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Prospects for Liquefied Natural Gas and other Alternative Fuels for Future Civil Air Transportation

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Abstract

Fundamental issues related to the possible introduction of liquid methane, propane or butane fuelled civil passenger transport aircraft are addressed. It is proposed that partial transition to one, or a mixture, of these alternative fuels may provide an operational interim option when supplies of Avtur become prohibitively expensive. Preliminary criteria to determine the suitability of alternative fuels are also included.

Keywords: Cyrogenic Aircraft, Methane (LNG), Biomethane, Propane, Butane, Liquefied Petroleum Gas (LPG).

Introduction

At current production and consumption rates, the projected reserves of crude oil are likely to be exhausted before those of natural gas (especially when largely unknown stores of benthic methane clathrates are included). Consequently, within the civil aviation sector, Liquefied Natural Gas (LNG) and/or Liquefied Petroleum Gas (LPG) could become a viable interim alternative to Avtur (kerosene), prior to the introduction of a commercially viable and sustainable alternative, e.g., biofuel, Fig. 1.

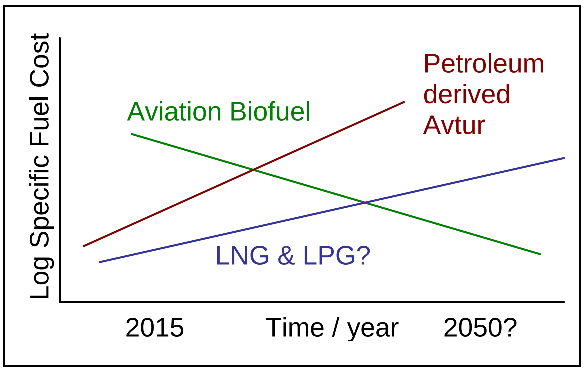

Fig. 1 Possible simplified future global fuel scenario

Proposals for LNG fuelled aircraft in have been made before. In 1980, Lockheed reported a detailed design study on a liquid methane (LCH_4) fuelled subsonic transport [1]. Also since the 1980's, Tupolev [2] have carried-out design and flight-test studies on prototype LNG fuelled civil passenger aircraft (see, for example, Fig. 2). These studies collectively demonstrate that LNG fuelled aircraft are technically feasible, but evidently they have not yet been sufficiently economically attractive to be widely implemented in the civil aviation sector.

However, LNG or LPG aircraft may become highly-attractive as in interim option in order to mitigate predicted escalations in Avtur costs, as well as partly meeting targets for greenhouse gas emissions set for 2020. Of course such a radical replacement would require extensive changes to airport infrastructure as well as significant modifications in aircraft design and engine technology. Despite this infrastructure barrier, renewed Russian activity [3] with LNG-LPG aircraft is worth noting. Furthermore, Boeing [4] has recently indicated in the NASA-led "Subsonic Ultra Green Aircraft Research (SUGAR)" programme that LNG could be a viable future alternative. Greitzer and Salter (2010) also advocated the possible use of LNG for "N+3" aircraft [5].

Fig. 2 Tupolev 155 LNG fuelled aircraft during test flight 18 Jan. 1989 [2].

This paper considers some of the fundamental issues that need to be addressed in order to evaluate whether or not a partial global aviation transition from Avtur to LNG/LPG is feasible and worthy of further detailed investigation.

Some Background on Alternative Aviation Fuels

LNG and LPG

LNG typically contains about 85% LCH_4. It is produced directly from ground-extracted natural gas and involves the relatively low cost separation of heavier hydrocarbons, as well as other impurities. Australia is currently the fourth largest LNG exporter in the world, exporting 18.9 million tonnes in 2011, with a value of around AU$ 11.1 billion [6].

LPG is mainly a mixture of liquid propane (LC_3H_8) and liquid butane (LC_4H_{10}), with the latter component typically less than about 60% (maximum). Australia currently produces about 5.3×10^9 litres of LPG per annum (mainly from natural gas), which is comparable to its refinery output of Avtur [7].

