



Alternate Fuels for Use in Commercial Aircraft

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Summary

The engine and aircraft Research and Development (R&D) communities have been investigating the practicality of using alternative fuels in near-term, midterm, 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 midterm aircraft may use a biojet and synthetic fuel blend in ultra-efficient airplane designs. Future far-term engines and aircraft in 50-plus years 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 contain 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. Because synthetic fuels have very good performance and have already been in use for many years at the 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 midterm solution (i.e., 10 to 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 biofuels with the synthetic fuel. The major challenges of using pure biofuels in a commercial aircraft are their propensity to freeze at normal operating cruising temperatures, poorer high-temperature thermal stability characteristics in the engine, and poor storage stability over time. For these reasons, biojet 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 biofuels 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 biofuels would be their environmentally balanced CO₂ impact and capability to become a sustainable fuel. Their use may also result in lower engine emissions. If the sustainability, performance, and cost liabilities can be overcome, biofuels are envisioned to be blended with synthetic jet or Jet-A fuels and thus have near-term potential in terms of global climatic concerns.

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 these or other 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 must be made to the design of 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 thus engine and airplane design. Many life-cycle environmental questions will also need to be addressed.

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 that will happen midcentury (fig. 2). In any regard, mitigation options must be implemented many years, perhaps decades, in advance of the actual peak oil event to ensure a smooth transition to alternate fuels (ref. 2).

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 to 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 5 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.

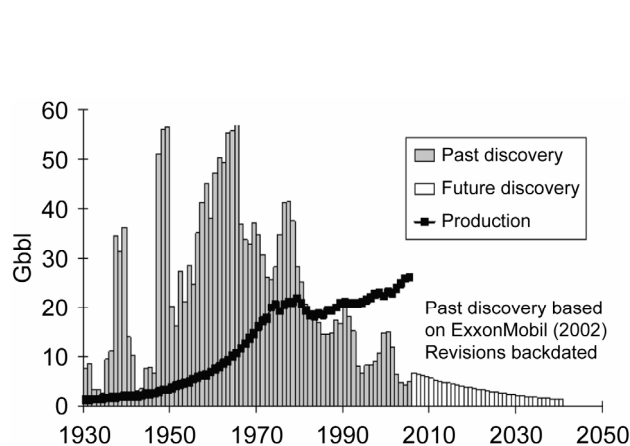


Figure 1.—Rate of oil discovery compared with rate of oil consumption (from ref. 1).

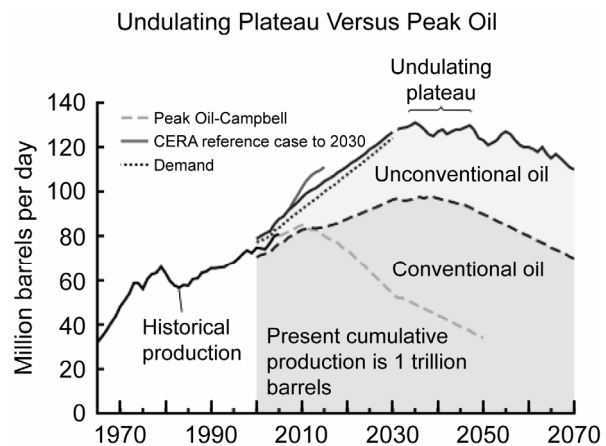


Figure 2.—Peak oil predictions (from Cambridge Energy Research Association (CERA), ref. 3).

Introduction

Fuels derived from feedstocks such as coal, natural gas, bio-oils and cellulose matter were widely used during World War 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 nonparaffins. A typical hydrocarbon spectrum of a widely known nonrenewable synthetic fuel (synfuel) is illustrated in figure 3(a).

Plant-derived fuels (fig. 3(b)) 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, bioderived 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, because of its high specific volume, its application may necessarily be characterized by a huge storage tank (fig. 3(c)).

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

Discussion

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

Synthetic Fuels

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

The positive attributes of FT fuels include (1) they are cleaner burning fuels with no sulfur and (2) they have higher thermal stability, resulting in less fuel system deposits, which is of importance to high-performance military aircraft engines (fig. 4).

Test results have shown that FT fuels result in engine emissions with less particulates. Compared with conventional jet fuels, these fuels show excellent low-temperature properties, maintaining a low viscosity at lower ambient temperatures (fig. 5). This could improve high-altitude operability and low-temperature starts of the engine.

The negative attributes include poorer lubrication properties, lower volumetric heat content, possible contribution 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 compared with that of jet fuel derived from crude oil. Figure 6 shows the relative CO₂ emissions produced during the life cycles of various fuels, using current jet fuel as the baseline. The FT fuels can only be considered as a viable alternative to petroleum if the CO₂ emissions generated during production can be captured and permanently sequestered. However, this can add substantially to the cost of FT fuels (ref. 5).

