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Alternative Fuels and Their Potential Impact on Aviation

D. Daggett and O. Hadaller
Boeing Commercial Airplanes, Seattle, Washington

R. Hendricks
Glenn Research Center, Cleveland, Ohio

R. Walther
MTU Aero Engines GmbH, Munich, Germany

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D. Daggett and O. Hadaller
Boeing Commercial Airplanes, Seattle, Washington

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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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Boeing Commercial Airplanes
Seattle, Washington 98124

R. Hendricks
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

R. Walther
MTU Aero Engines GmbH
80995 Munich, Germany

Abstract

With a growing gap between the growth rate of petroleum production and demand, and with mounting environmental needs, the aircraft industry is investigating issues related to fuel availability, candidates for alternative fuels, and improved aircraft fuel efficiency.

Bio-derived fuels, methanol, ethanol, liquid natural gas, liquid hydrogen, and synthetic fuels are considered in this study for their potential to replace or supplement conventional jet fuels. Most of these fuels present the airplane designers with safety, logistical, and performance challenges.

Synthetic fuel made from coal, natural gas, or other hydrocarbon feedstock shows significant promise as a fuel that could be easily integrated into present and future aircraft with little or no modification to current aircraft designs.

Alternatives, such as biofuel, and in the longer term hydrogen, have good potential but presently appear to be better suited for use in ground transportation. With the increased use of these fuels, a greater portion of a barrel of crude oil can be used for producing jet fuel because aircraft are not as fuel-flexible as ground vehicles.

1. Introduction

The airline industry has experienced substantial improvements in fuel efficiency. Demand for air travel continues to grow, so much so that the industry's rate of growth is anticipated to outstrip aviation's fuel-efficiency gains. Underlying this growth projection is an assumption that the industry will not be constrained by fuel availability or undue price escalations. Future crude oil production may not be able to keep pace with world demand (ref. 1), thereby forcing the transition to using alternative fuels. The purpose of this discussion is to investigate the feasibility and assess the impacts at the airplane level of using alternative fuels.

2. Results

The only currently known drop-in alternative jet fuel was found to be a synthetic manufactured fuel. Alternative aviation fuels synthesized by using a Fischer-Tropsch-type process, are ideally suited to supplement, and even replace, conventional kerosene fuels. Although this fuel, and its manufacturing process, does not help address global warming issues, it was found to be the most easily implemented approach.

Another possible alternative, biofuel, could be blended in small quantities (i.e., 5 to 20 percent) with current jet fuel. This bio-jet-fuel blend can be derived from sustainable plant products, which makes it attractive as a step toward a "carbon neutral" fuel that will help address global warming issues. However, because of aviation's high-performance fuel specification needs, direct biofuels would need to go through an additional, possibly costly, fuel processing step.

Reduced particulate emissions have been one of the benefits observed in diesel engines and smaller gas turbine engines (ref. 2), but they have not been substantiated in new-technology, large turbine engine tests. Therefore, as aircraft use a small proportion of fossil fuels, and unless some other beneficial properties are found, it appears that biofuel will be easier to use and will offer more global warming benefits when used in ground transportation vehicles. Because of the limited availability of arable land, biofuels will be able to supply only a small percentage of most countries' energy needs.

Other alternative fuels result in airplane performance penalties. For example, liquid hydrogen (LH_2) not only presents very substantial airport infrastructure and airplane design issues, but because of the need for heavy fuel tanks, a short-range airplane would experience a 28 percent decrease in energy efficiency while on a 500-nautical-mile (nmi) mission. However, because airplanes need to carry much more fuel for a long range flight, and Liquid Hydrogen (LH_2) fuel is quite lightweight the lighter takeoff weight of the airplane results in an energy efficiency loss of only 2 percent while on a 3,000-nm mission.

Ethanol takes up 64 percent more room and weighs 60 percent more compared with Jet-A fuel. This type of alternative-fueled airplane would experience a 15 percent decrease in fuel efficiency on a 500-nmi mission and a 26 percent efficiency decrease on a 3,000-nmi mission compared with a Jet-A fueled airplane.

3. Discussion

The following discusses in more detail why alternative fuels need to be developed and the feasible candidates, their qualities, sustainability, and impact on aircraft and engines.

3.1 Needs

It is essential that alternatives to crude oil be developed to help stabilize energy supplies and their associated prices and to address global warming issues.

Current aircraft have experienced dramatic improvements in fuel efficiency since the introduction of commercial jet aircraft in the 1960s. Future aircraft will see another 15 to 20 percent improvement in fuel efficiency, making air travel one of the most efficient means of transportation. However, Boeing predicts air travel growth to continue at over 5 percent per year (fig. 1). 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.