In their survey of possible alternative future aviation fuels, Daggett et al. [8] effectively dismiss LNG/LPG. They state that LPG "has many of same storage and transfer problems associated with a cryogen". They also state that the "natural supply is not sufficient to support a worldwide aviation fleet", and also that "their manufacture offers no availability, cost, or environmental advantage as a replacement for conventional jet fuel". This viewpoint should be contended for the following reasons:

1. The future world aviation fleets may evolve into a mixed fuel strategy (somewhat like the automotive sector), with possible strategic alliances (or agreements) being formed between major LNG/LPG producing countries.
2. The transfer, transportation and storage of 100 K+ cryogens are common practice. The storage of LCH_4 is far less demanding than ultra-low temperature cryogens such as liquid hydrogen. LC_4H_{10} is easily stored at room temperature (e.g., in cigarette lighters). LCH_4, LC_3H_8 and LC_4H_{10} also all have the advantage of not being prone to freezing in the stratosphere (at $\approx$ 220 K).
3. The hydrogen-to-carbon ratios of LC_3H_8 and LC_4H_{10} are higher than that of kerosene, and consequently the CO_2 produced per kilogram burned is about 4% lower. LCH_4 offers a 12% reduction based on equal mass, and up to 28% CO_2 reduction based on equal heat release.

Of course, there are other factors that may prevail against the direct use LNG/LPG in aircraft. In particular, if the petroleum sector develops viable schemes to convert natural gas to a storable Avtur alternative, e.g., through the Fischer-Tropsch (FT) process, then the development of LNG/LPG fuelled aircraft will probably not occur. However, such economically and environmentally viable conversion processes have yet to be fully-demonstrated, i.e. FT-kerosene is still prohibitively expensive.

Storage of LCH_4, LC_3H_8 and LC_4H_{10}

The equilibrium states of various fuels stored at 0.1 MPa are listed in Table 1. To store LCH_4 and LC_3H_8 at room temperature, tank pressures in excess of 1 MPa are required, whereas only 0.35 MPa is required to store LC_4H_{10} at 310 K.

Table 1 Saturation states at 0.1 MPa

Fuel	Temperature /(K)	Density/(kg m^{-3})
Butane C_4H_{10}	272	602
LPG (50% C_3H_{10}, 50% C_4H_{10})	242	600
Propane C_3H_{10}	231	581
Ethane C_2H_6	184	544
Methane CH_4	111	423
Gulf coast gas	111	439

At sub-cooled states, liquid densities of LCH_4 and LC_3H_8 are significantly higher than the values listed in Table 1. For example, the density of sub-cooled LCH_4 reaches 452 kgm^{-3} at about 91 K and sub-cooled LC_3H_8 reaches 732 kgm^{-3} at about 86 K. Although deep sub-cooling of LCH_4 reduces tank volume, reduces boil-off rates and permits reduced tank pressures, it was not considered economically beneficial by Carson et al. [1]. However, the density gain offered by ultra-sub-cooled LC_3H_8 is much greater than that of LCH_4 and may warrant investigation. It may even be worthwhile to investigate slush-LCH_4 stored close to the triple point e.g., as advocated by Tomsik et al. [9] for space propulsion applications, although pre-heaters would be required to permit pumping and to prevent CH_4 ice particulate blockage in supply lines.

Biofuels

In the past decade, biofuels have been frequently proposed as the best (if not the only) future sustainable aviation strategy [8]. However, one major problem with biofuels is the predicted lack of available arable land area (not just regionally, but globally) to grow suitable plant crops, as well as inevitable conflicts with fresh water supplies and food production [10]. Generation of sustainable biofuel supplies from lacustrine algae may be viable, but at present algae-derived bio-kerosene is prohibitively expensive [11].

The use of LCH_4, LC_3H_8 and LC_4H_{10} could form a suitable operational extension strategy within the civil aviation sector, until the production of low-cost biofuels (or some other truly sustainable solution) becomes economically feasible. Of course, the incentive for aviation fuel alternatives will not only be driven by Avtur price, but perhaps more importantly by future carbon emission targets. In this regard, it should be noted that liquid biomethane [12-13] could be blended as a minor constituent with LNG, resulting in a further 5-10% net carbon emission reduction. There are also recent reports that suggest that the production of biobutane from wood [14] might be commercially viable sometime in the future.

Comparison of fuels

The heating values and saturated liquid densities of LCH_4, LC_3H_8 and LC_4H_{10} are compared with Avtur, dodecane and Fatty Acid Methyl Ester (FAME) representative of a typical first generation biofuel, in Table 2. Relative Breguet ranges (flight range divided by range achieved with Avtur) are inversely proportional to thrust specific fuel consumption, SFC, for constant propulsive efficiency and lift-to-drag ratio. On an equal gross and fuel mass basis, the ranges of LCH_4, LC_3H_8 and LC_4H_{10} aircraft are therefore substantially improved. However, increased tank volume is required to use the low density alternatives listed (especially LCH_4) resulting in a payload penalty compared with Avtur.

