Alternate Fuels for use in Commercial Aircraft

David L. Daggett
Boeing Commercial Airplane, Seattle, WA, 98124

Robert C. Hendricks
NASA Glenn Research Center, Cleveland, OH, 44135

Rainer Walther
MTU Aero Engines GmbH, Munich, Germany

Edwin Corporan
Air Force Research Laboratory, Dayton, OH

Abstract

The engine and commercial aircraft research and development communities have been investigating the practicality of using alternative fuels in near, mid, and far-term aircraft. Presently, it appears that an approach of using a “drop in” jet fuel replacement, which may consist of a kerosene and synthetic fuel blend, will be possible for use in existing and near term aircraft. Future mid-term aircraft may use a bio-jet and synthetic fuel blend in ultra-efficient airplane designs. Future, long-term engines and aircraft in the 50-plus year horizon, may be specifically designed to use a low or zero-carbon fuel.

Synthetic jet fuels are manufactured, using a Fischer-Tropsch process, from coal, natural gas or other hydrocarbon feedstocks. These fuels are very similar in performance to conventional jet fuel, but have almost zero sulfur and aromatics. This may result in lower particulate exhaust emissions. In addition, synthetic fuels exhibit excellent low-temperature properties, maintaining a low viscosity at lower ambient temperatures. Thermal stability properties are also improved, resulting in less fuel system deposits. As synthetic fuels have very good performance, and have already been in use for many years in Johannesburg airport (Sasol fuel) it will be easy to supplement current jet fuel supplies with synthetic derived fuel. If the additional CO₂ that is produced during the manufacturing process can be captured and permanently sequestered, synthetic fuel could be a good near-term supplement.

For a possible mid-term solution (i.e., 10-50 years from now) it is envisioned that alternate fuels will make up a much larger percentage of jet fuels. These fuels may also involve the blending of bio-fuels with the synthetic fuel. The major challenges of using pure bio-fuels in a commercial aircraft are its propensity to freeze at normal operating cruising temperatures, its poorer high temperature thermal stability characteristics in the engine, and its storage stability over time. For these reasons, bio-jet fuels need to be developed that address these issues and so will be especially tailored for jet aircraft. Another drawback is that, because of limited excess farmland, present bio-fuels are not capable of supplying a large percentage of fuel without displacing food production. However, higher yielding future feedstocks, such as algae, may dramatically improve supply capability. The advantages of using bio-fuels would be its environmentally balanced CO₂ impact, its capability to become a sustainable fuel, and it may result in lower engine emissions. If the performance and resulting cost liabilities can be overcome, bio-fuels are envisioned to be blended with synthetic jet or Jet-A fuels.

Long-term solutions will need to dramatically reduce the emissions of greenhouse gases. Therefore, alternate fuels with low to zero carbon content, such as liquid hydrogen or liquid methane, might be used. To use liquid, cryogenic fuels in aircraft engines, modifications are necessary to the combustor and fuel system components. Early tests with cryogenically stored fuels demonstrated that a heat exchanger will be required for vaporizing the fuel prior to combustion. Compromises are necessary to the airframe to address fuel tank insulation requirements and pressure issues. The need for heavy insulated fuel tanks would result in a decrease in the aircraft’s energy efficiency on short range flights. On the other hand, vast quantities of methane currently trapped in the forms of methane hydrates could become readily available in the future. Either of these new aircraft fuels will require an enormous change in infrastructure and engine-airplane
design. Many life-cycle environmental questions will need to be addressed.

1. Background

Several sources have documented the diminishing discovery of new petroleum sources and the ever increasing global demand, Fig. 1.

Some sources claim we have already reached a point where half of the world’s crude oil has been consumed, while others indicate mid-century, Fig. 2. In any regard, mitigation options must be implemented many years, perhaps decades, in advance of the actual peak oil event to assure a smooth transition to alternate fuels.²

Figure 1. The rate of oil discovery is falling while the rate of oil consumption is increasing.¹

Figure 2. Alternate fuel sources will need to be developed to offset the anticipated peak production of conventional oil supply.³

Current aircraft have experienced dramatic improvements in fuel efficiency since the introduction of commercial jet aircraft in the 1960s. Next-generation aircraft will see another 15-20 percent improvement in fuel efficiency, making air travel one of the most efficient means of transportation. However, air travel growth is predicted to continue at five percent per year and the future rate of gains in fuel efficiency will thus be outpaced by the projected growth in air traffic. So the aircraft industry will still require an increasing amount of fuel.

