tail engine configurations have recently been considered by Airbus [31], in the past two decades Airbus and Boeing have selected the under-wing engine arrangement. Given the aforementioned leakage issue, through fuselage LCH_4 piping is rejected and under-wing engine configurations are preferred (**Figure 4**).

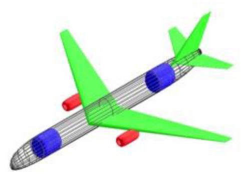
Configuration Option	Image	Pros	Cons
A. Fuel Tanks & Engines Under Wings		- Reduces bending moment on wing. - Ease of maintenance - Short fuel piping	- Wing flow interference - Reduced cruise lift-drag
B. Fuel Tanks in Wing Box and Under Wing Pods; Engines Under Wing		- Same as A, but dual mode boil-off rate possible	- Same as A, but reduced pod size
C. Fuel Tanks in Fuselage & Engines Under Wings		- Large volume-to-area ratio - Reduced boil-off - No possibility of bird strike damage	- Tank mounting must meet higher FAA g-load limits - Possibility of vapour leakage into fuselage. - Lost cargo volume
D. Fuel Tanks in Enlarged Wing Box & Engines Above Tail		- Reduced ground noise when shielded by H tail - Improved cruise lift-to-drag - Fuel weight relieves bending moment on wing (improves span loading)	- Long fuel pipes running through fuselage - Shorter tail moment - Must increase wing box volume by 45%
E. Fuel Tanks in Enlarged Wing Box & Engines Under Wing		- Same as D, minus engine placement advantages - No cryogenic fuel lines in fuselage	- Same as D, minus engine placement disadvantages

Figure 4. Bio-LNG aircraft concepts to achieve increased fuel tank volume

3.2. Propulsion

Necessary changes to the turbofan engine technology are relatively minor. Bio-LNG fuelled turbofan engines will have at least 10% reduced specific fuel consumption compared with Jet-A [14]. Along with the decrease in CO_2 (and CO) emissions, a 30-50% reduction in NO_x emissions is also reported by Fulton [32]. Introduction of compressor intercooling and integration with direct methane fed Solid Oxide Fuel Cells, could offer further performance gains [33, 34].

3.3. Use of a Goldschmied-Type Annular Suction-Slot to Reduce External Pod Drag

Using Goldschmied's experimental data [35-37] the predicted drag penalty of the under-wing pods can be substantially reduced by using a small turbofan (or APU powered air-pump) mounted aft of each pod (**Figure 5**). This would result in a minimal increase in overall fuel consumption (in comparison with a non-integrated system). It is estimated that the effective drag penalty caused by the under-wing pods is less than 5% of overall cruise drag [38]. However, it is also recognized that aerodynamic testing of this promising concept at Reynolds numbers in excess of 10^7 and Mach 0.8 is required.

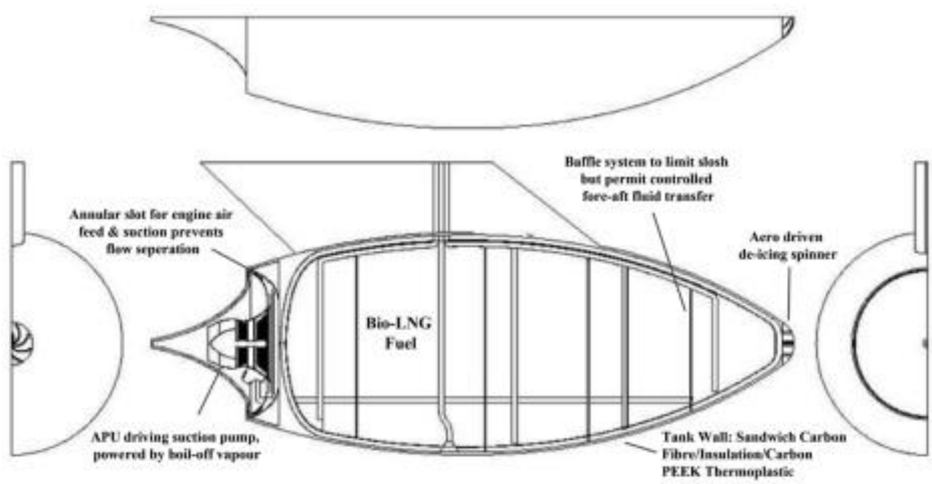


Figure 5. Under-wing pod cutaway, with boundary layer suction and active drag reduction

4. Technical Challenges

Many technological challenges associated with the introduction of Bio-LNG were identified, including: on ground and in-flight boil-off of Bio-LNG; prevention of wing and pod icing; specific safety issues concerned with Bio-LNG aircraft operations; necessary propulsion system changes (within the powerplant itself); Bio-LNG pumping requirements and the need for insulated fuel piping; monitoring of Bio-LNG fuel usage and fuel tank state; airframe changes and unique structural issues such as cyclic thermal shock; centre of gravity management by fore-aft Bio-LNG fuel transfer; Bio-LNG ground refuelling operations and offloading Bio-LNG as required. Only a few of these items will be addressed here.

