BIOFUELS: AN ALTERNATIVE TO U.S. AIR FORCE PETROLEUM FUEL DEPENDENCY

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14. ABSTRACT
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Abstract

The United States Air Force (USAF) is the largest energy consumer in the Department of Defense (DoD). Volatile oil prices force the USAF to divert money from training budgets and weapon system procurement accounts in order to cover increased costs due to unbudgeted fuel expenses. In conjunction with the President's mandate to reduce dependency on foreign procured oil and in an effort to stem unfunded fuel expenses, the USAF established an active alternative energy program focused on increased conservation and the development of new, domestic sources of fuel.

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Chapter 1
Introduction

Access to energy sources has long been of vital interest to national security. Japanese involvement in World War II was driven by a need to secure access to oil in the South Pacific, and the 1990 United States decision to evict Iraq from Kuwait was driven by an international need to secure Western access to Middle East oil reserves. With daily consumption of 19.8 million barrels per day (BPD), the U.S. is the single largest consumer of petroleum.[1] Worldwide oil consumption, currently 80.1 million BPD, is expected to increase to approximately 110.7 million BPD by the year 2025.[2] In order to address U.S. energy concerns, President George W. Bush established a new vision for U.S. energy security, "America is addicted to oil, which is often imported from unstable parts of the world. The best way to break this addiction is through technology…new technologies will help us reach another great goal: to replace more than 75 percent of our oil imports from the Middle East by 2025."[3] The President's vision relies on a combination of conservation, oil alternatives derived from other fossil sources, and biologically produced fuel alternatives.

U.S. Air Force (USAF) leaders echo the President's concerns and as the number one consumer of Department of Defense (DoD) energy, have established an aggressive program to reduce Air Force reliance on foreign oil through a program of conservation and the development of oil alternatives.[4] With aviation consuming 82 percent of all USAF petroleum, it is critical that the USAF program not only promotes fuel conservation, but also seeks to develop aviation fuel alternatives.[5] The thesis of this paper is that by the year 2025 non-petroleum, biologically produced fuels can replace the Air Force's 3.2 billion gallon annual aviation fuel requirement.[6]

In order to show the feasibility of a biological solution to USAF aviation fuel demand, this paper first establishes the need for a biological fuel alternative then discusses four potential sources of biological fuel: Ethanol, terrestrial-produced biodiesel, algae-produced oil, and bio-butanol. Analysis of these alternatives considers three requirements that must be met in order to replace USAF aviation fuel requirements by the year 2025:

- The fuel must meet current JP-8 energy density standards
- The petroleum fuel alternative must not require major engine modifications or prevent the use of petroleum-based JP-8
- Fuel production must meet Air Force fuel demand in terms of quantity, transportability and stability

If successful, a biological alternative to aviation fuel will meet the President's energy vision as well as reduce vulnerabilities presented by the USAF petroleum fuel dependency.

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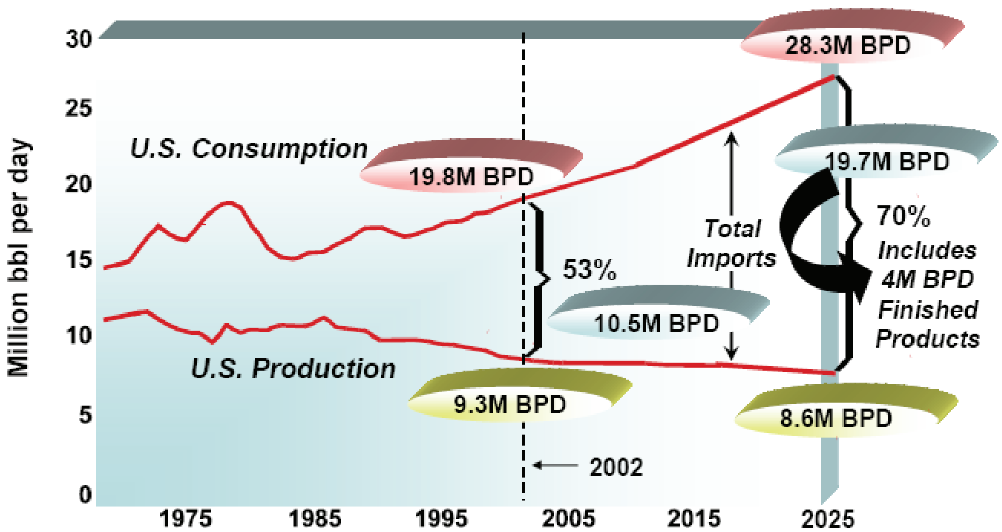
Chapter 2
Why Pursue Bio-fuel Alternatives?