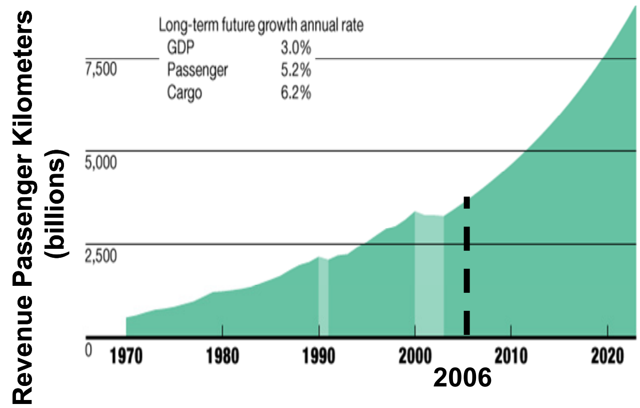

Figure 1.—Despite improvements in aircraft fuel efficiency, the growth in air travel is expected to lead to higher demand for fuel.

3.2 Alternative Fuels

Currently, almost all alternative fuels present some challenges to implement when compared with conventional kerosene jet fuel.

As shown in figure 2, fundamental requirements for a commercial jet fuel are that it have (1) a low weight per unit heat of combustion (BTU) to allow the transport of revenue-producing payload and (2) a low volume per unit heat of combustion to allow fuel storage without compromising aircraft size, weight, or performance.

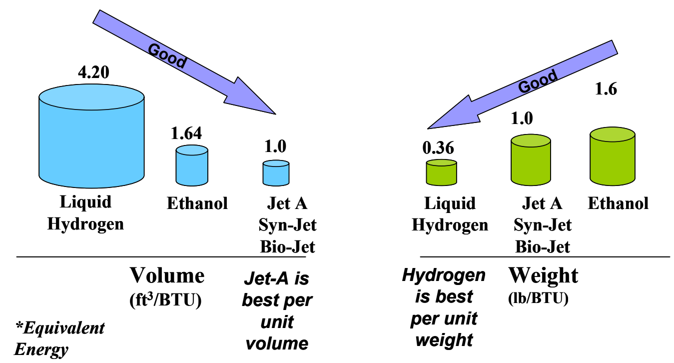

Figure 2.—Aircraft fuels need to have high energy content per unit weight and volume.

3.2.1 Hydrogen Fuel.—H_2, publicized as the most environmentally benign alternative to petroleum, has its own drawbacks and is not a source of energy in itself. H_2 production needs an abundantly available source of energy, such as electrical power, produced from nuclear fusion and a large source of clean water.

Although combustion of H_2 emits no carbon dioxide (CO_2) emissions and is lightweight, its production, handling, infrastructure, and storage offer significant challenges. The volumetric heat of combustion for LH_2 is so poor that it would force airplane design compromises.

The use of LH_2 (or methane) will also require an entirely new and more complex ground transportation, storage, distribution, and vent capture system.

3.2.2 Other Liquefied Fuels.—The liquefied petroleum gases, propane and butane, are not cryogens, but they have many of the same storage and transfer problems associated with a cryogen. In-depth studies of these fuels have not been conducted because the natural supply is not sufficient to support a worldwide aviation fleet. Manufacturing propane or butane offers no availability, cost, or environmental advantage as a replacement for conventional jet fuel.

3.2.3 Alcohols.—The alcohols (methanol and ethanol) have very poor mass and volumetric heats of combustion and are not satisfactory for use as a commercial aircraft fuel. Even though they are not useful for commercial aviation, their widespread production and use could influence the supply and cost of conventional jet fuel by freeing up additional petroleum resources for aircraft. Their production might have merit in that context

3.2.4 Biofuels.—Biofuels are combustible liquids that are manufactured from renewable resources such as plant crops or animal fats. Crops with high oil content such as soybeans, rapeseed (canola), and sunflowers are the starting materials used to produce bio-oils or bio-blending components that can be mixed with petroleum fuels.

The oil is obtained by first cleaning, cracking, and conditioning the beans. The beans are subsequently compressed into flakes. The oil is then extracted from the flakes by a solvent extraction process. The primary components of bio-oils are fatty acids. The first process in utilizing these bio-oils is to crack and convert the raw oil into an ester. These esters can be used directly or can be modified into a variety of products. The ester from soybeans is called SME (soy methyl ester) and from rapeseed, RME.

One of the challenges of using SME in a commercial aircraft is its propensity to freeze at normal operating cruise temperatures (fig. 3).

By selecting specific fatty acids and the method of esterification, different properties, such as freezing point, can be obtained. Another option is to use a separation process to enable a lower freezing point for bio-jet fuel (fig. 4).

Another challenge of SME is the stability of the oil over time. Currently, it is advised that the product be used within 6 months of manufacture. The lack of product consistency and storage stability—as exhibited by the cloudiness shown in figure 5—are common problems of biofuels. For these reasons, SME is usually blended with petroleum diesel and limited to a 20 percent blend.

For biofuels to be viable in the commercial aviation industry, significant technical and logistical hurdles need to be overcome. However, the task is not insurmountable, and no single issue makes biofuel unfit for aviation use. Aircraft equipment manufacturers and regulatory agencies will require a great deal of testing before biofuels can be approved. With adequate development, biofuels could play some role in commercial aviation fuel supplies.