4.1. Boil-off and Thermal Management

According to Kawai [25], foam insulated tanks would not permit a sufficiently low LNG boil-off rate and he recommends heavy vacuum-insulated (Dewar-type) tanks. However, in reaching this decision, Kawai assumed that the boil-off rate on the ground (without any cryo-cooling system) would have to be limited 'to 0.1% per day' or just 0.0011 kg/s (4 kg/h) for an A350-900. If, instead, it is assumed that the aircraft has to supply a CH_4 vapour fed APU system with an output of 127 kW, then the gas feed rate would need to be at least 0.122 kg/s (440 kg/h). Thus, the boil-off rate during periods of unsupported ground operation can be two orders of magnitude higher than Kawai estimates. Moreover, if CH_4 vapour feed is also assumed during take-off and climb periods, then there is a demand for much higher boil-off rates. For an A350-900 sized aircraft, the high thrust boil-off rate needs to be approximately 1.8 kg/s (6500 kg/h). A dual mode fuel subsystem, whereby Bio-LNG is pumped between a well-insulated under wing pod, and a lesser insulated wing-box tank with a much higher surface area to volume ratio, is attractive.

4.2. Icing Prevention

Icing is not thought to be major problem at one third of the chord where in wing-box cryogenic Bio-LNG storage is proposed. Icing occurs at the leading edge and heat transfer between the wing-box and the leading edge is relatively minor. Hence, conventional leading edge de-icing systems [39] should be sufficient to prevent in-flight icing [38], despite predictions that central wing region surface temperatures could drop to 180 K while in the stratosphere. Icing is predicted to occur on the nose of each under-wing pod. To address this, a free spinning aerodynamic tip on the pod nose to shed any ice accumulation is proposed. This design solution was inspired by the Rolls-Royce rubber nose tip used on the spinners of their aero-engines [40].

4.3. Safety Issues

There are many safety considerations associated with the use of Bio-LNG. Two are prominent. Firstly, vapour leakage from pipes into closed areas containing air might allow an explosive gaseous mixture to form. To mitigate this during the configuration study, it was decided that elimination of in-fuselage tank storage was necessary. Internal wing zones filled with air (either side of wing box) can be readily flushed with secondary airflow. Secondly, impacts with ground vehicles, bullets and bird strikes were considered. Further work is needed to determine acceptable structural design solutions.

5. Design Study Outcomes

A simplified decision matrix (**Figure 6**) was used to select the final preferred configuration. Of course, this is just a down-selection procedure, but it serves the purpose of illustrating the impact of pertinent design issues.

Configuration “Z” (**Figure 7**) was provisionally found to best satisfy the system requirements and technology challenges (Section 2.1 and Section 4). In particular, this configuration appears to offer sufficiently low boil-off rates for ground storage and higher boil-off rates during flight (Section 4.1), whilst having an acceptable cruise L/D and dry mass penalties (Section 2.3)

The evaluation methods used in this study were commensurate with a conceptual design study, and therefore require further substantiation. In particular, key technical areas that require attention are primarily concerned with icing (Section 4.2) and safety issues (Section 4.3).

Requirement	*Weighting Factor*	*Config. X (Bio-LNG in enlarged wing-box)*	*Config. Y (Bio-LNG in under-wing pods)*	*Config. Z (Bio-LNG in wing-box and pods)*
				
Low boil-off rate	*3*	*1*	*3*	*2*
High boil-off rate (for engine/apu vapour feed)	*1*	*3*	*1*	*2*
Drag penalty < 5%	*2*	*3*	*1*	*2*
Weight penalty < 5%	*1*	*2*	*3*	*1*
Range penalty < 5%	*2*	*2*	*1*	*3*
Design Change < 10%	*1*	*1*	*3*	*2*
Weighted Score		***19***	***20***	***21***

Figure 6. Configuration Decision Matrix

Figure 7. Selected Design (Configuration "Z")

6. Recommendations

Despite the use of simplified methodologies and assumptions, the design outcome appears to be realistic and promising in terms of feasibility and sustainability.

