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# Alternative Jet Fuels



A supplement to Chevron's *Aviation Fuels Technical Review*

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Alternative Jet Fuels, Addendum 1 to Aviation Fuels Technical Review (FTR-3/A1)

# Alternative Jet Fuels

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Petroleum products have always been the preferred transportation fuels because they offer the best combination of energy content, performance, availability, ease of handling and price. However, the recent increase in the price of oil has prompted the industry to look at alternatives. National concerns about energy security and the concern about the continued availability of petroleum, the “peak oil” debate, are also important issues.<sup>1</sup>

Besides price, other factors must be taken into account when considering alternative fuels. Of course, safe and reliable operation of the engine and aircraft must not be compromised in any way. The environmental effects of any alternative fuel must also be considered. This includes both emissions from the engine and also life-cycle effects associated with the production and use of an alternative fuel.

Alternative fuels for aviation have been considered since the early days of turbine engines. Cryogenic fuels such as liquid hydrogen and other more exotic fuels such as boron compounds were studied in the 1950s and 1960s.<sup>2</sup> Research into alternative fuels was conducted after the 1973 U.S. energy crisis when fuel prices increased dramatically. Quite a bit of work was done at that time on biomass conversion to fuel.<sup>3, 4</sup> However, only petroleum-derived jet fuels have been found to be economically practical for widespread, routine use.

Are there viable alternatives to conventional jet fuel available today?<sup>5</sup> What are some of the issues associated with alternatives to conventional jet fuel? What is the approval process for use of alternative jet fuels? This review will address these questions and discuss the successful use of an alternative jet fuel in South Africa.

## Scale of Operations

World consumption of jet fuel in 2003, the most recent data available, was about 190 million gallons (720 million liters) per day.<sup>6</sup> Assuming a moderate 2 percent growth rate, we are now using over 200 million gallons per day (757 million liters) in 2006. That’s about the volume of an Olympic-sized swimming pool (2.5 million liters) every 5 minutes.

This fuel is consumed at the approximately 3500 commercial airports worldwide, accommodating tens of thousands of daily flights, as well as numerous smaller general aviation airports and military locations. Fuel is transported from refineries to airports through a complex system of pipelines, ships, trucks and intermediate storage terminals. Any alternative fuel would have to be compatible with conventional fuel or it would require a separate storage and airport delivery system.

- 1 “Future Energy Supply” Oil & Gas Journal, July14 – August 18, 2003.
- 2 “Aviation Fuels” Maxwell Smith, G.T. Foulis & Co Ltd, 1970, p.414.
- 3 “Biomass as a Nonfossil Fuel Source”, D.L. Klass ed. ACS Symposium Series 144, American Chemical Society 1981.
- 4 “Biomass as an Alternative Fuel”, C.W. Hall, Government Institutes, Inc. 1981.
- 5 The term “conventional jet fuel” means jet fuel refined from petroleum (crude oil).
- 6 U.S. Department of Energy, Energy Information Administration, International Energy Annual 2004. IATA estimates that 55 billion gallons of jet fuel was used in 2005 by commercial aviation.

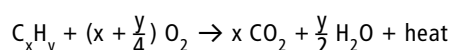
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This fuel volume and simplified infrastructure description illustrate the complexity involved for an alternative fuel to displace even a small percentage of conventional jet fuel.

## Fuel Properties

### Energy Content

The primary function of fuel is to provide a source of energy to propel the aircraft. The turbine engine converts the chemical energy stored in fuel into mechanical energy, providing the thrust that powers flight. The chemical energy in fuel is released by combustion, a rapid reaction with oxygen at high temperature. For hydrocarbon fuels, combustion is described by the following equation.



The energy released during this reaction is called the *heat of combustion*. The amount of heat released depends on whether the water formed by the reaction is in the gaseous state (lower or net heat of combustion) or is condensed to a liquid (higher or gross heat of combustion). Since engines emit water as a vapor, the net heat is the appropriate value to use.

Some potential alternative fuels contain oxygen, for example, alcohols or esters. These fuels have lower energy content because the oxygen in the fuel molecule doesn't contribute any energy during combustion. Energy is released by breaking carbon-carbon and carbon-hydrogen bonds in hydrocarbons and converting them to carbon-oxygen and hydrogen-oxygen bonds; starting with carbon-oxygen bonds in the molecule doesn't gain anything. It's like carrying a little air in with the fuel; instead of all the oxygen needed for combustion coming from air, some of the oxygen is already in the fuel molecule. As a result, these fuels have lower energy content than hydrocarbon fuels, which can lead to reduced flight range.