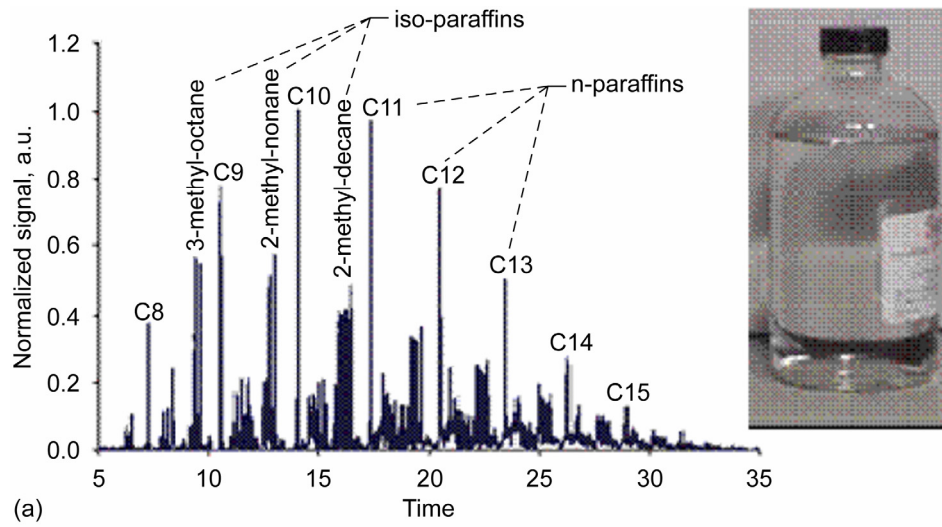


Figure 3.—Examples of alternate jet fuels. (a) Synthetic Fischer-Tropsch fuel: hydrocarbon spectrum. (b) Bioderived renewable fuels: soybeans as oil-based feedstock. (c) Space shuttle liquid hydrogen tank.

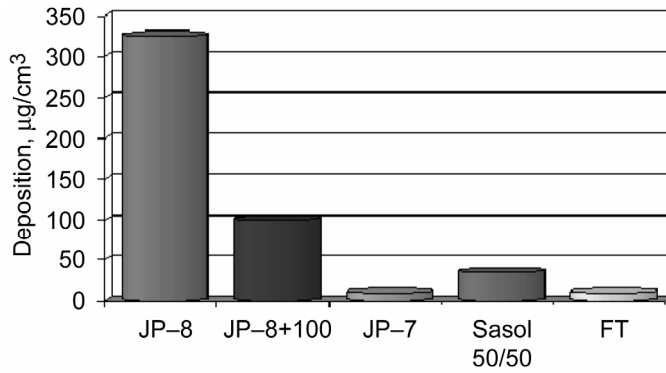


Figure 4.—Thermal deposition of various fuels after 6 hr in Air Force Research Laboratory single-tube flow reactor (ECAT) test rig (ref. 4).

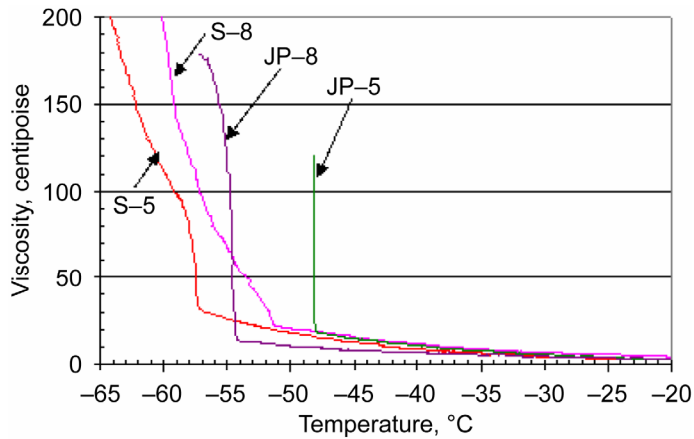


Figure 5.—Freezing qualities of Fischer-Tropche synthetic fuels S-8 and S-5, synthetic replacements of JP-8 and JP-5 (ref. 4).

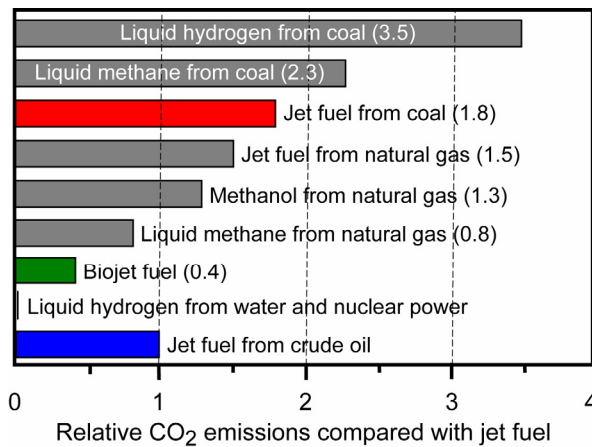


Figure 6.—Relative life-cycle CO₂ emissions of various fuels compared with current jet fuel (Jet-A).