3.2.5. Synthetic Jet Fuel.—Jet fuels produced from synthesis processes are somewhat different from petroleum-based jet fuel and are currently being investigated by the aviation industry. The positive attributes of this fuel include a cleaner fuel with no sulfur (fig. 6), higher thermal stability, and possible lower particulate engine emissions. The negative attributes include poorer lubricating properties, lower volumetric heat content, possible contributor to fuel system elastomer leakage, and increased CO_2 emissions during its manufacture.

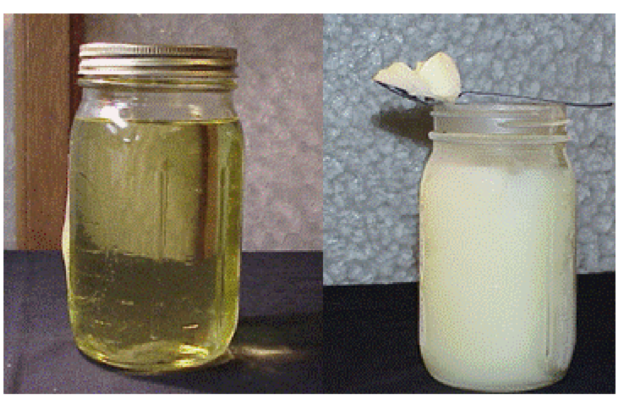

Figure 3.—One issue to address is that regular bio-diesel fuel (left) freezes at the cold (i.e., –20 °C) operating conditions of aircraft (right) (ref. 3).

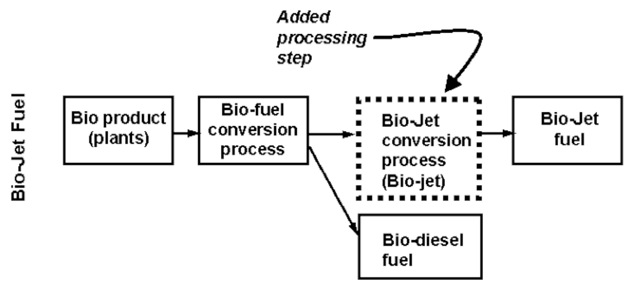

Figure 4.—Aircraft biofuel requires an additional processing step to address fuel-freezing issues.

Figure 5.—Biofuel (right) would need to be mixed at a maximum 20 percent ratio to avoid stability issues over time (left) (ref. 3).

Figure 6.—Synthetic fuel (right) tends to be cleaner than crude-oil-derived Jet-A (left).

There are still enormous quantities of coal reserves, and these can be made into synthetic transportation fuels by two routes. One method is a direct liquefaction technique; however, this is complex and expensive. The other, most favored process, is partial oxidation, or the Fischer-Tropsch (FT) process.

The feedstock, such as coal, is mined and crushed, then converted into carbon monoxide (CO), H_2 gases, and ash. The ratio of CO to H_2 is adjusted before the mixture goes into a synthesis unit to produce the jet fuel. Large quantities of energy are used in this process that can result in the release of large quantities of CO_2 into the atmosphere. The process can be considered only as a long-term, viable alternative to petroleum if the CO_2 emissions can be captured and permanently sequestered.

A similar method, called gas-to-liquids (GTL), which also uses the FT process, is receiving a lot of attention these days. In this method, natural gas is used as the feedstock (fig. 7). Waste or natural gas that cannot be marketed is partially oxidized into CO and H_2 gases. This synthesis gas is then supplied to a synthesis unit to similarly produce a liquid fuel.

The development of synthetic jet fuels to augment petroleum fuels is becoming reenergized with the U.S. Government's Total Energy Development (TED) program. The technical hurdles for a pure synthetic jet fuel are not insurmountable, but manufacturers and regulatory agencies will still need to evaluate and test these fuels before approving them for unlimited use.

3.3 Sustainability

For a long-term energy solution, a fuel should be sustainable. Fuels generated from a renewable energy source, such as solar, wind, or hydroelectric, are considered sustainable.

Synthetic fuels derived from nonrenewable energy sources, such as coal or natural gas, are not considered sustainable. However, this process may be able to use vast untapped energy resources, such as coal, stranded natural gas, and methane hydrates, which could provide energy for many decades to come. Global warming issues with synthetic fuel would ultimately also make it unsustainable.

Biofuels are derived from plants and may be considered sustainable if a sufficient quantity of crops can be grown to support the demand for fuel (ref. 4). Unfortunately, many countries would be unable to grow sufficient fuel feedstock to produce enough biofuel to supply the country's energy needs. For example, figure 8 shows that Germany's land mass consists of 34 percent arable land.

To replace only the diesel fuel demand of Germany (56.6 million-tonnes in 2005 (ref. 5)) with bio-diesel would require four times the land area and the replacement of every current crop with rapeseed (Europe's favorite bio-diesel feedstock.) The resulting shortfall in food production would become a crucial issue.

For a few counties that have lower oil demand and more arable land, such as Brazil, the answer could be different.