It is desirable to minimize both the mass and volume of fuel on an aircraft, so both the gravimetric and volumetric energy content of the fuel are important.<sup>7</sup> Aircraft are rated at maximum take-off weight (MTOW), which includes the weight of fuel, passengers and cargo. If an aircraft reaches MTOW before its fuel tanks are full, fuel with a higher gravimetric energy content (specific energy) will allow more passengers and cargo on a given route, or will carry the same passenger and cargo load a longer distance. Volumetric energy content is also important as this affects the flight range available with a full load of fuel, especially in smaller aircraft and military aircraft.

Figure 1 lists specific energy (based on the lower or net energy content), density and energy density of potential alternative fuels along with conventional Jet A/ Jet A-1 for comparison. Figure 2 is a plot of the mass of fuel required to give a certain amount of energy vs. the volume of the same fuel to give the same amount of energy. The amount of energy, 100 MJ, provides a common basis for comparison. Lower values are preferred on both axes.

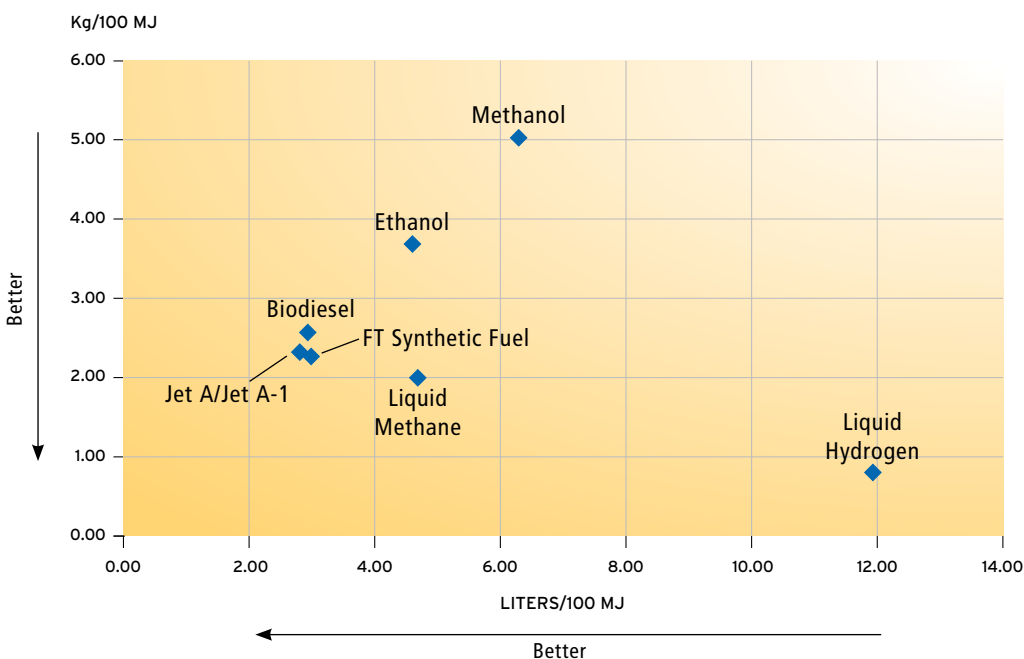
<sup>7</sup> Gravimetric energy content is the amount of energy per unit mass (weight) of fuel. It is also called the specific energy of the fuel. SI units are megajoules per kilogram (MJ/kg), common units are British thermal units per pound (Btu/lb). 1 MJ/kg = 429.9 Btu/lb.

Hydrogen has the highest gravimetric energy content, but the low density of the liquid results in a very low volumetric energy content. Similarly for liquid methane, the high gravimetric energy content is offset by low density. The gravimetric energy content of the alcohols and biodiesel reflects their oxygen content. Biodiesels are closer to conventional jet fuel because oxygen represents a smaller percentage of the fuel mass. FT synthetic fuels have slightly higher gravimetric energy content than conventional jet fuel, but correspondingly slightly lower volumetric energy content.