In 2002, the United States consumed 19.8 million BPD with daily consumption exceeding domestic production by 10.5 million barrels.[7] This amounts to a 53 percent reliance on foreign obtained petroleum to fuel the American economy. Figure 1 shows current and future projections of U.S. petroleum consumption. Unless consumption is reduced, or an alternative to petroleum is discovered, it is estimated U.S. petroleum demand will increase

Figure 1. Projected U.S. Reliance on Petroleum Imports (Million Barrels/Day)[8]



to 28.3 million BPD by the year 2025 with an increased reliance on foreign procured oil exceeding an astounding 19.7 million BPD.[9] This figure amounts to a 70 percent reliance on foreign procured petroleum by the year 2025.

In light of America's dependency on imported oil, President Bush, in his January 31, 2006, State of the Union Address established a new vision for U.S. energy self-sufficiency, "Keeping America competitive requires affordable energy. And here we have a serious problem: America is addicted to oil, which is often imported from unstable parts of the world. The best way to break this addiction is through technology."[10] The President proposed to increase Department of Energy (DOE) funding to accelerate research into petroleum alternatives such as nuclear energy, solar, wind, fuel-cells, hybrids and biofuel alternatives in order to move our nation beyond its petroleum dependency.[11]

The USAF's interest in curbing petroleum-based fuel dependency is three-fold. First, just as dependency on foreign fuel threatens America's economic security, it also threatens USAF mission accomplishment. Second, by reducing petroleum-based fuel needs the AF supports the Presidents vision of reducing America's oil addiction. Finally, rising fuel costs consume a large portion of the Air Force budget with increased costs adding no value to mission accomplishment. In fact, petroleum price volatility forces the movement of USAF funds in order to cover unbudgeted fuel costs.[12] These three concerns drive current USAF alternative fuel research and provide a compelling argument for continued efforts.

The U.S. and USAF Vulnerability

The Air Force mission is truly powered by petroleum. The Air Force mission is, "to deliver sovereign options for the defense of the United States of America and its global interests…to fly and fight in air, space, and cyberspace."[13] In order for the Air Force to provide global power projection in the form of global strike and rapid global mobility capabilities, the Air Force relies on unrestricted access to worldwide oil supplies.[14] In order to provide "sovereign options" in defense of U.S. interests, the USAF must insure uninterrupted access to global petroleum reserves.

To understand the vulnerability posed by U.S. reliance on foreign-procured petroleum, one must first understand who possesses petroleum reserves, how long these reserves will last based given anticipated worldwide consumption rates, and must understand that those nations who control large energy reserves have a tremendous ability to leverage these reserves and affect U.S. economic security.

Who Owns the Worlds Petroleum?

The United States is the top petroleum consumer in the world. The U.S. consumes 24 percent of all oil produced worldwide and imports over 10 million BPD in order to keep up with current demand.[15] With 53 percent of daily oil needs imported, the U.S. economy is dependent on other nations to meet daily needs. Table 1 summarizes the top suppliers of U.S. crude oil. Of note, OPEC member nations fill 25 percent of U.S. oil demand.[16] An examination of where crude oil reserves reside indicates that U.S. dependency on foreign oil imports will continue and will in fact grow as U.S. demand increases. Although the U.S. is the third largest oil producer, it is estimated that if the U.S. had to depend solely on its own 21.4 billion barrels of proven reserves, the U.S. would exhaust indigenous reserves in 4 to 5 years.[17] Figure 2 shows who controls the 1.278 trillion barrels of proven oil reserves. U.S. petroleum dependency is an economic Achilles' heel, as well as the cornerstone of U.S. military force projection. The fact is the U.S. does not have enough indigenous petroleum reserves to keep up with U.S. demand and must rely on a stable flow of imported oil in order to keep pace with growing U.S. requirements.