It is therefore recommended that a preliminary concurrent design study of the promising concept(s) that are presented is justified and should be undertaken. A concurrent approach is necessary, since many inter-related pertinent issues need to be considered simultaneously. These issues not only include extensive technical changes to aircraft systems, but also changes to ground infrastructure including whole matter of sustainable biomethane production. In summary, a comprehensive eco-economic (Life Cycle Cost) super-system model is needed to support concept design selection and preliminary aircraft design optimization.

Acknowledgements

Authors MB, TC, LS and MS undertook the work presented here as part of a proposal bid for “Round 2” of the Airbus “Fly-Your-Ideas” Competition in 2013 and received useful feedback from Dr. Paulo Lage and Enrique Tobias-Pena. The same authors wish to thank Prof. Aleksandar Subic, Head of the School of Aerospace, Mechanical and Manufacturing Engineering at RMIT, for supporting the project including the opportunity to display the design concept at the 2013 Avalon Airshow.

References

[1] IATA. *Financial forecast*. 2012 [cited 2013 March 3rd]; Available from: http://www.iata.org/whatwedo/Documents/economics/Industry-Outlook-Dec2012.pdf.

[2] IATA. *Fact sheet: climate change*. 2012 [cited 2013 March 1st]; Available from: https://www.iata.org/pressroom/facts_figures/fact_sheets/pages/environment.aspx.

[3] Airbus S.A.S. *Global market forecast 2012-2031: Navigating the future*. 2012 [cited 2013 20th March]; Available from: http://www.airbus.com/company/market/forecast/.

[4] W. Gibbons and S. Hughes, *Distributed, integrated production of second and third generation biofuels*, in *in (Ed.) Economic effects of biofuel production,*2011, National Center for Agricultural Utilization Research.

[5] D.L. Daggett, et al., *Alternate fuels for use in commercial aircraft*, in *ISABE,* 2007, NASA / The Boeing Company: Beijing (China).

[6] T.F. Rahmes, et al., *Sustainable bio-derived synthetic paraffinic (Bio-SPK) jet fuel flights and engine tests program results*, in *9th AIAA Aviation Technology, Integration, and Operations Conference*2009: Hilton Head, South Carolina.

[7] Australian Aviation. *Qantas spruiks biofuels with A330 flight*. 2012 [cited 2013 March 27th]; Available from: http://australianaviation.com.au/2012/04/qantas-spruiks-biofuels-with-a330-flight/.

[8] A. Petrova, 2012., *Biofuels as Alternative Sources of Energy*, in *Saint-Petersburg State University of Aerospace Instrumentation*2012: Saint-Petersburg.

[9] P. O'Brien and B. Fargher, *Biofuels in australia - issues and prospects*, 2007, Commonwealth Scientific and Industrial Research Organisation (CSIRO).

[10] J. Hileman, Ortiz, DS, Bartis, JT, Wong, HM, Donohoo, PE, Weiss, MA, Walts, IA, *Near-Term Feasibility of Alternative Jet Fuels*, F.A. Administration, Editor 2009, RAND: Santa Monica, CA.

[11] P. Jaramillo, W.M. Griffin, and H.S. Matthews, *Comparative analysis of the production costs and life-cycle GHG emissions of FT liquid fuels from coal and natural gas.* Environmental Science and Technology, 2008. **42**(20): p. 7559-7565.

[12] IATA. *Fuel price analysis*. 2013 [cited 2013 20 March]; Available from: http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx.

[13] EIA. *Price of US Natural Gas LNG Imports*. 2013 [cited 2013 March 15th]; Available from: http://www.eia.gov/dnav/ng/hist/n9103us3m.htm.