Figure 1  
Specific Energy, Density and Energy Density

Fuel	Specific Energy, MJ/kg	Density 15°C	Energy Density MJ/l
FT Synfuel	44.2	0.759	33.6
Jet A/Jet A-1	43.2	0.808	34.9
Liquid Hydrogen	120	0.071	8.4
Liquid Methane	50	0.424	21.2
Methanol	19.9	0.796	15.9
Ethanol	27.2	0.794	21.6
Biodiesel (typical)	38.9	0.87	33.9

Figure 2  
Mass of Fuel vs. Volume of Fuel per Unit Energy



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## Other Fuel Requirements

In addition to its primary function as a source of energy, fuel is used to absorb excess heat, it is used as a hydraulic operating fluid in engine control systems, and it serves as a lubricant in engine control systems and pumps.

Alternative fuels would have to be examined for their ability to perform these functions as well as conventional fuels do. Fuel must be thermally stable to absorb excess heat from the engine and not degrade. Fuels with poor thermal stability will leave deposits in the engine fuel system which will degrade performance and require more frequent maintenance. This is a very demanding requirement for jet fuel and may become even more so in the future. Additionally, any new fuel for current aircraft would also have to be compatible with all of the materials found in aircraft fuel systems, including various metals, epoxy-type coatings and elastomeric seals.

## Potential Alternative Fuels

### Fuels from Fossil Sources

Almost all jet fuel today is manufactured from petroleum (crude oil). A relatively small percentage is made from oil sands, mainly those from Canada and Venezuela. There are other fossil fuel sources that could potentially be used to manufacture jet fuel, namely, natural gas, shale oil and coal. Several regions of the world have very large reserves of these materials. The total energy content of these other fossil fuels is estimated to be larger than that of petroleum. If practical and economical conversion processes can be developed, these shale and coal reserves could provide alternate sources for jet fuel that would be essentially the same as conventional, petroleum-derived jet fuel.

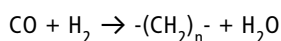
In the 1970s and 1980s the U.S. Air Force conducted a large research program to evaluate shale-derived jet fuel. The technology involved mining the shale, separating the shale oil using a high temperature retorting process and finally upgrading the shale oil to fuels using hydroprocessing. The program was successful and shale-derived jet fuel is acceptable under the current fuel specifications; however, the technology has not been used commercially because it has not been economical to do so. New technologies are under development that would separate the shale oil by heating underground. This would eliminate the problems associated with mining and waste disposal, but the shale oil would still need to be highly processed to produce jet fuel.

Coal liquefaction could potentially be used to make jet fuel. The technology has been demonstrated on a laboratory scale, but has not been used on a commercial scale. The U.S. Air Force has sponsored research into coal-derived jet fuel. This research was directed toward finding a fuel with very high thermal stability for use in future high performance aircraft.<sup>8</sup> Aside from this use, the research showed that coal could potentially be used to produce a blend component for commercial jet fuel, though any coal-derived jet fuel would require approval by the fuel specification bodies.

<sup>8</sup> L. M. Balster, et. al. "Development of an Advanced, Thermally Stable, Coal-Based Jet Fuel", Fuel Processing Technology (submitted 2005).

### Fischer-Tropsch Synthetic Fuel

Fischer-Tropsch (FT) synthesis converts a mixture of carbon monoxide and hydrogen, called synthesis gas, into higher molecular weight hydrocarbons.<sup>9</sup> It can be thought of as a catalytic polymerization of carbon monoxide accompanied by reaction with hydrogen to make the CH<sub>2</sub> methylene units of paraffins.



The process makes mainly straight chain hydrocarbons. The product composition will vary somewhat depending on the hydrogen to carbon monoxide ratio and the catalyst and process conditions. This raw product of FT synthesis must be further processed to make an acceptable fuel. This processing includes cracking the long chains into smaller units and rearranging some of the atoms (isomerizing) to provide the desired properties. This upgrading process produces a wide boiling range material encompassing naphtha (gasoline boiling range), kerosine, and diesel.<sup>10</sup> This material is then distilled into final products.