Rank	Country	Crude Oil	Products	Total
1	Canada	1,633	548	2,181
2	Mexico	1,556	106	1,662
3	Saudi Arabia*	1,445	92	1,537
4	Venezuela*	1,241	288	1,529
5	Nigeria*	1,077	89	1,166
6	Iraq*	527	4	531
7	Algeria*	228	250	478
8	Angola	456	17	473
9	Russia	199	211	410
10	United Kingdom	224	173	396
11	Virgin Islands	0	328	328
12	Ecuador	276	7	283
13	Kuwait*	227	16	243
14	Norway	119	114	233
15	Columbia	156	40	196
	Total	**10,126**	**3,588**	**13,714**
	Persian Gulf	2,207	127	2,334
* OPEC Nations				

Table 1. Top Suppliers Of Us Crude Oil And Petroleum, 2005 (Thousands Barrels per Day)[18]

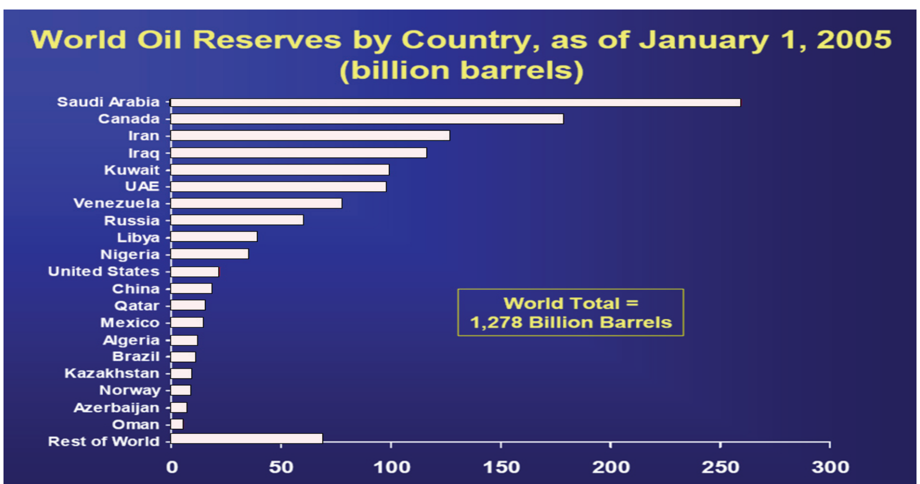


Figure 2. Proven World Oil Reserves (Billion Barrels)[19]

Added to this, worldwide energy consumption will have grown by 57 percent between 2002 and 2025 with the strongest growth occurring in emerging economies, particularly in Asia.[20] Figure 3 shows projected worldwide energy demand through the year 2025. This increased demand will create competition for finite resources, and as large industrializing nations such as China and India seek new energy supplies, oil will become even more expensive.[21] Added to increased financial costs is the increased political and economic advantage afforded those nations possessing vast oil reserves.

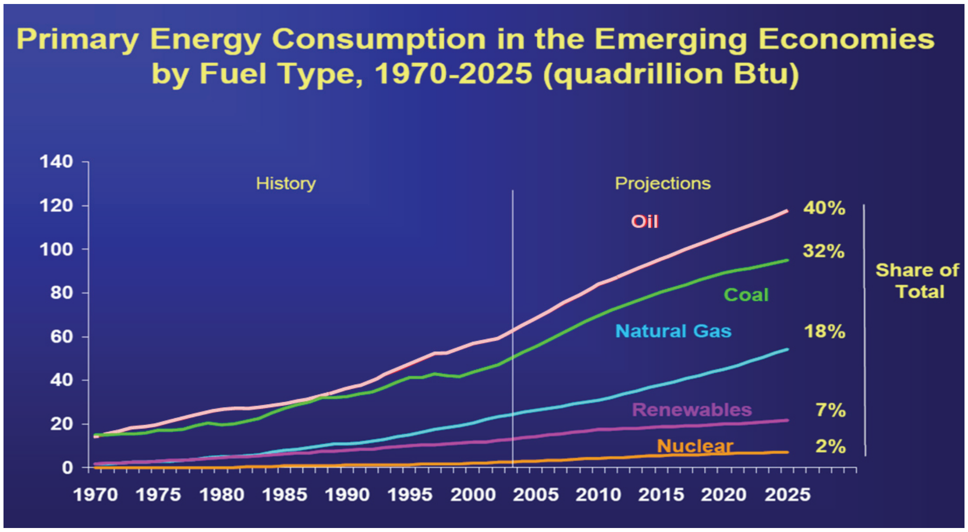


Figure 3. Projected Worldwide Energy Consumption by Fuel Type (Quadrillion BTUs)[22]

Senator Richard G. Lugar warns that adversarial regimes such as Venezuela, Iran and Russia are using energy supplies as leverage against their neighbors. "Our current dependence on imported oil has put the United States in a position that no great power should tolerate. Our economic health is subject to forces far beyond our control, including the decisions of hostile countries. We maintain a massive military presence overseas, partly to preserve our oil lifeline."[23] As global demand increases, uninterrupted access to oil will become more challenging. As the President stated, the U.S. must reduce this dependency through conservation and development of alternative energy sources.