As a consequence, the aviation industry is interested in alternate energy sources and alternate fuels in particular. The key issues center on finding a sustainable source of fuel for the future that will keep the fuel costs at a reasonable level. In addition, potential alternate fuels should exhibit environmental benefits, by providing airline operators with potential CO₂ credits.

2. Introduction

Fuels derived from feedstocks such as coal, natural gas, bio-oils and cellulose matter were widely used during WW-II. The most pervasive method of conversion includes reforming the feedstocks through heat and catalytic reactions to syngas (CO and H₂) followed by conversion of the syngas into synthetic crude via the Fischer-Tropsch (FT) process. The synthetic crude is further hydrofractured to synthesize paraffins with a small percentage of non-paraffins. A typical hydrocarbon spectra of a widely known non-renewable synthetic fuel (synfuel) is illustrated in Fig. 3.

Plant derived fuels include feedstocks derived from soybean oils, palm oils, corn, switchgrass and algae. These resources are considered renewable, but most would require large areas for plant nurturing. As such, bio-derived fuels offer a reduction in life cycle CO₂ and many can be very attractive fuel candidates.

Longer-term alternate fuels could be liquid hydrogen and liquid methane. The use of hydrogen in space programs is well understood, however, due to its high specific volume, its application may be characterized by a huge storage tank, Fig. 3.

Aircraft fuels, such as Jet-A, developed over many years of application, have relatively high energy per unit weight and volume. A typical FT jet fuel possesses very similar properties as Jet-A fuel. Most other alternate fuels may suffer from the lack of one or the other characteristic, i.e. hydrogen shows a superior energy content per unit weight, but exhibits a high specific volume.
3. Discussion

Aircraft and engine companies are currently investigating FT fuels and bio-fuels. The type of fuel of immediate interest to aviation is termed a “drop in” fuel (i.e. direct replacement) as one that can be blended with, or completely replace, Jet-A without necessitating any substantial modifications to engine or aircraft.

3.1 Synthetic Fuels

Presently, natural gas and coal are the most used candidate feedstocks for FT plant processing. Currently, FT fuels with Jet-A blends can be considered as “drop in” fuels.

The positive attributes of these fuels include: cleaner burning fuels with no sulfur and higher thermal stability resulting in less fuel system deposits, which is of importance to high performance military aircraft engines, Fig. 4.

The negative attributes include poorer lubrication properties, lower volumetric heat content, possible contributor to fuel system elastomer leakage (lack of aromatics reduces seal swell), and increased CO2 emissions during its manufacture. Large quantities of energy are used during the FT manufacturing process that release about 1.8 times more CO2 into the atmosphere as compared to crude oil derived jet fuel. Figure 6 shows the relative life cycle CO2 emissions from various fuels, using current jet fuel as the baseline. FT fuels can only be considered as a viable alternative to petroleum if the CO2 emissions generated during production can be captured and permanently stored.
sequestered. However, this can add substantially to the cost of FT fuels.\(^5\)

![Relative CO₂ emissions as compared to Jet fuel](image)

**Figure 6.** FT fuels exhibit high life-cycle CO₂ emissions, requiring carbon sequestration during the manufacturing phase. Bio-fuels have much lower CO₂.

### 3.2 Bio-fuels

In order to be viable in the commercial aviation industry, bio-fuels need to overcome several technical hurdles. However, the task is not insurmountable, and there is no single issue making bio-fuel unfit for aviation use. Bio-fuels need to be developed and have to be especially tailored for jet aircraft applications, which we term as “bio-jet.”

One of the challenges is its propensity to freeze at normal operating cruise temperatures, which represents far more extreme operation capability compared to conventional bio-diesel. A first look at bio-fuels found them unable to pass the freeze point requirements with only a fraction of the tolerance required of Jet-A, Fig 7.

![Freezing Point, (°C) per ASTM D 5972](image)

**Figure 7.** 100% pure bio-jet fuels tested thus far are starting to approach the minimum freeze requirements.

Another challenge is its poor high thermal stability characteristics in the engine. However, a blend of 20 percent bio-jet with 80 percent Jet-A passed the jet fuel thermal stability requirements as shown in Fig. 9. This is much improved over the results for 100 percent biodiesel as shown in the rightmost bar in Figure 9.