FT synthesis gives a product virtually free from the trace sulfur- and nitrogen-containing compounds found in conventional jet fuel. The product is also free from aromatic compounds, but this property has both advantages and disadvantages. The main advantage of the aromatic-free fuel is that it is cleaner burning; FT fuel emits fewer particulates than conventional jet fuel, and, because it is sulfur-free, there are no sulfur dioxide (SO<sub>2</sub>) or sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) aerosol emissions.<sup>11</sup>

However, there are two disadvantages of not having aromatics in the fuel. First, FT kerosine that meets all other jet fuel specification properties will be below the minimum density requirement. Second, the aromatics in conventional fuel cause some types of elastomers used in aircraft fuel systems to swell. There is concern in the industry that switching from conventional jet fuel to aromatic-free FT synthetic fuel will cause some of these elastomers to shrink, which may lead to fuel leaks. The effects of aromatics on elastomers is an area of active research in the industry. A possible solution may be to find an additive that would ensure elastomer swell even in the absence of aromatics.

These two disadvantages disappear if FT synfuel is blended with conventional jet fuel, although the advantage of lower emissions is reduced. The conventional jet fuel contains the aromatics that cause elastomer swell and also increase the fuel density to meet the minimum requirement. The industry is using 8 percent aromatics content as a guiding minimum. This minimum is based mainly on experience and could be revised, up or down, in the future.

The FT process was developed in Germany during World War II. Sasol developed the technology further and operates a commercial plant in South Africa which uses coal as the raw material. Coal

<sup>9</sup> "Fischer-Tropsch Technology", A.P. Steynberg and M.E. Dry eds. Elsevier, 2004.

<sup>10</sup> The FT process can also be used to make lube oil base stock, wax and other products.

<sup>11</sup> E. Corporan et. al. "Reduction of Turbine Engine Particulate Emissions using Synthetic Jet Fuel" American Chemical Society Division of Fuel Chemistry Preprints 2005, 50(1), p. 338.

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is first gasified and treated to remove contaminants including a significant amount of ash. The treated synthesis gas then undergoes the FT synthesis.

Since the FT synthesis starts with carbon monoxide, any source of carbon can potentially be used. The first plants used coal as the starting material; this conversion is called coal-to-liquids or CTL. The current generation of plants will use natural gas as the starting material; this is called gas-to-liquids or GTL. Biomass can also be used as the starting material by going through a gasification step to produce carbon monoxide; this process is called biomass-to-liquids or BTL. During the gasification step, the connection to the starting material is lost, so FT liquids produced from any starting material will be essentially the same.<sup>12</sup>

The FT industry appears to be on the verge of a period of expansion. Several major companies have announced plans to build large plants. If completed, these projects could yield about 1 million barrels per day of total product by 2020, some of which could potentially be used as an aviation fuel. These projections may be optimistic and the reality will be dictated by the market and its acceptance.

### Bio-Derived Jet Fuel

Biomass is being increasingly considered as an alternative raw material of transportation fuels.<sup>13</sup> Ethanol and biodiesel have been used in recent years as blend components for gasoline and diesel fuel respectively, and this use is likely to continue to expand as a result of government mandates in many countries and a desire to diversify energy sources.

#### Ethanol

Most ethanol today is produced by fermenting corn or sugar cane. Conversion of cellulosic biomass to ethanol is an area of active study. Cellulose can not be fermented to produce ethanol like the sugars found in corn, so a different conversion process must be developed. It may be possible to grow crops specifically for ethanol production or waste biomass could be used. This has the promise of being a more efficient process and may be the next generation of ethanol production. Regardless of the source, the properties of the ethanol are the same.

Ethanol contains about 35 percent oxygen by weight, so it has lower gravimetric energy content than conventional jet fuel. Ethanol is significantly more volatile than jet fuel and boils at a single temperature (78°C). Jet fuel boils over the range of approximately 150° to 300°C. Ethanol has a significantly higher heat of vaporization than hydrocarbons due to its intermolecular hydrogen bonding. These properties are related to fuel atomization and vaporization in the combustor.

- 12 There are several FT processes available that use different catalysts, process conditions and upgrading schemes and the products can vary slightly. However, for a given process and H<sub>2</sub>:CO ratio, the product composition will be independent of the starting material.
- 13 The term *biomass* means any plant-derived organic matter. Biomass available for energy on a sustainable basis includes herbaceous and woody energy crops, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, and other waste materials including some municipal wastes. Definition from National Renewable Energy Laboratory, U.S. Department of Energy.