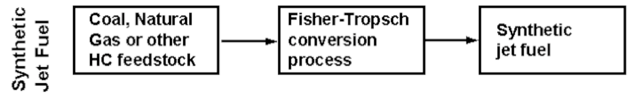

Figure 7.—Synthetic jet fuel is commonly produced by using the Fischer-Tropsch process on a variety of feedstocks.

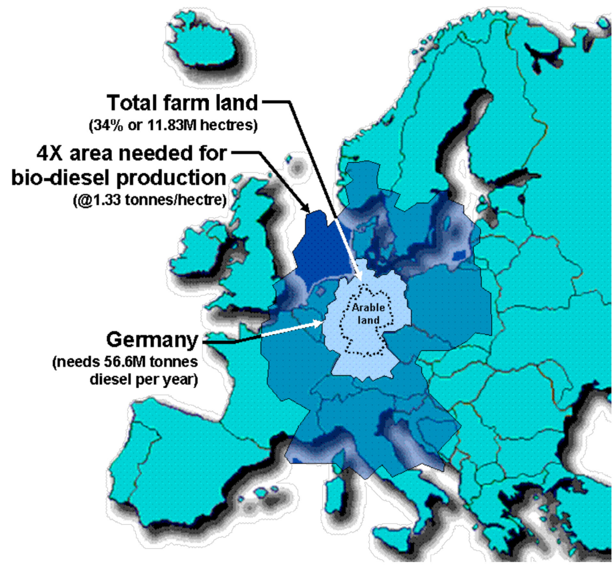

Figure 8.—Germany's available land is insufficient to meet its biofuel needs

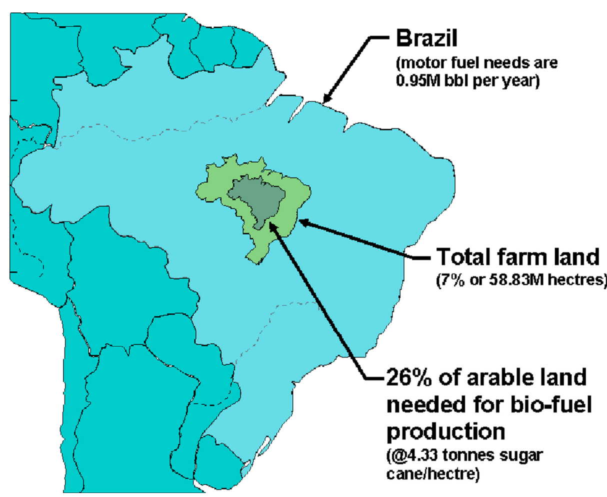

Figure 9.—Brazil has sufficient arable land to meet ethanol-motor-fuel replacement demands.

The United States uses about 9.5 times more oil than Brazil, a country about the size of US and with 1/3 the arable land. Since the last energy crisis of the early 80's, Brazil has become a nation running on ethanol fuel with some 34,000 automotive refilling stations. By using 26 percent of their arable land to grow sugarcane (at 4.33 tonnes/hectare) for ethanol, Brazil has the bio-potential to produce all their motor-fuel needs, as shown in figure 9. Using nearly

2.1Mbbl/day of oil, with a total annual energy use of 9.8 Quad, Brazil also has the bio-potential to become energy independent and the first to become CO_2 neutral.

Supplying the world's commercial airline fleets with biofuel would not be as easy. Even supplying a 15 percent blend of bio-jet fuel would be challenging. For example, in 2004 the U.S. commercial fleet used about 13.6 billion gal of jet fuel. A 15 percent blend of bio-jet fuel would require 2.04 billion gal of this fuel per year. A crop, such as soybeans (U.S. favorite, bio-diesel feedstock) yielding about 60 gal of biofuel per acre, would require 34 million acres of agricultural land, about the land size of the state of Florida (fig. 10).

Other biofuels might look more attractive. For instance, feedstocks that could be used to produce ethanol appear to offer much higher energy yields in the future. Figure 11 compares acreage required to produce bio-diesel (or bio-jet) fuel versus that needed to produce the cellulose feedstock for ethanol. A feedstock such as switchgrass has been shown to produce enough material to make up to 1,000 U.S. gallons of ethanol per acre (we used 500 average) depending on ambient temperature, irrigation, and fertilizer application. Although ethanol can not be easily used in aircraft, it does blend well with gasoline for use in ground transportation.

Although a few countries, such as Ukraine and Brazil, have relatively low oil demands and large amounts of arable land, most industrialized countries would be able to replace only a small percentage of their oil needs with biofuels.

There is also a need to consider the energy obtained from using the fuel versus that needed to grow and convert the feedstock product. Although a few researchers argue that ethanol production has a negative energy balance (ref. 6), most say that using more modern processing methods will result in a positive energy balance (fig. 12) (ref. 7). In the future, it appears that using genome processing methods to make cellulosic-based ethanol may result in even more of a positive energy balance. Bio-diesel fuel may have the capability to achieve an even higher energy balance than ethanol, on the order of 2 to 3 times the amount of energy input, but this needs to be balanced against the poorer fuel yield per acre for bio-diesel crops.