Note: in such comparisons the use of lower calorific value requires careful consideration, e.g., since LCH_4 could be pre-heated by lightweight regenerative heat exchanger systems.

Table 2 Comparison of fuels

Fuel	**Heat value** /(MJN^{-1})	**Density** /(kgm^{-3})	**SFC_{kero}/SFC**
LCH_4	5.67	423	1.30
LC_3H_8	5.13	585	1.18
LC_4H_{10}	5.08	601	1.17
Dodecane	4.82	745	1.11
Avtur	4.36	800	1
FAME	3.81	869	0.87

System Considerations

Aircraft Design

If the fuselage of an aircraft has to be enlarged to cater for increased fuel volume, then there would be a reduction in lift-to-drag ratio, as well as an increase in dry mass. The former adverse effect is quite small: if the fuselage contributes about 30% to the overall drag, then a 15% fuselage volume increase would only result in a drag penalty of about 3%. The dry mass increase is appreciable for LCH_4 aircraft, since the storage tank(s) is effectively a heavy cryogenic dewar with thick insulation. In the case of LC_4H_{10} storage (possibly in the wing) would not require any insulation and impose a far lower dry weight penalty.

Unlike Avtur, LNG and LPG cannot be primarily stored within the limited wing volume of conventional passenger aircraft. Several alternative configurations need to be compared. One category has the LNG/LPG tanks integrated with the main fuselage, either running above the passenger cabin, or bisecting it near the wing, or with two tanks placed at either end of the passenger cabin [1-4]. The other category involves wing-mounted fuel tank pods. The latter introduces a higher drag penalty, but might be considered as an intermediate retro-fit modification option.

Note: the possible introduction of so-called Blended-Wing-Body aircraft [15] could result in substantive increases in available tank volume.

Preliminary Performance Comparison

For illustrative purposes, it is useful to compare the approximate relative performance of an LCH_4 aircraft vis-à-vis one fuelled with Avtur. The key performance parameters of primary interest are the relative payload ratio and the relative CO_2 release per unit payload (or passenger) which is proportional to the relative fuel burn to payload ratio. The payload ratio of both the LCH_4 and Avtur aircraft are simply given by,

$$m_\lambda / m_0 = 1 - m_{dry} / m_0 - m_f / m_0 \qquad [1]$$

The dry mass fractions of both aircraft may be expressed as a simple function of the tank volume,

$$m_{dry} / m_0 = \frac{(m_{dry} / m_0)_{avtur}}{(1 + c_1)} \left[1 + c_1 \frac{(m_f / \rho_f)^n}{(m_{avtur} / \rho_{avtur})^n} \right] \qquad [2]$$

The fuel mass fraction of both aircraft may be approximated by the standard inverted Breguet equation,

$$m_f / m_0 = 1 - \exp\left[\frac{-Rg_0 SFC}{U_{cruise}(L/D)} \right] \qquad [3]$$

where the lift-to-drag ratio may also be expressed as a function on tank volume,

$$(L/D)^{-1} = (L/D)^{-1}_{avtur} + c_2 \{1 - (m_{avtur} / \rho_{avtur})^{2/3} / (m_f / \rho_f)^{2/3}\} \qquad [4]$$

Figure 3 shows that relative performance is dependent on the two unknown variables c_1 and c_2 that both effectively dictate the extent of the negative impacts of increased tank mass and size. If $c_1 \cong 0.4$ and $c_2 \cong 0.007$ are achievable, then the relative payload loss of the LCH_4 aircraft may be reduced to about 5-10%, with a CO_2 per passenger-km reduction of around 15-20%. Furthermore, a significant saving would achieved be in direct operating costs (the gain obviously depending on the relative prices of LCH_4 and Avtur). These finds are relatively insensitive to changes in operating range and aircraft gross mass.