Ethanol is a strong solvent and its effect on fuel system materials would have to be investigated. Ethanol and water are miscible (able to be mixed), in contrast to hydrocarbon fuels and water, which are essentially immiscible.

Use of 100 percent ethanol as an aviation fuel would require a separate storage and distribution system from conventional jet fuel. Blends of ethanol with conventional jet fuel also pose problems because of the significantly different physical and chemical properties of ethanol and jet fuel.

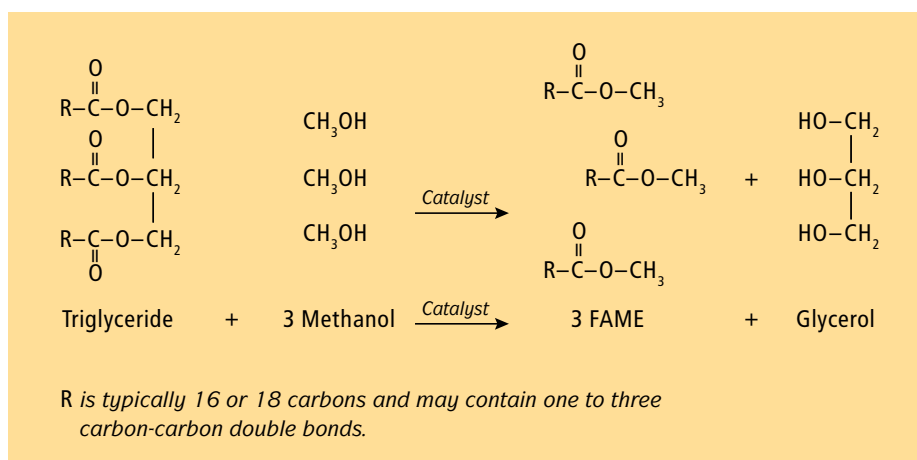
### Biodiesel

Biodiesel has been in the news in recent years as a possible alternative to conventional, petroleum-derived diesel, and is being considered as an aviation fuel as well. In general usage, the term biodiesel covers a variety of materials made from vegetable oils or animal fats. Various crops are used in different parts of the world to make biodiesel. In the U.S., soybean oil is the largest source for biodiesel, although oil from other vegetation can be used as well. In Europe, rapeseed oil is commonly used while in Asia, palm oil and coconut oil are used. Research is being conducted into using algae as a source of biodiesel.

Vegetable oils or animal fats themselves are not generally used as fuels, although they can be used directly in some applications. However, the oils and fats can be combined with methanol in a process known as transesterification to produce a material with better properties. The oils and fats are triglycerides of fatty acids. The transesterification reaction converts triglycerides into the fatty acid methyl esters (FAMES) and glycerol.

Figure 3

Transesterification of Vegetable Oil to Biodiesel



These esters have chemical and physical properties that are similar to conventional diesel fuel. Biodiesel properties depend on the starting material. Triglycerides from different sources have different numbers of carbon atoms and varying degrees of unsaturation (number of

carbon–carbon double bonds). These differences are reflected in the properties of the derived FAMEs. Some typical properties for biodiesel are compared to conventional jet fuel below.

Figure 4

Properties of Biodiesel and Conventional Jet Fuel

Fuel Property	Biodiesel (typical)	Conventional Jet Fuel
Flash Point, °C	100	40 – 45
Viscosity 40°C, Cst	4.7	1.2
Sulfur, wt%	< 0.05	0.05 – 0.15
Net Heat of Combustion, MJ/kg	36 – 39	43.2
Relative Density, 15°C	0.87 – 0.89	0.80
Freezing Point, °C	~ 0	< -40
Approximate Carbon Number	C16 – C22	C8 – C16

Source: National Soy Diesel Development Board and National Biodiesel Board

The gravimetric energy content of biodiesel is somewhat lower than that of conventional jet fuel. It has good lubricity properties and contains essentially no sulfur or aromatics. Biodiesel is biodegradable, but this property may lead to increased biological growth during storage. The ester group in FAMEs makes them slightly polar; this could lead to formation of emulsions and could have an effect on water separation.