At today's crude oil prices, biofuels are becoming cost competitive. Bio-jet fuels will require additional processing beyond bio-diesel or ethanol fuels. Therefore, a bio-jet fuel is anticipated to cost more than bio-diesel fuel. Synthetic fuels from coal or natural gas are likely to continue to be more cost competitive than biofuels.

3.4 Aircraft Design

Because synthetic jet fuel and bio-jet fuel have approximately the same weight, volume, and performance characteristics of current oil-derived jet fuel, they would be relatively easy to use and not affect the design of the airplane.

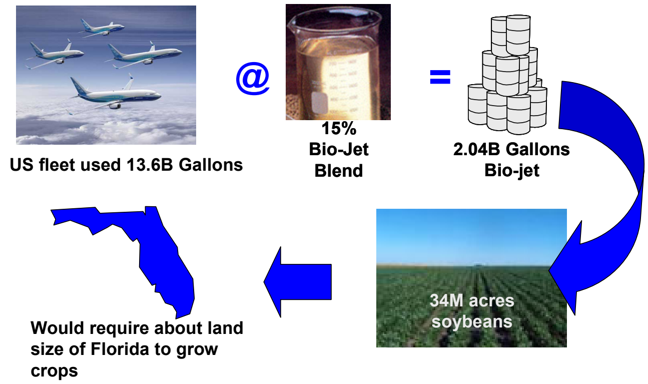

Figure 10.—A very large amount of agricultural land would be needed to supply a 15 percent bio-jet blend.

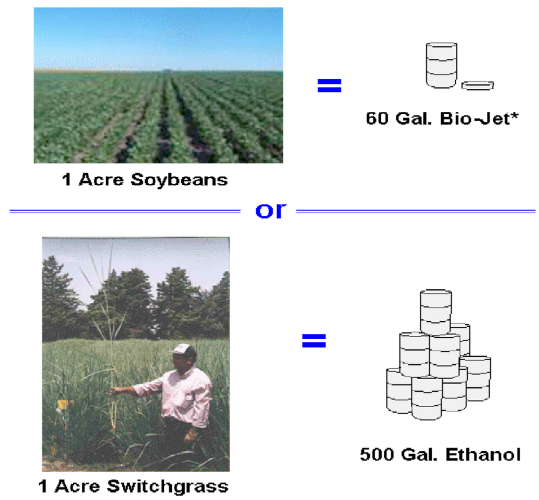

Figure 11.—Cellulose-based feedstocks may prove to be better choices to produce ethanol for use in ground transportation rather than soybeans for bio-jet fuel.

Chronological Summary of Net Energy Balance Studies Since 1995

Study author(s)	Date	Net energy value (Btu/gal)	Net energy value ratio[1]
Shapouri, H., et al. (USDA)	1995	16,193	1.21
Lorenz & Morris (Institute for Local Self-Reliance)	1995	30,589	1.40
Agri-Food Canada	1999	29,826	1.39
Wang, M., et al. (Argonne Natl. Labs)	1999	22,500	1.29
Pimentel, D. (Cornell University)	2001	–33,562	–1.44
Shapouri, H., et al. (USDA)	2002	21,105	1.28
Kim & Dale (Michigan State University)	2002	23,886 to 35,463	1.31 to 1.46
Graboski (Colorado School of Mines)	2002	17,508	1.23
Pimentel, D. (Cornell University)	2003	–22,300	–1.29
Wang, Shapouri, et al. (Argonne Natl. Labs/USDA)	2003	21,105	1.34[2]
Shapouri, H., et al. (USDA)	2004	30,528	1.67[3]
Pimentel & Patzek (Cornell/UC-Berkeley)	2005	–22,300	–1.29
Average findings (incl. Pimentel)		**11,739**	**1.15**
Average findings (excl. Pimentel)		**24,336**	**1.32**

[1]NEV ratio is calculated by adding/subtracting net energy gain/loss to baseline low heat value of ethanol (76,330 Btu) and dividing by 76,330 Btu
[2]The Energy Balance of Corn Ethanol Revisited (2003) by M. Wang et al. included a new energy credit for the coproduct distillers dried grains with solubles (DDGS).
[3]The 2001 Net Energy Balance of Corn-Ethanol (2004) by Shapouri H., J.A., Duffield, and M. Wang included a revised energy credit for DDGS.

Figure 12.—Most researchers agree that biofuels, such as ethanol, provide more energy (indicated by positive values) than is required to make them (ref. 7).

3.4.1 Hydrogen Airplane Design.—Because H_2 (and methane) must be used in its liquid cryogenic form, aircraft design compromises are necessary. Insulation requirements and pressurization issues mean that cryogenic fuels cannot be stored in the wings as kerosene fuels can.

Figure 13 shows a Boeing 737-sized airplane designed to use LH_2. The heavy cryogenic fuel tanks increase the operating empty weight (OEW) of the aircraft some 13 percent above a kerosene fueled aircraft. However, because the fuel itself is very lightweight, the takeoff weight of the aircraft is about 5 percent lighter.