Biofuels

In order to be viable in the commercial aviation industry, biofuels need to overcome several technical hurdles. However, the task is not insurmountable, and there is no single issue making biofuel unfit for aviation use. Biofuels need to be developed that are especially tailored for jet aircraft applications; these are called “biojet” fuels.

One of the challenges are their propensity to freeze at normal operating cruise temperatures, which presents a far more extreme operation capability requirement than that required of conventional biodiesel. A first look at biofuels found them unable to pass the freeze point requirements with only a fraction of the tolerance required of Jet-A (fig. 7).

However, more recently developed biojet fuels have been substantially improved (fig. 8).

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

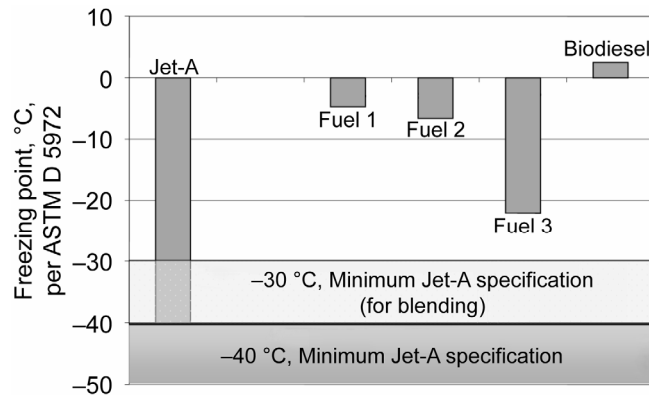


Figure 7.—Freezing points of pure biojet fuels compared with jet fuel minimum freeze requirements.

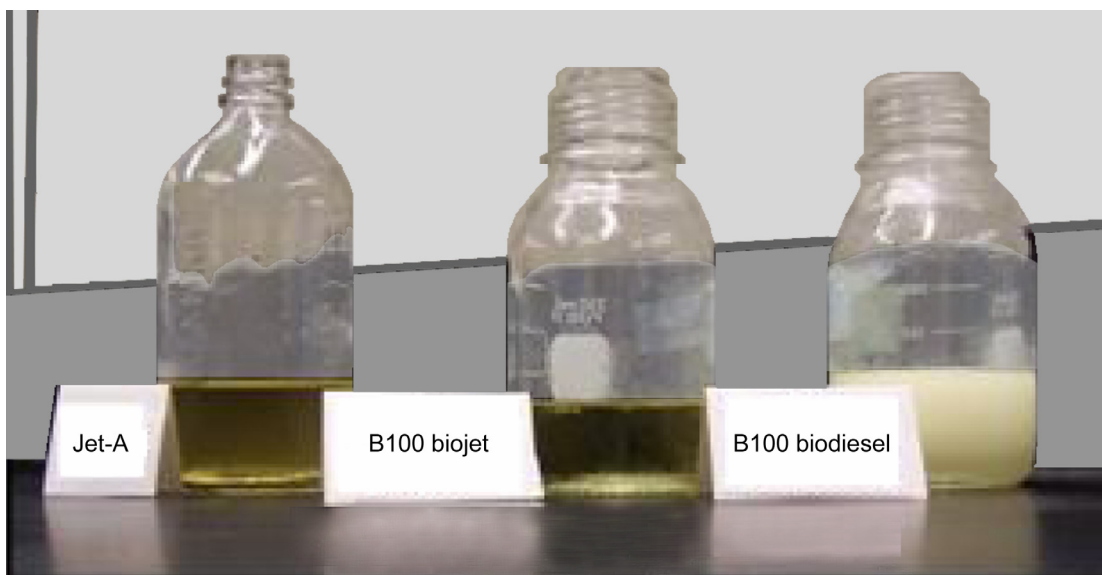


Figure 8.—Recent biojet fuels capable of meeting freezing point requirements at $-30\text{ }^{\circ}\text{C}$.

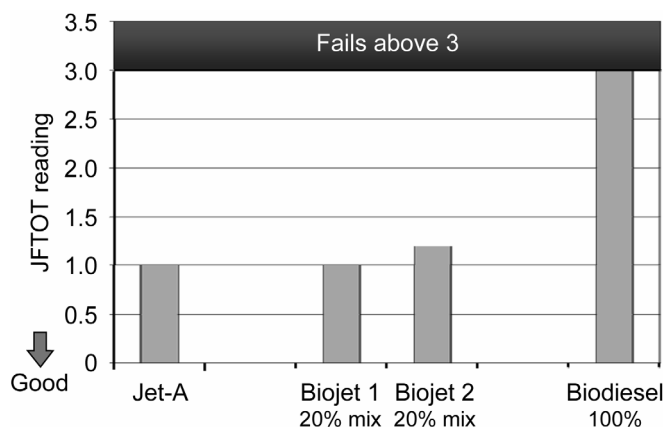


Figure 9.—Jet fuel thermal stability test (JFTOT) readings for conventional fuels and 20% biofuel blends with Jet-A.