Support the President's Vision

The second reason the USAF military must reduce dependency on foreign procured oil is to support our Presidents vision. In a "Letter to Airman: Energy Conservation," Secretary of the Air Force, Michael W. Wynne, acknowledged the USAF commitment to reducing military dependency on foreign energy. "As the largest user of energy in the DoD, the Air Force has developed a two-pronged energy strategy to attack this [dependency] problem.

This strategy of assured domestic supply and aggressive energy conservation will benefit our entire Air Force…Our research labs are hard at work developing synthetic hydrocarbon fuels made from coal, oil shale and biomass. Look for our first test flight, on a B-52 using synthetic fuel later this month."[24] Having reduced facility energy use 30 percent over the past 20 years, the Air Force is now primed to reduce petroleum-based fuel requirements for its aircraft fleet.[25]

Budget Constraints

Finally, fluctuating fuel prices create volatility in the Air Force Budget increasing operating costs and requiring additional congressional appropriations or forcing diversion of money from training and weapon system procurement programs. The military consumes 1.9 percent of the 20 million barrels of oil consumed each day in the U.S.[26] Although this may not sound impressive, the DoD is the largest single energy consumer in the United States.[27] Military consumption equates to 300,000 BPD of which 73.5 percent is consumed by aircraft, costing the AF over $ 10 million per day.[28] Paying more for fuel adversely affects the AF mission. According to then Major General Stephen R. Lorenz, former Deputy Assistant Secretary for Budget, the 2006 Air Force flying hour budget was increased by $800 million to cover increased fuel costs.[29] In order to cover increased fuel costs, the Air Force was forced to "slow operations [and] throttle back."[30] In his article, "Fuel Hedging: Lessons from the Airlines," Lieutenant Colonel Lawrence Spinetta describes how FY06 fuel costs negatively impacted the DoD budget:

> Eleventh-hour budget cuts, resulting from Program Budget Directive (PBD) 723, allowed the Air Force to escape much of the financial burden from unfunded FY06 fuel costs, but the other Services were not as lucky. The Pentagon's comptroller allocated $1.1B in new Air Force funding, mostly to cover fuel costs, but slashed $4B in non-fuel programs from the Army, Navy, and Marine Corps budgets. Although PBD 723 was favorable from an Air Force perspective, it was far from ideal. It delayed the Airborne Laser Program and cut $100M from the Joint Strike Fighter engine account.[31]

Not only do unanticipated fuel costs divert money from programmed weapon system procurement, but Air Force readiness is also impacted. In 2005 the Air Force paid approximately $4.2 billion for petroleum—almost $1.4 billion more than in fiscal year 2004. Mr. Wine, a British Petroleum (BP) spokesman, attributed the rising cost of fuel to worldwide supply and demand, uncertainty in the petroleum market, and political tension.[32] With a 31 percent increase in fuel costs, the Air Force and Air Combat Command (ACC) were required to make significant budget changes just to cover operating expenses. Mr. John Cilento, ACC Flying-hour Program Analyst, stated, “The shrinking budget has caused the Air Force to reduce the funding available for flying hours used to train ACC aircrews…ACC programs are based on the minimum requirements to train our aircrews, so any reduction is a loss of an already maxed-out training capability.”[33] Continual flying hour cuts not only hurt training, but also lower the combat readiness of the aircrews. When an increase in the price of oil of $10/barrel increases USAF fuel costs by $600 million over the course of a single year, it is imperative the USAF explore alternatives that allow oil price stabilization.[34]

The USAF recognizes the vulnerabilities presented by fluctuating fuel costs and uncertain access to worldwide oil reserves. On July 12, 2006, the Defense Advanced Research Projects Agency (DARPA) released a solicitation calling for exploration into aviation fuel alternatives. As outlined, the goal of this biofuels program is to develop an affordable biodiesel alternative production process that will achieve a 60 percent greater energy content than current synthetic and biofuels and elucidate a path to a 90 percent conversion.[35]

In a series of tests, first in engines mounted on blocks, then with B-52’s in flight, the Air Force proved its aircraft can burn a 50-50 blend of synthetic and JP-8 fuel.[36] The fuel, known as syntroleum, is synthetic kerosene produced from natural gas through the Fischer-Tropsch (F-T) process.[37] With its initial success, the USAF is laying a strong foundation for energy independence. But, the use of non-renewable fossil fuels to provide jet fuel should be seen as the beginning of this initiative, and not the end state.