Because the aircraft engines are typically sized to power the airplane during the heaviest part of its mission (takeoff), it is possible to downsize the LH_2 airplane's engines to deliver about 25 percent less thrust, thereby enabling smaller, lighter weight engines to be used. It is possible to downsize the wing only slightly, as it still needs to be able to carry the additional weight of the fuel tanks during the airplane's slow approach to the airport. Because of these tanks, the airplane will need about 28 percent more energy on a typical 500-nmi mission. For longer durations, the lightweight properties of the fuel start to overcome the drawbacks of the heavy tanks. On a 3,000-nmi mission, the aircraft will only use 2 percent more energy than a jet-fueled aircraft. Longer range airplanes would most likely experience a fuel savings benefit of using LH_2 over Jet-A fuel.

For a cryogenic liquid, a 1-hr aircraft turnaround requirement will make the current jet fuel refueling process more complex. The saturation pressure of the cryogen in the ground supply system must be matched to the saturation pressure of the cryogen in the aircraft tanks.

3.4.2 Ethanol Airplane Design.—Ethanol-powered airplanes would also have to be specifically designed. Figure 14 shows one such Boeing 737-sized airplane. Ethanol fuel is much easier to store and handle than LH_2. However, its performance is much worse than LH_2 or Jet-A fuel. Ethanol requires 64 percent more storage volume for the same amount of energy as kerosene fuel contains. This leads to an aircraft design with a 25 percent larger wing, resulting in a 20 percent increase in the airplane's empty weight. Ethanol also weighs more, and so the takeoff weight of the airplane increases to 35 percent more than a Jet-A fueled airplane. This increased takeoff weight requires an engine with 50 percent more thrust. All of these factors result in an airplane that requires 15 percent more energy for a 500-nmi mission.

As ethanol fuel is rather heavy, the airplane's fuel efficiency decreases further on longer range missions and so requires 26 percent more energy on a 3,000-nmi mission.

The fuel tank penalty associated with liquefied gaseous fuels (e.g., LH_2, LNG, and LPG) and fuel performance properties of alcohol fuels (e.g., ethanol) make them unattractive for use in aircraft. However, synthetic jet fuel and bio-jet fueled airplanes do not experience these types of penalties, making them more attractive.

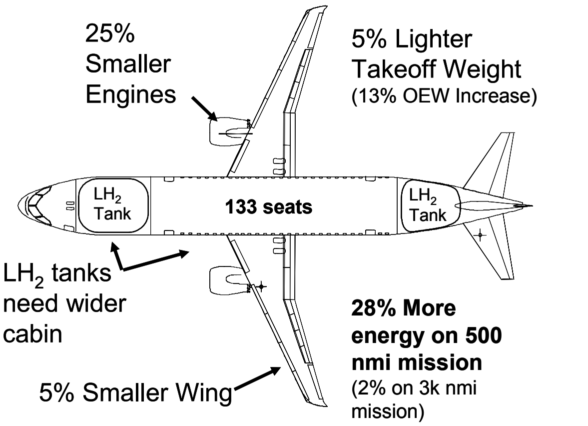

Figure 13.—Hydrogen-powered airplanes need a larger tank, which reduces the fuel efficiency of short-range aircraft.

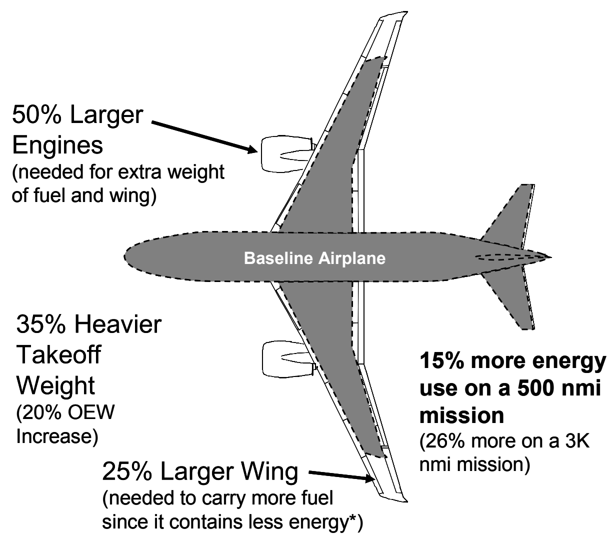

Figure 14.—An ethanol-fueled airplane requires a larger wing and engines, thus reducing the airplane's fuel efficiency.

3.5 Engine Impact

3.5.1 Synthetic-Fueled Engines.—The approval for the use of synthetic fuels in modern aero engines is currently being conducted by major engine manufacturers. To date, a number of advantageous physical features of synthetic Fischer-Tropsch (FT) fuels have been found with respect to environmental compatibility, efficiency, and operability.