Another drawback of biofuels is that, because of limited excess farmland, biofuels 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 biojet. For example, the use of a 15 percent biojet and 85 percent Jet-A blend in the U.S. domestic commercial aircraft fleet would require more than 2 billion gallons of biojet. 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 biofeedstock.

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 farmland capacities, deforestation, using slash-and-burn practices, can take an extreme toll on rainforests. The resulting CO₂ emissions are anticipated to exacerbate global warming issues. Thus, great care has to be taken to ensure that biofeedstock is sustainable and will not cause new anthropogenic issues through deforestation (fig. 10), which, for example, could exacerbate CO₂ issues associated with global warming. Proposed airline testing (ref. 6) of Jet-A and low-percentage biofuel blends to reduce greenhouse gas emissions underscores the importance the airline industry is placing on the environmental impact on global climate change (ref. 7).

Every region throughout the world may have specific solutions. For example, one sustainable solution might be to harvest the nuts obtained from native Brazilian palm trees called “Babassu.” Plantations of these trees could mitigate deforestation and its effects. The oil from these nuts might provide a sustainable source of oil for biojet fuel in Brazil. Airframe manufacturers are working with local entities in a joint effort to evaluate the possibility of these biojet fuels (fig. 11).

Future biofuels may also involve other sources of oil feedstock. One promising feedstock is algae, which have been evaluated by the U.S. Department of Energy (ref. 8). This feedstock is projected to produce anywhere from 10 000 to 20 000 gallons/acre/year of bioderived oil. With such a high production rate, algae could produce 150 to 300 times more oil than a crop of soybeans (fig. 12).

With the potential for algae to provide 10 000 gal/acre/year, some 85 billion gallons of biojet could be produced on a landmass equivalent to the size of the U.S. state of Maryland (8.5 million acres). Moreover, if these biojet 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) well into the future.

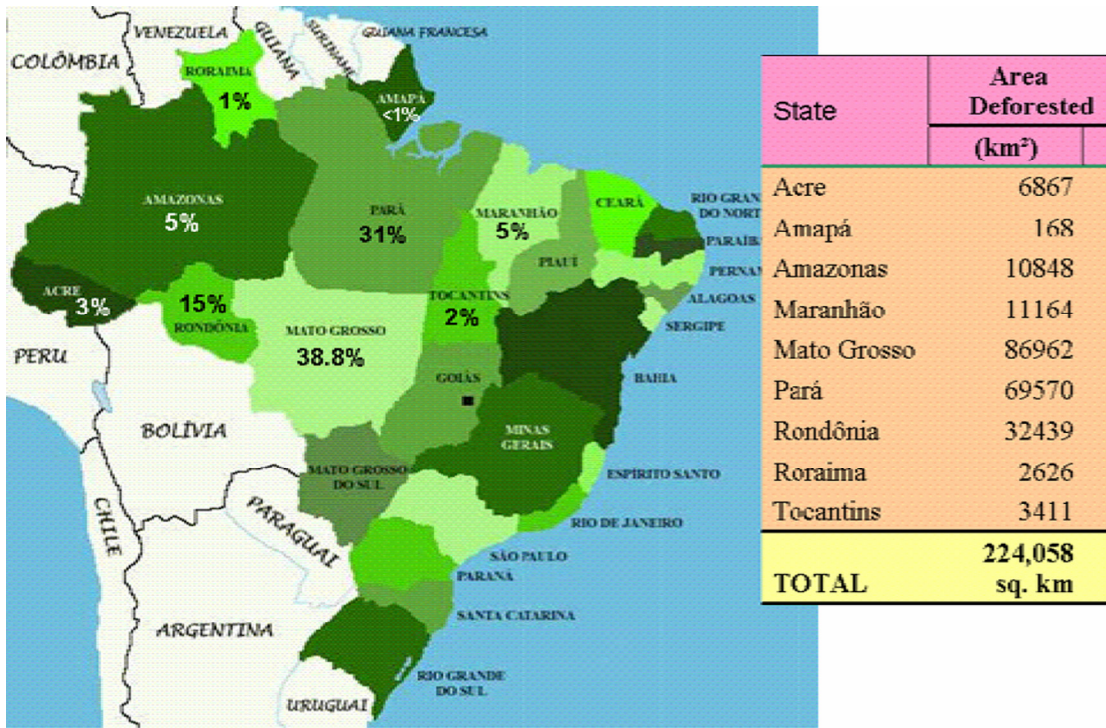


Figure 10.—Deforestation (North Brazil shown) to make way for biofuel feedstocks (ref. 7).