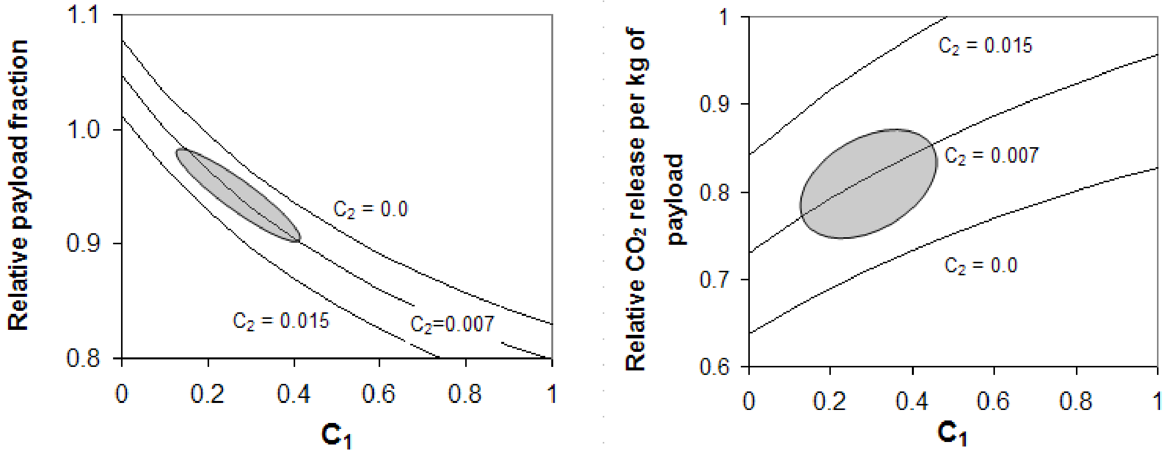

Fig. 3. Example of preliminary performance evaluation of LCH_4 fuelled aircraft relative to Avtur fuelled baseline, with the following parameters: R = 4000 km, m_0 = 230 tonnes, $m_{dry\,Avtur}$ = 119.6 tonnes, SFC_{Avtur} =1.3 x10^{-5} kgs^{-1}N^{-1} (0.46 lb/h/lbf), U_{cruise}=243 ms^{-1}, $(L/D)_{Avtur}$= 18, n = 0.8. The shaded areas represent a likely feasible design target.

Dual Fuel Solutions

Previous flight tests by Tupolev [2] involved dual fuel (Avtur plus LNG) operation. There is an obvious advantage of keeping a storable fuel for contingency reserves; however this introduces complexity and a weight penalty. Mixing Avtur and LNG through-pylon feed lines introduces the problem of Avtur freezing. Hence an LNG plus LPG solution may be attractive. Demonstrations of LNG-only operations would have to prove that boil-off during extended time periods (flight delays) is manageable.

Tank insulation

Tank heat transfer rates will probably dictated by the insulation material (typically a low density, low thermal conductivity foam). In the 1980s, it is worth noting that Beech Aircraft Corporation developed a LCH_4 storage vessel with an ultra-low low boil rate for general aviation use [16].

Powerplant Implications

The performance calculations above assume constant propulsive eficiency. However, Graham and Glassman [17] have already shown that the cooling properties of LCH_4 could be used to raise turbo-prop engine efficiency. They suggest that direct stator cooling is feasible. Compressor inter-cooling could also be used to raise overall thermal efficiency [18]. Renewed studies are needed, reflecting the advances in contemporary engine technology. For example, the use of superconductors operating in the 100-120 K range is worthy of investigation.

Airport Refuelling System Changes

Any transition from Avtur to LNG/LPG will undoubtedly be impeded by the demanding requirements for extensive changes to the ground refuelling infrastructure (which is not the case for direct replacement aviation biofuels).

The stringent requirements for the provision of Avtur are well established [19]. Currently, at most airports, Avtur is stored in the fuel tank area which is situated away from other infrastructure in the airport precinct. The storage capacity of the tanks typically permits a continuous fuel supply for 1-3 days [18]. Aircraft are refuelled either from an airport hydrant system, directly from fuel pits, or by mobile fuel tankers [20]. In the hydrant system, pipes located beneath the airport apron are connected to the fuel storage area. Flush-mounted hydrant valves are provided at each airport gate position. Avtur can be quickly pumped into the parked aircraft by attaching the fuel dispenser to the closest hydrant valve. At large airports, underground pipelines are generally regarded as the safest distribution scheme [20]. Clearly, such underground piping would have to be completely replaced in order to carry LNG or LPG. At smaller airports mobile Avtur tankers are used [20]. These tankers carry their own pumps, reels, meters, fuel filters etc. They are capable of carrying fuel loads up to 8000 U.S. gallons and specifically designed for operating on airport aprons [21].