Biological fuel alternatives, combined with the current USAF F-T initiative, offer a potential long-term renewable solution to Air Force fuel vulnerabilities. Biologically produced aviation fuel has the potential to reduce, and even eliminate, the need for foreign oil, supports the energy vision articulated by President Bush and Air Force leaders, and offers a long-term solution to energy price volatility by allowing Air Force fuel needs to be filled through domestic production. This paper now turns its focus on the ability of specific biotechnologies to develop fuels that meet USAF aviation fuel specifications.

Chapter 3
Bio-fuel Alternatives

Biofuels are not a new concept. The Ford Model T, produced between 1903 and 1926 was specifically designed to run on ethanol. However, when crude oil began being cheaply extracted from the ground, demand for the cheaper petroleum-based fuels negated the need for the biologically produced fuel alternative.[38] The oil shortage of 1973 and 1979 reinvigorated interest in biofuels as a cheap alternative to petroleum, but once again crude oil prices fell and decreased demand for alternative fuel research. Renewed interest in biofuels is a direct result of economic pressure combined with potential environmental impacts of greenhouse gas emissions. Increases in world fuel prices, along with the impact of hurricane damage on U.S. refineries, drove oil prices to over $84 per barrel during 2005.[39] When combined with political instability in Middle East petroleum producing nations, these pressures created a renewed interest in biofuel alternatives for the nation, and for the USAF as well.[40]

The two primary types of biologically produced transport fuel are ethanol and biodiesel, making up three percent of the U.S. transport fuel market.[41] Added to these two primary sources are two emerging sources of liquid fuel: algae-produced oil and biobutanol. Before analyzing the ability of each of these sources of biofuel to meet USAF aviation fuel demand, it is important to first have a general understanding of how these fuels are derived, and also an understanding of each fuel's advantages and disadvantages.

Ethanol

The primary biological replacement for automobile gasoline is ethanol. Most consumers are familiar with ethanol-blended gasoline. Combustion engines can run on gasoline "stretched" with as much as ten percent ethanol without any mechanical modification, but higher concentrations of ethanol require special engine modifications. These modified automobiles are known as "flex-fuel" vehicles because of their ability to run on either straight gasoline or gasoline blended with more than ten percent ethanol.[42] Just like automobiles, aircraft can be modified to operate on ethanol fuel. The owner of an air-taxi service in Mineiros, Brazil, with a fleet of twelve planes, needed to reduce fuel costs. He spent twenty percent of his revenue purchasing fuel for his aircraft. "Flying on ethanol distilled from sugarcane slashed his fuel bill by 40 percent, at no cost to performance."[43]

Ethanol is produced through the fermentation of sugar from enzymes produced by specific varieties of yeast.[44] The source of this sugar is biomass.

The U.S. Department of Energy defines biomass as, "Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal manure, municipal residues, and other residue materials."[45] The principle source of biomass in the U.S. ethanol industry is corn because it is readily fermentable and can produce high yields of ethanol.[46]

There are numerous advantages to burning ethanol instead of petroleum-based fuel. Unlike oil, no one country dominates the market for ethanol. Therefore, regardless of indigenous petroleum reserves, the U.S. can produce ethanol domestically or purchase it on the open market.[47] Additionally, whereas petroleum releases carbon that had been previously trapped underground, the carbon in biofuel emissions has simply been captured from the atmosphere by crops during photosynthesis. The effect, biofuel advocates say, is up to a 90 percent reduction in greenhouse-gas emissions due to recycling carbon as opposed to producing more carbon.[48] A third advantage of ethanol is the price. In Brazil, with 30 percent of automobiles running on ethanol, it is less than half the price of crude oil at only $25 a barrel.[49] These three characteristics of ethanol make it an attractive and affordable alternative to petroleum-based fuels.

In April 2005, the U.S. Department of Energy and the U.S. Department of Agriculture published a joint study titled, "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply."[50] The purpose of the study was to determine whether the land resources of the United States are capable of producing a sustainable supply of biomass in order to replace 30 percent of current U.S. petroleum consumption by the year 2030. The study determined there is enough biomass, looking at just forestland and agricultural land, to produce over 1.3 billion dry tons of biomass per year (figure 4). The nearly one billion dry tons of biomass derived from agricultural sources would require only modest changes in land use, and would not impact U.S. ability to meet food, feed and export demands.[51] As a result, the U.S. Department of Energy and the U.S. Department of Agriculture are both strongly committed to expanding the role of biomass as an energy source.