Use Brazillian palm trees biojet fuel
(helps prevent destruction of the rain forest)

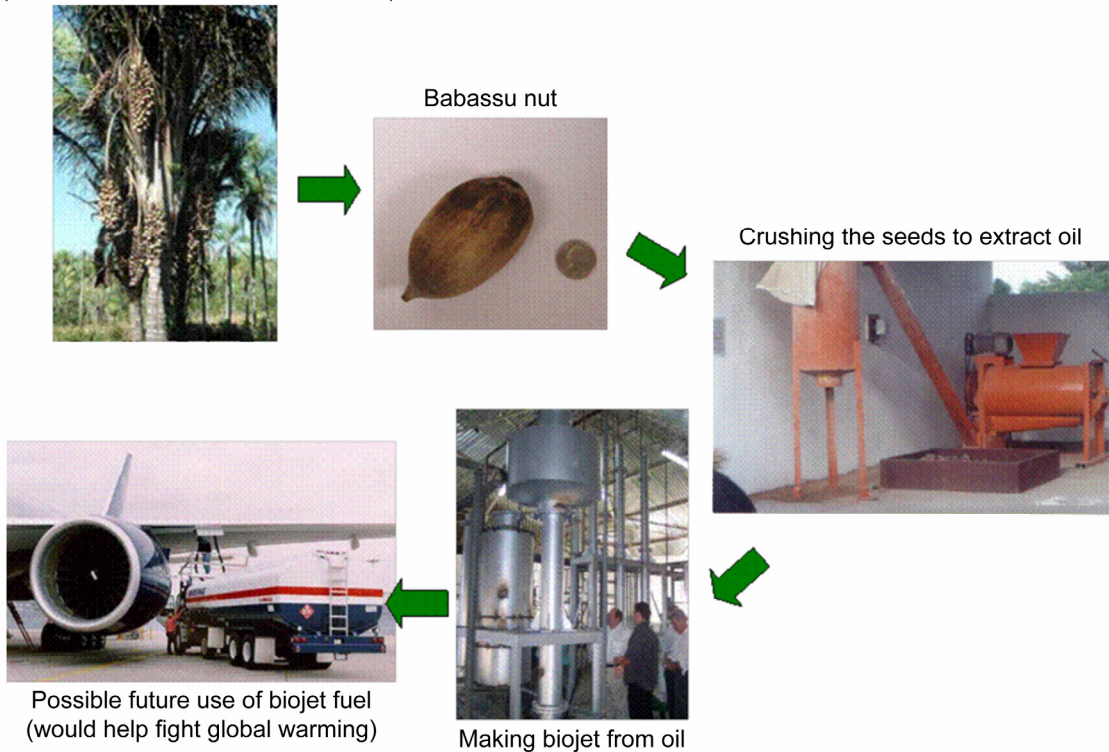


Figure 11.—Babassu palm sustainable feedstock for biojet fuel.

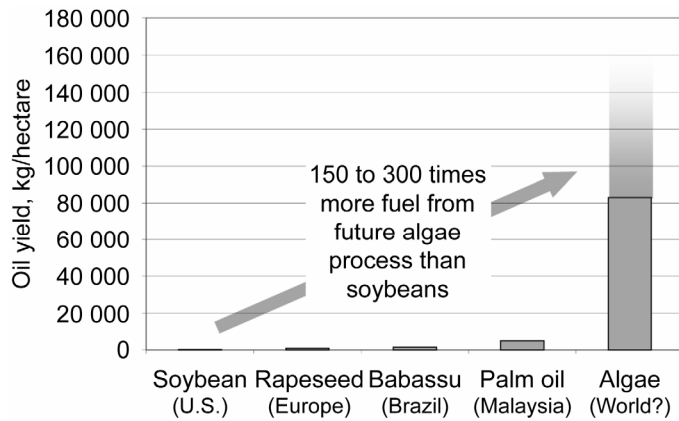


Figure 12.—Oil yields from biofuel feedstocks.