Avtur is presently transported to airport stores by pipeline directly from the production plant, by ship (or barge), by railway or by lorry-mounted container [19]. Direct ship transport of LNG/LPG to storage facilities located within/or near major airports might be possible in some cases. For example: Tokyo Haneda is located on Tokyo Bay, Hong Kong is located on Landau Island in a bay, Singapore is located close to the sea, and Sydney is located on Botany Bay. However, investigations are needed to determine whether or not LNG storage facilities could be accommodated. Depth of the water and tidal flows are other important issues to be considered.

Safety

The minimum ignition energy of CH_4 is far higher than hydrogen, and its flammability limits are narrower, hence it is arguably far safer than liquid hydrogen. An explosion of an LNG container fitted with pressure relief equipment is an unlikely event, although aircraft crash scenarios clearly require study. LNG is also less hazardous than Avtur and LPG as shown in Table 3. When LNG is spilled, it will spread and absorb heat from the surroundings and rapidly vaporize. The radiant heat effects from an ignited pool of LNG depend on the amount of flammable material and the supply of air to the fire. Small pool fires burn with a relatively clear flame. In the case of a large pool fire, there is insufficient air supply to support complete combustion, resulting in soot generation. Therefore, smaller pool fires may radiate more relative to their size, than larger pool fires. If there is no ignition source, then a vapour cloud will form. As the cloud warms, the vapour becomes lighter than air, rising into the atmosphere and dispersing with winds.

Table 3. Comparison of hazards for liquid fuels adapted from ref. [22].

Hazard	LNG	LPG	Avtur
Toxic or Carcinogenic	No	No	Yes
Asphyxiant	Yes, in confined spaces (e.g., leakage into passenger cabin).	Yes, same as LNG, but higher density encourages accumulation.	No
Other health hazards	Low temperature, possible freezing when not insulated	No	Eye irritant, narcosis, nausea, others
Behaviour, when spilled	Evaporates forming visible, flammable vapour cloud that disperses quickly	Evaporates forming flammable vapour cloud that tends to accumulate	Forms a flammable pool and flammable vapour cloud; environmental clean-up required

Other operational experience with LPG/butane aircraft

In the 1980's leading Russian aviation companies, petroleum industries and universities collectively proposed a new fuel as an alternative to Avtur. This new fuel called ACKT was a mixture of hydrocarbons with LC_4H_{10} as the dominant component. It was claimed that ACKT had superior qualities compared to Avtur [3, 23]. For example, it was significantly cheaper, non-toxic and less aggressive to sealants. The use of the ACKT was also estimated to reduce fuel costs by a factor of 3-8. In order to demonstrate the feasibility of the concept and explore its benefits, the Mil Helicopter organization conducted a development program [24], which resulted in the production of the Mi-8TG prototype using ACKT (carried in external pod tanks produced from automotive LPG tanks), see Figure 5.

Figure 5 Mi-8TG with external ACKT pods [25].

The first flight of the Mi-8TG took place on 7th of September 1987. This prototype displayed excellent characteristics. For example, the walls of the engine combustion chamber and turbine blades did not have residuals, and the observed power-specific fuel consumption was also reduced by 5% permitting increase in range.

A pre-serial production version of the helicopter was produced and demonstrated at the Zhukovsky Aerospace Show in 1995 [26]. The features of the helicopter included twin engines which could be fuelled by ACKT, or Avtur, or both. Modification of the helicopter with the tanks could be completed by an aviation maintenance centre within 2-3 weeks. The further plan to modify up to 50 Mi-8T helicopters into a dual-fuel version of the Mi-8TG was not implemented due to the absence of the required funding despite confident predictions of overall cost savings.

Conclusions

The introduction of LNG/LPG for aviation use will strongly depend on its relative price compared to Avtur, as well as carbon emission targets. It is not yet clear that Avtur prices (with associated carbon taxation) will exceed a critical level to bring-about any near-future transition; however, it would prudent to prepare for this eventuality. It is therefore concluded that renewed system level studies, on LNG/LPG fuelled aircraft (including airport infrastructure changes) are justified.

Consequently, it is recommended that a consortium comprising of university, aircraft and aero-engine design authorities and operators, LNG/LPG industries and other associated stakeholders commence comprehensive and integrated studies within Australia in the near future.

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