The primary concern with the use of biodiesel is its low temperature properties. Biodiesels have freezing points near 0°C, much higher than the maximum freezing point of jet fuel, -40°C. Fuel is exposed to very low temperatures at cruise altitude, and it must remain fluid in order to be pumped to the engine. Even blends of biodiesel with jet fuel have much higher freezing points than jet fuel. Additives could potentially improve low temperature operability of biodiesel blends, but only by a few degrees Celsius. Any new additive would have to be subjected to an extensive approval process.

Another important jet fuel property is thermal stability. The thermal stability of FAMEs and blends of FAMEs with conventional jet fuel has not been reported, but is an area of concern. The higher carbon number and viscosity of FAMEs compared to jet fuel could affect atomization and vaporization in the combustion chamber. All of these issues would have to be studied thoroughly and all issues resolved before FAMEs could be used in aviation.

Triglycerides and the resulting FAMEs are the most fuel-like biological products. However, even the FAMEs are not a good match for jet fuel properties. Significant molecular changes are required to transform triglycerides or any other biomass into “jet fuel molecules.” The most promising option is gasification, especially of waste biomass, followed by FT synthesis; however, it may be possible to develop new processing technologies to achieve the required molecular transformations.

## Cryogenic Fuels

The term cryogenic fuels refers to materials that are gases at normal ambient conditions that have been cooled to their boiling point and stored as low temperature liquids. Examples are liquid hydrogen and liquid methane. Figure 5 lists the energy content, boiling point and density for these fuels.

**Figure 5**  
Energy Content, Boiling Point and Density of Cryogenic Fuels

Fuel	Energy Content, MJ/kg	Boiling Point, C	Density at Boiling Point, g/cc
Hydrogen	120	-253	0.071
Methane	50	-162	0.424

Both of these fuels have very high gravimetric energy content, but their low density leads to low volumetric energy content (see Figure 1). Both fuels are fundamentally different from jet fuel and would require a new fuel infrastructure in addition to new engines and airframes.

Hydrogen from renewable resources is positioned as the fuel of the future. We are starting to see hydrogen used in fuel cells both for stationary power generation and to power ground vehicles. More than ninety percent of hydrogen produced today is generated by reforming natural gas, methane, into hydrogen and carbon dioxide. While meeting today's industrial hydrogen demands, the overall efficiency of this process for the production of transportation fuels should be questioned as it basically converts one fuel into another and generates carbon dioxide, a greenhouse gas. Before hydrogen will displace fossil fuels as a major source of energy, an efficient and economical process will be needed to generate hydrogen from water and other renewable resources such as solar or biomass.

Cryogenic fuels may be used in commercial aviation, but not for several decades.

## Aviation Fuel Approval Process

There are three major specifications for commercial jet fuel: UK MOD Defence Standard 91-91 Jet A-1 used in most of the world, ASTM D1655 Jet A/Jet A-1, with Jet A used in the U.S., and GOST 10227 TS-1 fuel used in Russia and other countries in the Commonwealth of Independent States. Many countries maintain their own specifications, but these are kept in alignment with one of the major specifications.

The ASTM and MOD specifications are the result of a collaborative process involving aircraft engine and airframe manufacturers, fuel suppliers, additive suppliers, national aviation regulatory agencies, and other interested groups. Ultimately the engine and airframe manufacturers determine the fuel properties required for safe and reliable operation of their equipment. These

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requirements are embodied in a fuel specification that is part of an aircraft's type certificate, which are issued by the national aviation regulatory authorities.

The jet fuel specifications are not true material specifications, but are based on experience with conventional petroleum-derived jet fuel and include implicit assumptions that are met by conventional jet fuel.<sup>14</sup> For example, since the specifications limit the maximum aromatics concentration, but do not specify a minimum, a fuel with zero aromatics would meet this part of the specification.

Jet fuels with high aromatics content will not burn as cleanly as fuels with lower aromatic content, so the specifications include a maximum aromatics concentration to limit this effect. There has never been a need to define a minimum aromatics concentration because conventionally refined petroleum-derived kerosine will have a significant aromatics concentration, typically between 8 percent and 22 percent by volume.

Boiling range is another example of implied assumptions in jet fuel specifications. The specifications include a maximum limit of 205°C on the 10 percent boiling point and a maximum limit of 300°C on the final boiling point. The expectation is that the fuel will have a smooth boiling range distribution with the 10 percent point below 205°C, but reasonably close to it, and the final boiling point will be below, but reasonably close to, 300°C and that the final boiling point will be significantly above the 10 percent point. But a single component with a boiling point of 200°C meets the distillation requirement, although this is not the intent or the expectation of the specification.