Ethanol Outlook

Agricultural residues such as stalks and leaves, also known as stover,[52] provide a tremendous source of biomass for ethanol production. At conversion yields of 60 to 100 gallons per dry ton of biomass, the available corn stover inventory would be sufficient to provide 7 to 12 billion gallons of ethanol per year.[53] There are currently 113 ethanol biorefineries operating in the U.S. producing nearly 4 billion gallons of ethanol in 2005.[54] Although there are 71 new biorefineries under construction and more in various stages of planning, these refineries will have to rely on

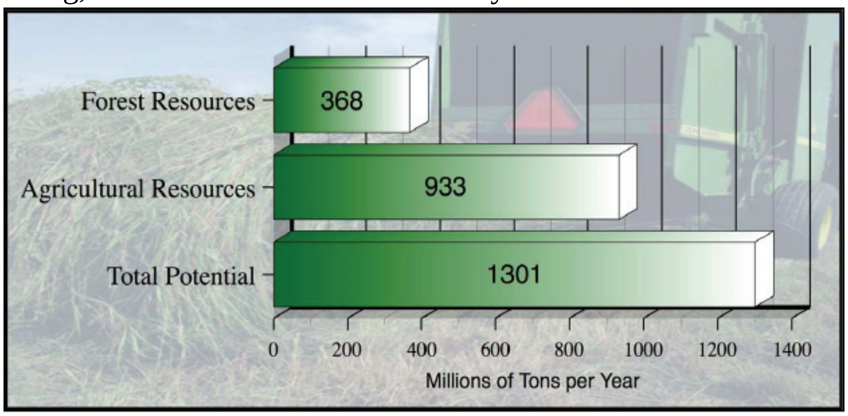


Figure 4. Annual Biomass Resource Potential from Forest and Agricultural Sources[55]

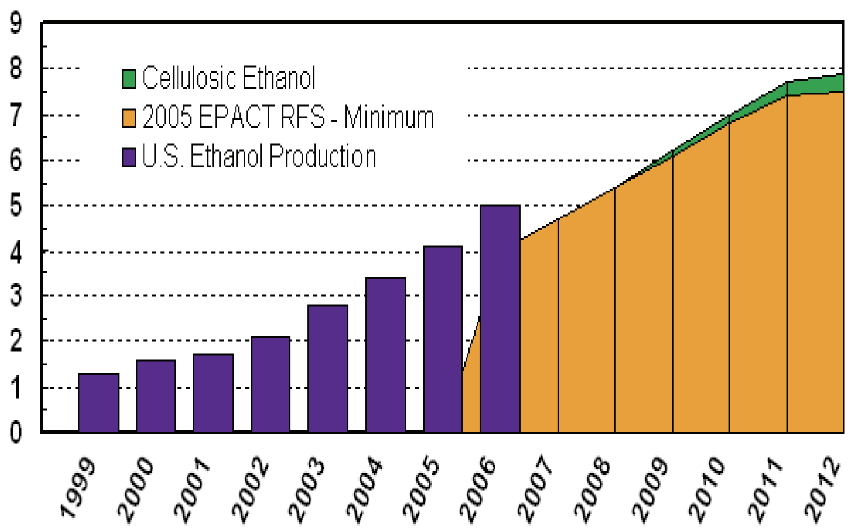


Figure 5. Actual and Projected U.S. Ethanol Production 1999-2012 (Billion Gallons of Production)[56]

another source of biomass or risk impacting the U.S. corn market.[57] Figure 5 shows actual and projected U.S. ethanol production from 1999 to 2012.

Increased production is not only a function of increased numbers of ethanol biorefineries, but also depends on the ability of using more than the starchy portion of biomass.

Current ethanol production relies on fermenting edible constituents of biomass. In order to improve ethanol yield, scientists are developing cost effective methods of producing ethanol from non-edible constituents of biomass, in particular cellulose. Cellulose is the most abundant form of carbon in the biosphere. Like starch, it is a polymer of glucose. However, unlike starch, the manner in which the glucose molecules are connected makes cellulose resistant to hydrolysis.[58] National Renewable Energy Laboratory (NREL) scientists, in conjunction with other organizations, continue development of low-cost conversion methods that allow economical ethanol production through cellulose conversion. Figure 6 shows the projected reduction in price per gallon of cellulosic ethanol as technology advances. Current technology allows only 65 gallons of ethanol production from one ton of cellulosic biomass at a cost of over two dollars per gallon. It is anticipated that by the year 2020, advances in enzymatic biotechnology will enable the production of 94 gallons of ethanol per ton of biomass and reduce selling prices to less than 75 cents per gallon.[59]