![Bio-jet fuels blended at 20 percent with Jet-A appear to pass the jet fuel thermal stability (JFTOT) requirement.](image)

**Figure 9.** Bio-jet fuels blended at 20 percent with Jet-A appear to pass the jet fuel thermal stability (JFTOT) requirement.

Another drawback of bio-fuels is that, because of limited excess farmland, bio-fuels are not capable of supplying a large percentage of fuel without displacing human food production. Thus, conventional feedstocks such as corn, soybeans, and rapeseed may limit the availability of bio-jet. For example, the use of a 15 percent bio-jet/85 percent Jet-A blend in the US domestic commercial aircraft fleet would require more than 2 billion gallons of bio-jet. The production of this amount of fuel would require 34 million acres of land, about the size of the state of Florida. A similar situation exists in other parts of the world where energy demands by far outstrip the ability to produce the required amount of bio-feedstock.
3.3 Sustainability

A recent trend has been to develop soybean crops as feedstock for lipid (i.e. oil-based) biofuels. However, in order to create sufficient farm land capacities, deforestation, using slash and burn practices, can take an extreme toll on rainforests. The resulting CO\textsubscript{2} emissions are anticipated to exacerbate global warming issues. Thus, great care has to be taken to assure that bio-feedstock is sustainable and will not cause new anthropogenic issues through deforestation as shown in Fig. 10.

Every region throughout the world may have specific solutions. For example, one sustainable solution might be to harvest nuts obtained from native Brazilian palm trees called “Babassu.” The oil from these nuts might provide a sustainable source of oil for bio-jet fuel in Brazil. Airframe manufacturers are working with local entities in a joint effort to evaluate the possibility of these bio-jet fuels, Fig. 11.

Future bio-fuels may also involve other sources of oil feedstock. One promising feedstock is algae which have been evaluated by the US DOE\textsuperscript{7}. This feedstock is projected to produce anywhere from 10k to 20k gallons/acre/year of bio-derived oil. With such a high production rate, algae could produce 150-300 times more oil than a crop of soybeans, Fig. 12.

With the potential for algae of providing 10,000 gal/acre/year, some 85 billion gallons of bio-jet could be produced on a landmass equivalent to the size of the US state of Maryland. Moreover, if these bio-jet fuels were fully compatible with legacy aircraft, it would be sufficient to supply the present world’s fleet with 100 percent of their fuel needs (fig. 13) as well into the future.

Another long term solution may be related to the huge amounts of methane gas, trapped in the forms of methane hydrates (clathrates). These hydrates are currently stable and are stored in the deep ocean floors and under some permafrost regions. They potentially could offer a fuel source for many hundreds of years,
Fig. 14. Whereas the world’s conventional methane resources are estimated to about $0.3 \times 10^{12}$ m$^3$ with most of it located in the middle-east and former Soviet-Union, the methane resources locked in methane-hydrates are estimated to about $21.10^{12}$ m$^3$, with most of it located in the Americas$^8$.

However, a number of still open questions with respect to its extraction have to be answered. Major issues concern the uncertain economics of recovery under unfamiliar and inconvenient deep undersea-conditions, as well as a number of environmental, technical feasibility and safety aspects$^9$. On the other hand, extraction of these deposits in permafrost areas may be required in order to help control global warming. As the earth and oceans warm, the deposits presently locked under permafrost may become exposed. The methane released could be a far more potent greenhouse gas contributor than CO$_2$ is today.

4. Present, Mid-term and Future Fuel Solutions

Currently, nearly 100 percent of all aviation fuel is petroleum derived, based on conventional and well-known refining technology with the ability to supply billions of gallons of jet fuel annually, (Jet-A and JP-8). In the past, these sources have been highly reliable and cost effective. The most recent price fluctuations and vulnerability of petroleum sources for transportation fuels are driving the need for synthetic fuels and synthetic fuels /Jet-A blends to reduce these fluctuations and secure sources of supply.

Presently, coal and natural gas are good candidate feedstocks for FT plant processing into synthetic jet-fuel (synjet). Synjet is being blended and used in up to 50 percent blends with Jet-A fuel in South Africa (Sasol fuel) without reported detrimental effects on aircraft or engine performance. The recently performed USAF B-52 testing program with a 50/50 JP-8-synjet blend also demonstrated no detrimental effects on either engine or aircraft. As a result, synjet-Jet-A blends are being considered as “drop in” fuels for the present, Fig. 15. If the additional CO$_2$ that is produced during the manufacturing process can be captured and permanently sequestered, synthetic and Jet-A fuel blends will be an acceptable near-term supplement.