Typical refinery processing will produce a smooth boiling range distribution. All fuels used in testing and development of aircraft engines have had this property. So the specifications only need to include minimal limits on distillation properties and the industry can have confidence, based on knowledge and experience, that conventionally processed petroleum-derived jet fuel will have the desired smooth boiling range distribution.

When alternative fuels are being considered, these implicit assumptions must be recognized. The candidate fuel must meet letter of the specification requirements, which were developed around petroleum-derived fuel. In addition, the fuel must meet the ultimate requirement – a fit-for-purpose aviation fuel.

Currently there is only one alternative fuel approved for aviation use. The synthetic FT isoparaffinic kerosine produced by Sasol in South Africa can be blended with conventional jet fuel up to

<sup>14</sup> Conventional jet fuel is a mixture of several hundred, perhaps a thousand, individual chemical compounds, so it is not possible to control the detailed composition in a specification. For a pure compound like hydrogen or ethanol, it is possible to write a complete material specification.

50 percent by volume (semi-synthetic jet fuel).<sup>15</sup> This approval, which is written into both the Defence Standard and ASTM specifications, was granted only after extensive testing was conducted to determine that this fuel met the fit-for-purpose criteria.

Some of the fuel properties tested include: dielectric constant, thermal conductivity, specific heat, bulk modulus, air solubility, surface tension, thermal and storage stability, additive solubility and effectiveness, and elastomer compatibility. This is just a partial list of the testing done to ensure that none of the assumptions implicit in the specification was violated and that the semi-synthetic fuel is fit-for-purpose.

Since this approval was granted in 1999, semi-synthetic jet fuel has been used routinely at Johannesburg International Airport in South Africa. There have been no reported fuel quality issues related to the use of semi-synthetic fuel. Based on this experience, the engine and airframe manufacturers have developed a certain comfort level with the use of FT synthetic fuel in a blend with conventional jet fuel.

To avoid going through this level of effort for every new source of FT synthetic fuel, the industry is developing a generic approval process. This will include a series of tests that must be done and guidelines for acceptable limits of the test results. If all fuel properties fit within accepted limits, approval should be less complex. The process will include check points and the engine and airframe manufacturers can request extra testing at any point if there are anomalies in test results. This streamlined approval process will apply only to FT synthetic fuel that will be used as a blend component with conventional fuel at up to 50 percent by volume. Any other alternative fuel would have to go through a full review before approval.

## Environmental

Environmental effects of an alternative fuel must be considered. The industry and the general public will only accept improvements on environment quality and stewardship.

Emissions testing has been conducted on FT synthetic fuel in combustor rigs.<sup>11</sup> FT fuels emit much lower concentrations of particulates, and, because they are sulfur-free, they emit no sulfur oxides (SO<sub>x</sub>) or sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) aerosols, which are implicated in contrail formation. When blended with conventional fuels, the emissions benefit is roughly proportional to the synthetic fuel content.

There are no data available on emissions from alcohol or biodiesel fueled turbine engines, but these are potentially a concern. When incompletely combusted, oxygenated fuels can emit aldehydes. These aldehyde emissions are classified as hazardous air pollutants by the U.S. Environmental Protection Agency and can cause eye irritation.

<sup>15</sup> Sasol has applied for approval of a 100 percent synthetic fuel that includes synthetic aromatics. Final testing is expected to be completed in the second half of 2006. If the test results are acceptable, this fuel could be approved in 2007.

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FAMEs are more viscous than conventional jet and have higher molecular weight. These properties could affect atomization and vaporization in the combustor and result in incomplete combustion and particulate emissions, especially at low engine power settings.

Hydrogen burns very cleanly producing only water vapor. However, the effect of emitting significant quantities of water vapor at cruise altitude would have to be understood before committing to hydrogen-fuelled aircraft.

Emissions from the engine are not the only environmental concern. The whole life-cycle of the fuel must be studied. When considering biofuels, issues such as land use, fertilizer use, water for irrigation, waste products etc. must be addressed. This type of analysis is called “cradle to grave” or “life cycle assessment” and has been conducted for several fuels.<sup>16, 17</sup> Similarly, with use of coal or shale, there are issues with mining, both deep-hole and strip mining, water use, run-off from mine sites, and waste material.