Advances in cellulosic ethanol production also open the door for new fuel feedstocks that do not compete with edible sources of biomass. According to the DOE Under Secretary for Science, Dr. Raymond Orbach, "Fine-tuning plants for biofuels production is one of the keys to making biofuels economically viable and cost effective."[60] To this end, in 2006, scientists led by the Department of Energy's Joint Genome Institute successfully sequenced the genome of the black cottonwood, laying the groundwork that may one day lead to the development of trees as the ideal feedstock for cellulosic ethanol.[61] Two factors led scientists to select the black

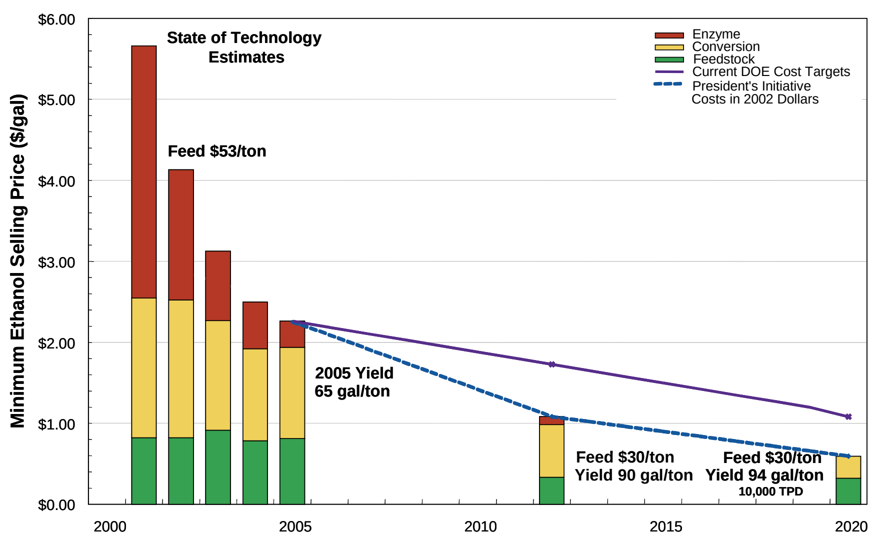


Figure 6. Reducing the Cost of Cellulosic Ethanol Production[62]

cottonwood for genetic sequencing; the poplar's extraordinarily rapid growth, and its relatively compact genome size. Dr. Sam Foster of the Department of the U.S. Forest Service states, "Under optimal conditions, poplars can add a dozen feet of growth each year and reach maturity in as few as four years, permitting selective breeding for large-scale sustainable plantation forestry."[63]

Advances in biotechnology combined with increasing ethanol production capacity and projected price reductions make ethanol an attractive biofuel alternative. Advances in cellulosic ethanol production offer the promise of dramatic increases in ethanol production without impacting the ability of farmers to provide edible food stores.

Biodiesel

Although ethanol offers many advantages to petroleum-based fuels, it is only one of several biofuels under development. Much like ethanol produced from biomass, biologically produced diesel fuel, biodiesel, has been in existence for over 100 years. In 1853, scientists E. Duffy and J. Patrick completed the first transesterification of a vegetable oil producing manmade diesel fuel. Current biodiesel use is typically limited to a 5 percent mixture with petroleum-based diesel but produces no ill effects to those engines using the blended fuel.[64] As oil prices increase, and with increased emphasis on reducing environmental impacts of petroleum use, biodiesel use has grown. In 2005, Minnesota became the first and only state requiring that all diesel fuel sold be mixed with biodiesel.[65]

There are several sources of biodiesel. Virgin oil feedstock such as rapeseed, and soybean oils are most commonly used, though other crops such as mustard, palm oil or hemp can be grown to produce biodiesel. A second source of biodiesel is waste vegetable oil.[66] Advocates of biodiesel suggest waste vegetable oils offer the best source of oil to produce biodiesel since restaurants produce over 300 million gallons annually.[67] Although waste oil offers a profitable method for obtaining biodiesel, other products made from waste oil, such as soap, offer even higher profit margins and therefore compete for biodiesel feedstocks. A third source of biodiesel is animal fats. Since animal fats are typically discarded and not used for other applications, their use as a source of biodiesel is only limited by the comparatively small amount available.[68]

Regardless of the source of biodiesel, the process used to obtain the diesel is the same. The transesterification process is used to convert the base oil to the desired ester. Figure 7 illustrates the process by which biodiesel is produced. Any free fatty acids in the base oil are either converted into soap and removed from the process or they are esterified (producing more biodiesel) using an acid catalyst.[69] After refining, biodiesel has combustion properties very similar to those of petroleum diesel.[70]