Mid-term solutions include the blends of synjet fuels and processed bio-fuels (bio-jet) along with major changes in engine configurations, Fig. 16. Whereas the synjet production plants are still most likely fed by coal or natural gas, the bio-feedstocks remain varied and most likely the oils will be provided from several sources to form a pre-blend of bio-kerosene that has to be further refined to bio-jet. These fuels will be blended with synthetic fuels but at a significantly reduced mixture ratio compared to synjet-Jet-A blends.
improved propulsion efficiency. In addition, thermal efficiency can be further raised by inter-cooled, recuperative engine concepts. Concepts such as these engines may be integrated into advanced aircraft designs.

Long-term fuel solutions will need to dramatically reduce greenhouse gas emissions. Therefore, alternate fuels with low or zero carbon content, such as cryogenic hydrogen or liquid methane, might be used. Hydrogen may be generated by solar or nuclear fusion energy. As vast quantities of methane could become available from methane hydrates, it could be liquefied for direct use in specially designed future aircraft or it could be used as a source to generate liquid hydrogen while sequestering the CO₂, Fig. 17.

Figure 17. Long-term aviation fuel may be hydrogen derived from solar and fusion power as well as methane hydrates.

In order to use liquid cryogenic fuels in aircraft engines, a number of significant modifications are necessary to the combustor and fuel system. Early tests with cryogenically stored fuels demonstrated that a heat exchanger will be required for vaporizing and heating the fuel prior to combustion. Compromises are necessary to the airframe to address the large fuel tank and the needed insulation. The need for heavy insulated tanks could result in a decrease in the aircraft’s energy efficiency, especially on short range flights.

These fueling options will require the redesign of both the engine and airframe taking into account the characteristics of cryogenic systems. Either of these new aircraft fuels will require completely different and creative aircraft and engine designs. They will have an enormous impact on fuel supply infrastructure.

5. Conclusion

The motivation to develop alternate fuels for commercial aviation is twofold: First, with respect to near-term concerns, alternate fuels will relieve the worldwide pressure on crude oil derived fuels. This will help to stabilize price fluctuations.

Secondly, with respect to mid-term concerns, alternate fuels should increase environmental performance of air transportation, including a substantial potential for reduction of CO₂ emissions over the life cycle.

Thus, the ideal alternate fuel will fulfill both requirements: to relieve the worldwide pressure for crude oil derived fuels and to significantly reduce CO₂ emissions.

The short-term option of synthetic fuels processed in the FT process meets the first target. It has the potential to release pressure from pure crude oil derived fuels, without a long delay. However, it will not reduce CO₂ emissions over the entire life cycle. Moreover, if the additional process related CO₂-emissions are not captured and sequestered, the total CO₂-emissions may double.

The mid-term options, including future renewable derived bio-fuels and its blends with synthetic fuels, offer the promise of a complete replacement for crude oil derived fuels. In addition, for at least the CO₂-emissions from the bio-derived fuel fraction, it offers the chance for an atmospheric neutral CO₂ balance fuel. Algae seem to be a promising future feedstock option which could provide a much higher oil yield per hectare than present bio-fuels. As such, it is presently the most attractive lipid-based biofuel feedstock to pursue for aviation. Other feedstocks, such as switchgrass, may provide the feedstock needed to produce cellulosic ethanol that could be efficiently and easily used in ground transportation.

The final long term option seems to be low carbon, liquefied gaseous fuels. Liquid methane, extracted from methane hydrates; or perhaps liquid hydrogen, produced from nuclear – or preferably – from solar power, are promising long term options. In combination with economically viable fuel saving technologies, both fuels may also completely replace the current crude oil derived fuel sources. In addition, hydrogen fuel could completely resolve CO₂-emissions. However, a number of technological challenges have to be solved prior to its use in air transportation: A low fuel volume density, even when stored onboard as cryogenic fuel, will result in large, heavy insulated fuel tanks that will no longer
be able to be integrated in the airframe wings. In addition, an economic and environmentally sound way of producing the fuel needs to be developed. Flight environmental factors, such as increased water vapor emissions, need to be understood. Lastly, a complete, worldwide cryogenic fuel infrastructure has to be established.

As hydrogen production and infrastructure issues are addressed for ground transportation, they will also provide new opportunities for air transportation. Finally, the storage of cryogenic fuels onboard and its use in advanced engines have to be solved by creative and highly advanced airframe designs which may completely differ from today’s airframe shapes.

References

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