Any processing of raw material into finished fuel is energy intensive, resulting in emissions of carbon dioxide, a significant greenhouse gas. In contrast, growth of biomass removes carbon dioxide from the atmosphere so use of biomass-derived fuel in place of fossil-derived fuel can potentially result in a net decrease in carbon dioxide emissions.

## Other Studies

Several other studies have addressed the question of alternatives to conventional jet fuel.

The International Panel on Climate Change (IPCC) concluded, “There would not appear to be any practical alternatives to kerosene-based fuels for commercial jet aircraft for the next several decades.”<sup>18</sup>

The U.K. Department for Trade and Industry commissioned a project entitled “The Potential for Renewable Energy Sources in Aviation” (PRESAV). The main findings are quoted below.<sup>19</sup>

Methanol, ethanol and biogas are unsuitable for jet aircraft and nuclear power is not a suitable alternative. Hydrogen, FT kerosene and biodiesel, however, all have the potential to bring savings in the sector’s use of non-renewable energy and emissions of greenhouse gases. These benefits are greatest for H<sub>2</sub>, FT kerosene then biodiesel, respectively. All three options would be significantly

<sup>16</sup> “Gas to Liquids Life Cycle Assessment Synthesis Report,” Five Winds International, 2004. [http://www.sasolchevron.com/pdf/publication/GTL\\_LCA\\_Synthesis\\_Report.pdf#search=%22life%20cycle%20assessment%20fuel%22](http://www.sasolchevron.com/pdf/publication/GTL_LCA_Synthesis_Report.pdf#search=%22life%20cycle%20assessment%20fuel%22).

<sup>17</sup> Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Argonne National Laboratory, <http://www.transportation.anl.gov/software/GREET/index.html>

<sup>18</sup> “Aviation and the Global Atmosphere”, Intergovernmental Panel on Climate Change, Cambridge University Press, 1999, J. E. Penner, (ed).

<sup>19</sup> <http://www.iccept.ic.ac.uk/pdfs/PRESAV%20final%20report%2003Sep03.pdf>

more expensive to produce compared to the cost of kerosene today (2003). In the long term, however, the costs of producing H<sub>2</sub> and FT kerosene may drop sufficiently for them to become viable options. Hydrogen aircraft would require new engines and airframes and are unlikely to be seen for at least several decades. In general, renewable fuels are likely to be used for uses such as road transport or electricity generation in preference to aviation.

Turbine engine manufacturers, General Electric, Honeywell, Pratt & Whitney and Rolls Royce presented a consensus position at the Aviation Alternative Fuel Workshop held in May 2006.<sup>20</sup> Some of their conclusions are summarized below.

- Kerosine based fuels are the preferred option.
- Biofuel (FAME) presents major technical and logistical risks at present.
- The FT process provides opportunity to produce aviation fuel from biomass at lower risk and shorter timescales.
- Liquefied gas options have non gas-turbine-related barriers.
- All alternative fuel options require further study and whole life cycle analysis.
- New fuels will require certification of aircraft and engines.

## Conclusion

There are plausible alternatives to conventional jet fuel, but these new fuels cannot jeopardize safety and reliability of aircraft systems. Producers of these new fuels must also account for the lifecycle of the fuel and its total environmental impact along with health and toxicological effects.

What sources of diversified energy could be used to make jet fuel? Engine and airframe designs for cryogenic fuels such as liquid hydrogen and liquid methane are still being tested but are many years away from commercialization. While first generation biofuels such as ethanol and biodiesel may be a better fit for ground and/or marine transportation, the FT synthetic jet fuel made from carbon sources such as biomass, coal, shale or natural gas and used in a blend with conventional jet fuel is the most viable pathway.

A rigorous approval process is necessary for all alternative fuels ensuring that unique requirements for the turbine engine and its operation in commercial service are satisfied. Lessons from Sasol's FT synthetic jet fuel approval serve as a model for the technical approval committees to develop a process streamlining the testing requirements and expediting the time required for manufacturers to introduce new FT synthetic jet fuels to the marketplace.

While there are challenges ahead, the aviation industry is poised to encourage the use of diverse energy resources and apply ingenuity to power the world's aircraft.

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