Compared with conventional kerosene fuel, synthetic FT fuels are characterized by a higher hydrogen-to-carbon ratio (H/C-ratio) and may result in lower particulate exhaust emissions. Tests performed so far with older style engines demonstrated a significant reduction in particulate emissions (fig. 15) (ref. 2). However, the results are highly dependent on engine technology status and should be validated by the testing of more modern, higher pressure ratio engines.

In addition, because FT fuels are sulfur free, the exhaust gases would not contain sulfur oxide (SO_x) emissions.

Another benefit of FT fuels is their superior thermal stability performance, allowing for the use of higher engine fuel temperatures. This could be used to improve engine fuel efficiency. A further potential use may be the ability to reduce the cooling air temperature for the turbine blades and reduce engine oil temperatures to improve engine durability.

Compared with conventional jet fuels, FT fuels show excellent low-temperature properties, maintaining a low viscosity at lower ambient temperatures. This could improve high-altitude operability and low-temperature starting of the engine.

3.5.2 Hydrogen-Fueled Engines.—To use LH_2 in aircraft engines, modifications are necessary to the combustor and fuel system components, such as pumps, supply pipes, and control valves. In addition, a heat exchanger will be required for vaporizing and heating the cryogenically stored LH_2 fuel (ref. 8). Early tests with H_2 demonstrated that only slight combustor modifications were necessary because H_2 fuel has a very wide ignition range, which is beneficial to combustor control.

Among the often cited benefits of H_2 is its potential to moderate pollutant emissions. Even though CO, CO_2, unburned hydrocarbons (UHC), and particulates are absent, oxides of nitrogen (NO_x) are still formed.

Figure 16 compares the major exhaust constituents using the fuels kerosene, natural gas (methane), and H_2, all adjusted to a constant heat release. Using conventional combustor technology, the higher NO_x emissions of H_2 result from an approximately 150 K increase in adiabatic flame temperature. For NO_x emissions, the potential reduction expected from implementation of low NO_x combustor technology is also shown by a lower bar (indicated with a *2*). This indicates that NO_x will not be any higher and may even possibly be lower with a specially designed H_2 combustor.

Although the use of LH_2 in modern aero engines is feasible, much technological development is needed.

Synthetic fuels manufactured from coal and natural gas by the FT process seem to be the best suited candidates for nearer term aero engine applications because they are essentially drop-in fuel replacements.

3.6 Future Vision.—Although we are not going to run out of crude oil anytime soon, alternative energy sources need to be developed quickly to help address the end of "cheap oil." These new energy sources will also help address world energy demands that may soon outstrip crude oil supply. Of particular note are the growing energy demands of developing countries. China expects to build 600 coal-fired power plants and India close to 200 over the next 25 years (ref. 9).

Because of the increasing concentration of CO_2 in the atmosphere, alternatives must also address global warming issues. The following chart suggests that only a few alternative jet fuel options are able to reduce CO_2 emissions.

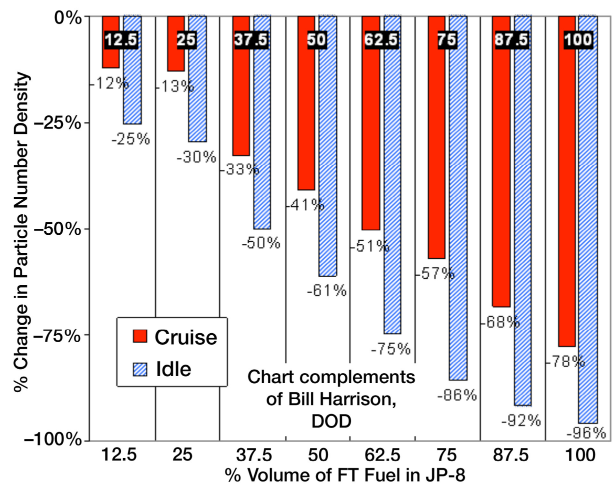

Figure 15.—Reduction of exhaust emission particulates has been found when using FT fuel blended in JP-8 9 (ref. 2).

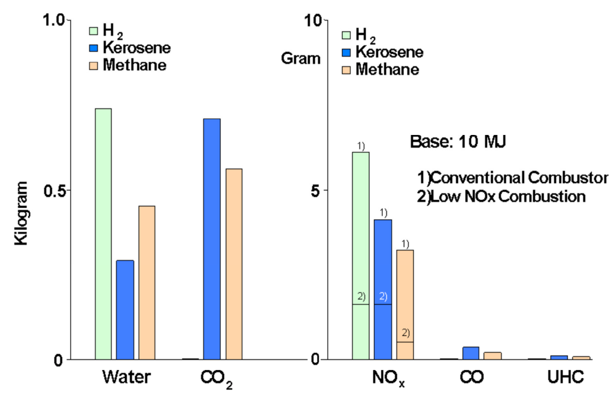

Figure 16.—Emissions vary with combustion of H_2, kerosene, and methane. Base: 10 MJ fuel (corresponds to 1.2 l H_2 or 0.3 l kerosene) (ref. 8).