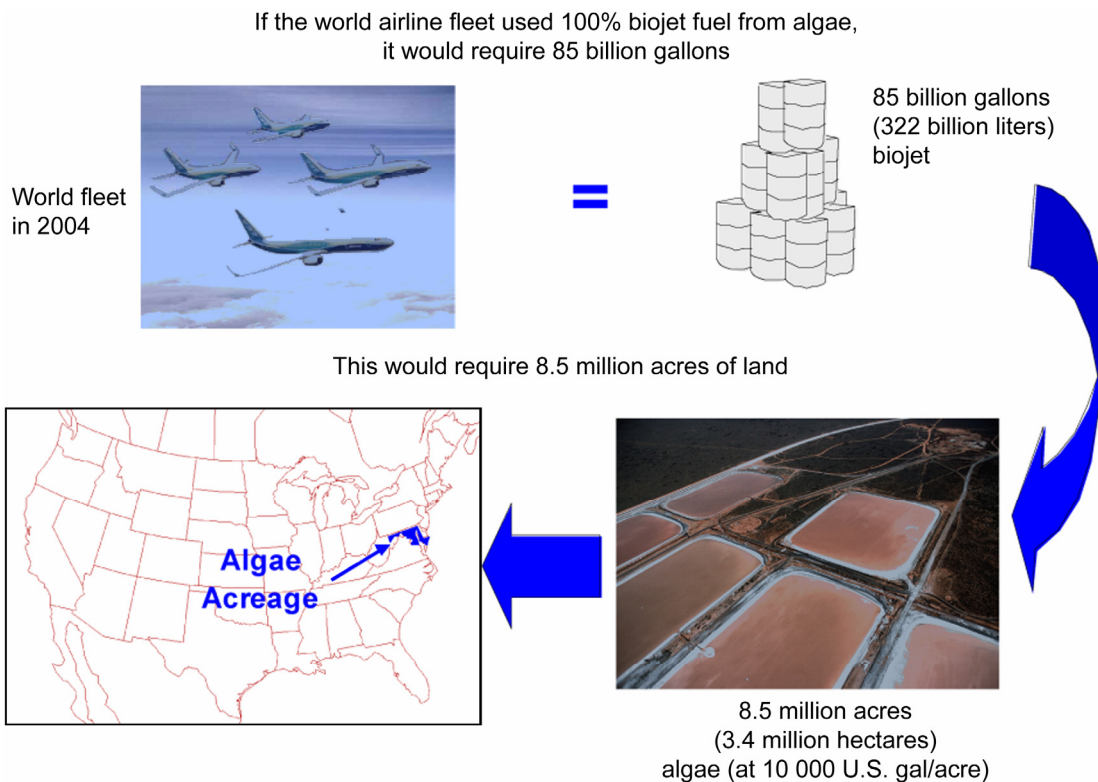


Figure 13.—Potential of algae ponds to supply biojet fuel for world's aviation.

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, stored in the deep ocean floors and under some permafrost regions. They could offer a fuel source for many hundreds of years (fig. 14). Whereas the world's conventional methane resources are estimated at about $175 \times 10^{12} \text{ m}^3$, with most of it located in the Middle East and former Soviet Union, the methane resources locked in methane hydrates are estimated to be well over 10^{16} m^3 , with most of it located in the Americas (refs. 10 and 11).

However, a number of questions are still open with respect to its extraction and have to be answered. Major issues concern the uncertain economics of recovery under unfamiliar and inconvenient deep under-sea conditions as well as a number of environmental, technical feasibility, and safety aspects (refs. 10 and 11). Another concern, extraction of these deposits in permafrost areas may be required in



Figure 14.—Burning methane hydrate (ref. 9).

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 contributor to greenhouse gases than CO₂ is today.

Present, Midterm, 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 blends of synthetic fuels and Jet-A 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 with Jet-A fuel up to 50 percent and used 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 (William E. Harrison III, 2006, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, personal communication). As a result, synjet/Jet-A blends are being considered as “drop in” fuels at the present (fig. 15). If the additional CO₂ 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.

Midterm solutions include the blends of synjet fuels and processed biofuels (biojet) 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 biofeedstocks remain varied, and most likely the oils will be provided from

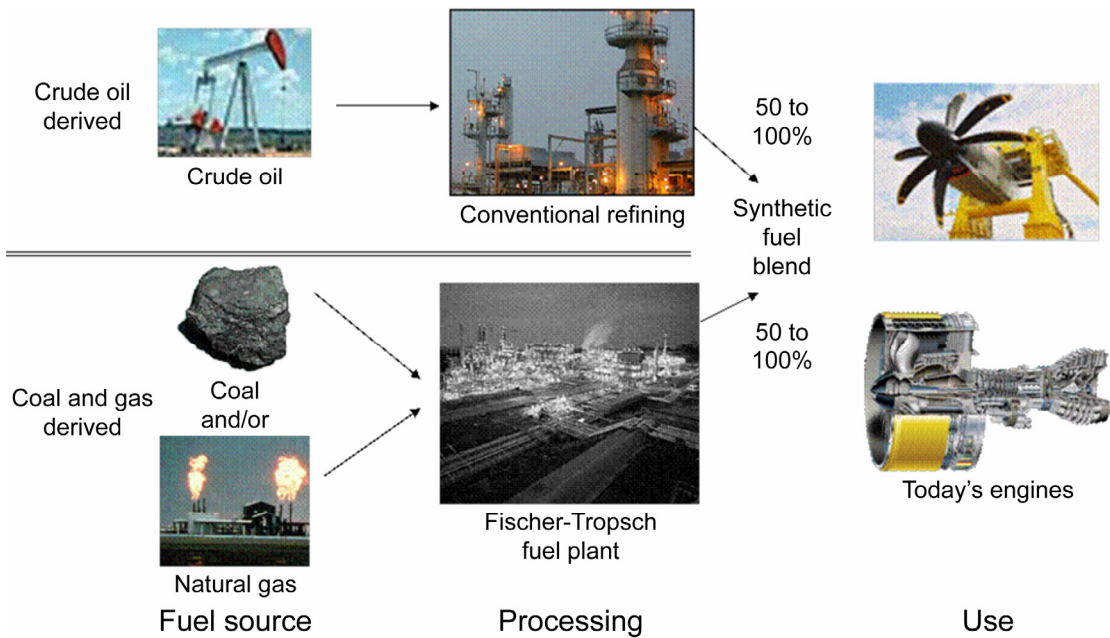


Figure 15.—Near-term aviation fuels derived from conventional and synthetic jet fuels (ref. 12).