[14] H.F. Brady and D. Del Duca, *Insulation systems for liquid methane fuel tanks for supersonic cruise aircraft*, 1972, NASA.
[15] GIIGNL. *Basic properties of LNG*. 2009 [cited 2012 October 16th]; Available from: http://www.giignl.org/fileadmin/user_upload/pdf/LNG_Safety/1-LNG_Basics_8.28.09_Final_HQ.pdf.
[16] U.S Energy Information Administration. *The global LNG market - status and outlook*. 2003 [cited 2012 February 16th]; Available from: http://www.eia.gov/oiaf/analysispaper/global/lngmarket.html.
[17] Airbus, *A319/A320/A321 Flight deck and systems briefing for pilots*, 1999, Airbus Industrie: France.
[18] E. Commission, *Flightpath 2050 - Europe's vision for aviation*. 2011.
[19] M. Lage. *The use of natural gas in the transportation industry: European LNG Blue Corridors*. 2012 [cited 2013 March 15th]; Available from: http://www.apvgn.pt/documentacao/lage_agn_out12.pdf.
[20] Gasrec. *Gasrec begins trial of liquid biomethane fuel for ground vehicle at east midlands airport*. 2010 [cited 2013 April 2nd]; Available from: http://cnch4.com/mediadetails.php?ID=19.
[21] FLIGHT International. *Beech flies with methane*. FLIGHT International 1981 10 October [cited 2013 16 March]; Available from: http://www.flightglobal.com/FlightPDFArchive/1981/1981%20-%203155.PDF.
[22] L.K. Carson, et al., *Study of methane fuel for subsonic transport aircraft*, in *NASA CR159320*1980, Lockheed-California Company: California.
[23] D. Kaminski-Morrow *Tupolev's cryogenic Tu-155- 20 years on!* Flight Global, 2008. 16.
[24] E.M. Greitzer, et al., *N+ 3 Aircraft concept designs and trade studies.* NASA/CR—2010-216794/VOL2, 2010.
[25] R.T. Kawai, *Benefit Potential for a Cost Efficient Dual Fuel BWB*, in *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*2013, AIAA: Texas.
[26] J. Gibbs, D. Seigel, and A. Donaldson, *A natural gas supplementary fuel system to improve air quality and energy security*, in *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. 2012, American Institute of Aeronautics and Astronautics.
[27] Airbus S.A.S. *A320 Family: the market leader*. 2012; Available from: http://www.airbus.com/fileadmin/media_gallery/files/brochures_publications/aircraft_families/A320_Family_market_leader-leaflet.pdf.
[28] Tupolev. *Cryogenic aircraft: development of cryogenic fuel aircraft*. 1989 [cited 2013 10th February]; Available from: http://www.tupolev.ru/english/Show.asp?SectionID=82.
[29] A. Westenberger, et al., *Liquid hydrogen fuelled aircraft - system analysis (cryoplane final technical report)*, 2003, Airbus Deutschland GmbH.
[30] D. Verstraete, et al., *Hydrogen fuel tanks for subsonic transport aircraft.* International Journal of Hydrogen Energy, 2010. **35**: p. 11085-98.
[31] Airbus. *Future Concepts*. 2013 [cited 2013 27 March]; Available from: http://www.airbus.com/innovation/eco-efficiency/design/future-concepts/.
[32] K. Fulton, *Cryogenic-Fueled Turbofans: Kuznetov Bureau's pioneer work on LH_2 and LNG dual-fueled engines*. Aircraft Engineering, 1993: p. 8-11.
[33] G. Wilfert, et al. , *New environmental friendly aero engine core concepts*, in *International Symposium on Air Breathing Engines* 2007, AIAA: Beijing, China.
[34] E.P. Murray, T. Tsai, and S. Barnett, *A direct-methane fuel cell with a ceria-based anode.* Nature, 1999. **400**(6745): p. 649-651.
[35] F.R. Goldschmied, *Wind Tunnel Demonstration of an Optimized LTA System with 65% Power Reduction and Neutral Static Stability*, in *Lighter-than-Air System Conference*1983, AIAA 83-38910: Anaheim, CA.
[36] F. Goldschmied, *Integrated hull deign, boundary-layer control, and propulsion of submerged bodies*. Journal of Hydronautics, 1967. **1**(1): p. 2-11.
[37] F. Goldschmied, *Aerodynamic Hull Design for HASPA LTA Optimization.* Journal of Aircraft, 1978. **15**(9): p. 634-638.
[38] F. Goldschmied, *Wind tunnel test of the modified goldschmied model with propulsion and empennage: analysis of test results*, 1986: Monroeville, PA.
[39] S.K. Thomas, R.P. Cassoni, and C.D. Macarthur, *Aircraft anti-icing and de-icing techniques and modeling.* Journal of aircraft, 1996. **33**(5): p. 841-854.
[40] K. Bottome, *Gas turbine engine nose cone*, U.S.P.A. Publication, Editor 2011, Rolls-Royce PLC: Great Britain.