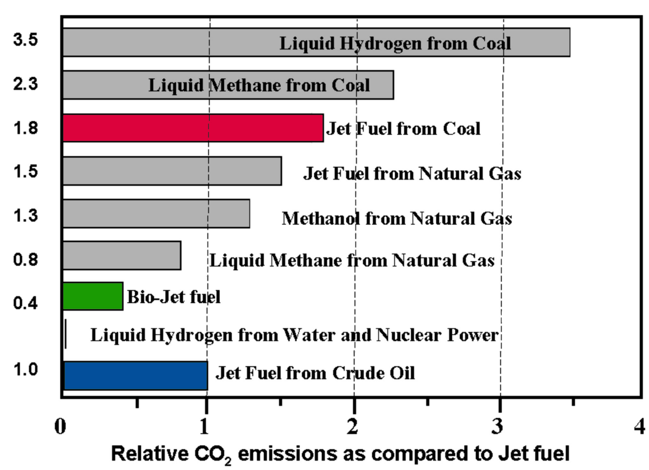

Figure 17.—CO_2 emissions are lower for biofuels and higher for most other alternatives than Jet fuel.

If fossil fuel resources are to be considered as an energy base for alternative synthetic fuels, this comparison suggests the need to capture and sequester CO_2 emissions.

It has become apparent that no single energy source, or alternative fuel, will be able to replace fossil fuels in the near term. The solution will most likely be a mix of improving energy efficiency and production, such as: increasing wind, nuclear, coal (with CO_2 sequestration), and solar power for electrical power generation; developing synthetic fuel for aircraft, trucks, and automobiles as well as adding biofuel to supplement ground transportation fuel. Commercial aircraft will continue improving their fuel efficiency, while the US ground transportation sector should reverse its worsening fuel efficiency trend. Perhaps the best hope lies in future research to develop as yet unknown (sustainable) energy resources or possibly in that governments will help to realize the vision of solar and fusion power. This would no doubt enable a much easier transition to a future "hydrogen economy." Aircraft might then consider a transition to H_2.

4. Conclusion

To seamlessly transition to the use of alternative fuels, research and development is needed. Developing alternative fuels will help to improve each country's energy independence, could help lessen global-warming effects, and will soften the economic uncertainty of crude oil peaking.

For most countries, it appears unlikely that enough bio feedstock (crops) could be grown to replace a sizable portion of crude oil production. Therefore, to efficiently utilize available agricultural lands, careful consideration should be given to crop selection, method of fuel processing, and the type of biofuel produced.

As jet fuel constitutes only about 6 percent of global oil consumption and requires high-performance characteristics, it makes more sense to use higher performing synthetic fuels in aviation. The lower performing biofuels should be used to help supplement 52 percent of the processed oil currently used to manufacture distillate fuel oil and gasoline for ground transportation (fig. 18).

Lastly, research and development in aviation biofuel needs to continue. If it is able to demonstrate additional benefits, such as exhaust pollutant and CO_2 reduction, the fuel would become more attractive to aviation, especially in the case of carbon trading.

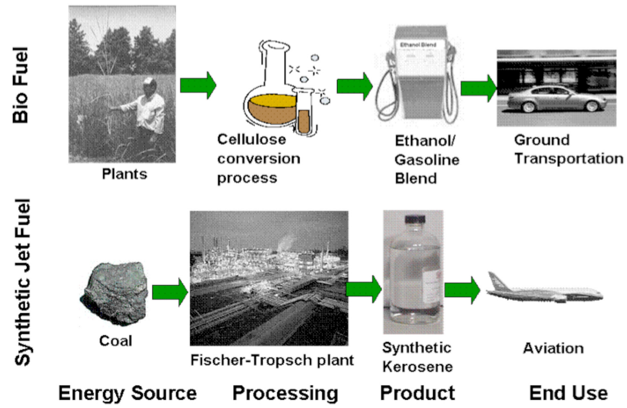

Figure 18.—Biofuel appears to be better suited for ground transportation, whereas synthetic jet fuel is ideally suited for aviation.

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D. Daggett, O. Hadaller, R. Hendricks, and R. Walther

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13. ABSTRACT ***(Maximum 200 words)***
With a growing gap between the growth rate of petroleum production and demand, and with mounting environmental needs, the aircraft industry is investigating issues related to fuel availability, candidates for alternative fuels, and improved aircraft fuel efficiency. Bio-derived fuels, methanol, ethanol, liquid natural gas, liquid hydrogen, and synthetic fuels are considered in this study for their potential to replace or supplement conventional jet fuels. Most of these fuels present the airplane designers with safety, logistical, and performance challenges. Synthetic fuel made from coal, natural gas, or other hydrocarbon feedstock shows significant promise as a fuel that could be easily integrated into present and future aircraft with little or no modification to current aircraft designs. Alternatives, such as biofuel, and in the longer term hydrogen, have good potential but presently appear to be better suited for use in ground transportation. With the increased use of these fuels, a greater portion of a barrel of crude oil can be used for producing jet fuel because aircraft are not as fuel-flexible as ground vehicles.

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