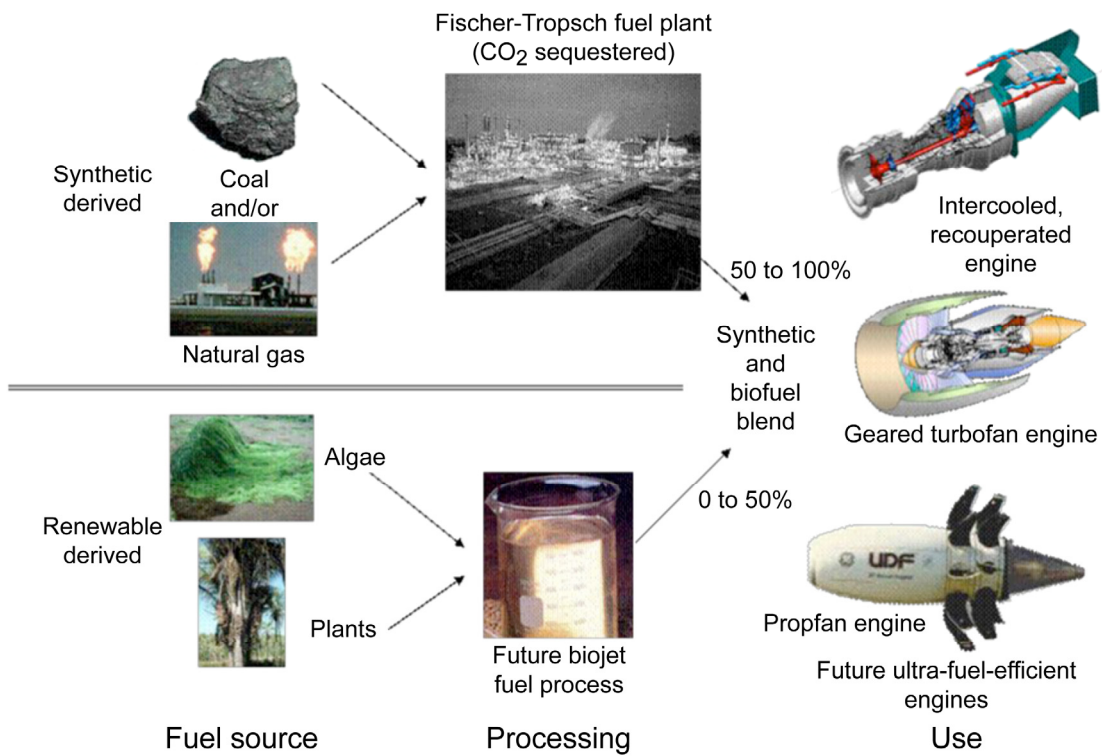


Figure 16.—Midterm aviation fuels derived from blends of synthetic and biojet fuels.

several sources to form a preblend of biokerosene that has to be further refined to biojet. These fuels will be blended with synthetic fuels but at a significantly reduced mixture ratio compared with blends of synjet and Jet-A.

The blends may range from 0 to 50 percent biojet with 100 to 50 percent synjet for use in highly advanced engine concepts. The future propulsion systems being contemplated range from geared turbofan engines with ducted or unducted propfans to designs realizing ultrahigh bypass ratios for significantly improved propulsion efficiency. In addition, thermal efficiency can be further raised with intercooled, recuperative engine concepts. Concepts such as these 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).

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 (ref. 13). Design compromises need to be made 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 (refs. 12 and 13).

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.

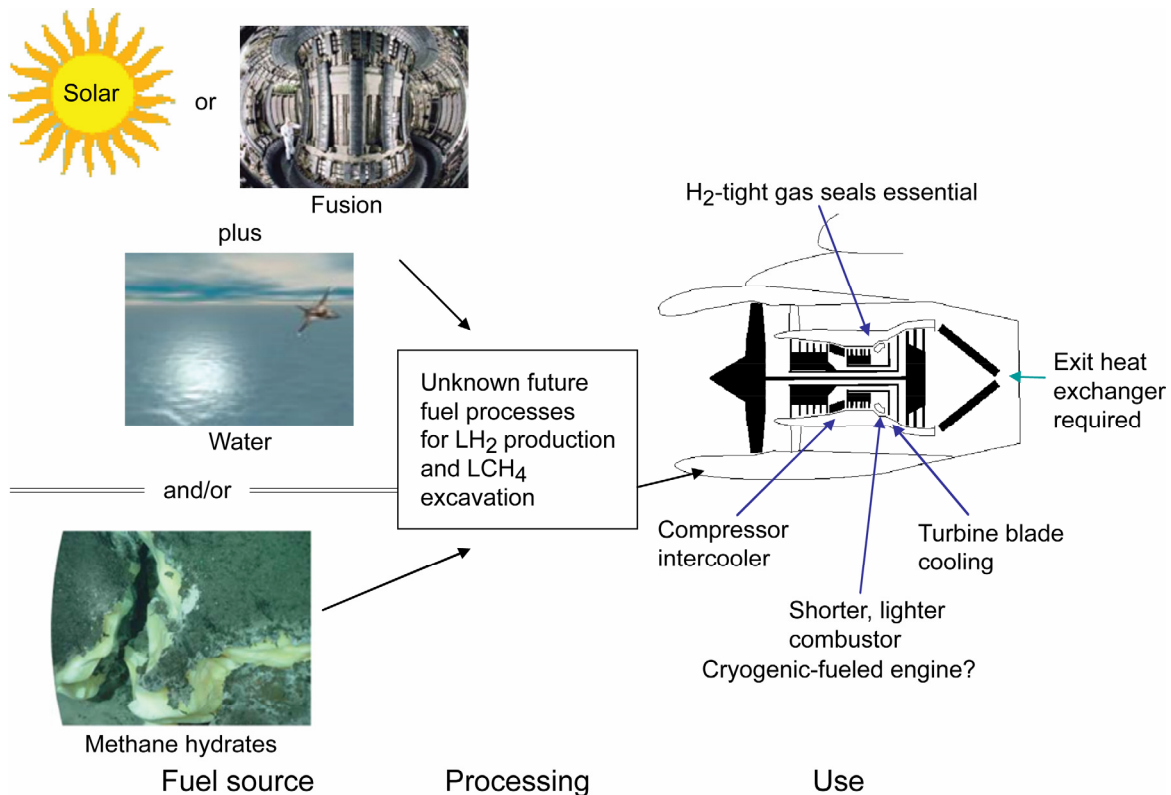


Figure 17.—Far-term aviation fuels hydrogen and methane.

Conclusion

There are two objectives behind the motivation to develop alternate fuels for commercial aviation: First, with respect to near-term concerns, alternate fuels will relieve the worldwide demand for fuels derived from crude oil. This will help to stabilize price fluctuations.

Secondly, 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 objectives: to relieve the worldwide demand for fuels derived from crude oil and to significantly reduce CO₂ emissions. Proposed airline testing of biofuel blends has direct consequences for the impact of greenhouse gas emissions on global climatic change.

The short-term option of synthetic fuels processed in the Fischer-Tropsch process meets the first objective. It has the potential to release pressure from the demand for pure fuels derived from crude oil, 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 midterm options, including future renewable derived biofuels and their 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 bioderived fuel fraction, it offers the chance for an atmospheric-neutral CO₂ balance fuel. Algae seem to be a promising future feedstock option that could provide a much higher oil yield per hectare than present biofuels. 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 solar—power are promising long-term options. In combination with economically viable fuel-saving technologies, both fuels may also completely replace the current fuel sources derived from crude oil. In addition, hydrogen fuel could completely resolve CO₂ emissions. However, a number of technological challenges have to be solved prior to their 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 would have 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 their use in advanced engines will have to be solved by creative and highly advanced airframe designs, which may differ completely from today's airframe shapes.

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14. ABSTRACT The engine and aircraft Research and Development (R&D) communities have been investigating alternative fueling in near-term, midterm, and far-term aircraft. A drop in jet fuel replacement, consisting of a kerosene (Jet-A) and synthetic fuel blend, will be possible for use in existing and near-term aircraft. Future midterm aircraft may use a biojet and synthetic fuel blend in ultra-efficient airplane designs. Future far-term engines and aircraft in 50-plus years may be specifically designed to use a low- or zero-carbon fuel. Synthetic jet fuels from coal, natural gas, or other hydrocarbon feedstocks are very similar in performance to conventional jet fuel, yet the additional CO ₂ produced during the manufacturing needs to be permanently sequestered. Biojet fuels need to be developed specifically for jet aircraft without displacing food production. Envisioned as midterm aircraft fuel, if the performance and cost liabilities can be overcome, biofuel blends with synthetic jet or Jet-A fuels have near-term potential in terms of global climatic concerns. Long-term solutions address dramatic emissions reductions through use of alternate aircraft fuels such as liquid hydrogen or liquid methane. Either of these new aircraft fuels will require an enormous change in infrastructure and thus engine and airplane design. Life-cycle environmental questions need to be addressed.					
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