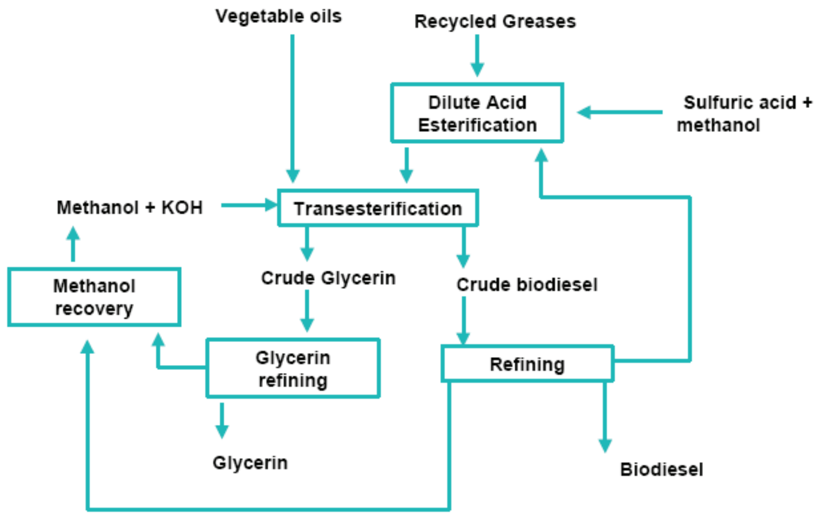


Figure 7. Biodiesel Production Process[71]

There are presently 85 companies producing biodiesel and another 65 companies with plants under construction. Figure 8 shows biodiesel production capacity growth from 1999 to 2005. The biodiesel industry continues to grow with production volume tripling from 25 million gallons in 2004 to 75 million gallons in 2005. The National Biodiesel Board expected biodiesel production to double or even triple again in 2006.[72]

Although biodiesel consumption continues to increase, it must overcome three shortcomings in order to completely replace petroleum-based oil supplies. The primary concern with biodiesel is its low temperature properties. Biodiesel has a freezing point near 0°C causing it to gel much faster than petrodiesel during cold weather use.[73] The increased viscosity can cause fuel filter clogging, as well as increased cloud formation from burning the fuel. A twenty percent blend of biodiesel with petrodiesel reduces the freezing point enabling the use of biodiesel under most conditions experienced by diesel-based automobiles.[74]

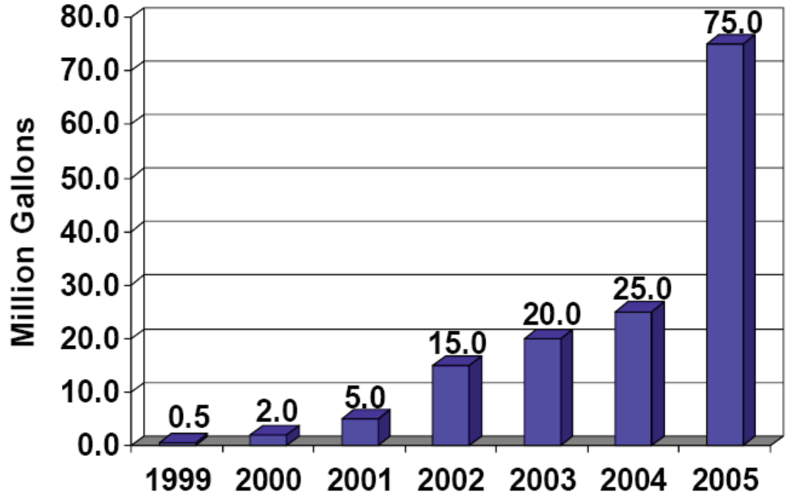


Figure 8. Biodiesel Production Capacity, 1999 to 2005[75]

Another option to solve cold weather issues under development by Robert O. Dunn, a scientist with the National Center for Agricultural Utilization Research involves mixing additives, chilling the fuel, and filtering out solids. In laboratory tests, researchers have produced biodiesel fuels capable of starting engines at temperatures as low as 5°F, making them closer in comparability to petroleum-based diesel fuels.[76]

A second issue with biodiesel is its affinity for water. Some of the water is a byproduct of the production process, and some comes from storage tank condensation. The effect of this increased water content is:

- Water reduces the heat of combustion causing more smoke, harder starting and less power

- Water causes corrosion of vital fuel system components: fuel pumps, injector plugs, and fuel lines

- The presence of water accelerates the growth of microbe colonies which can plug the fuel system

A third issue that must be overcome is feedstock availability. Table 2 summarizes U.S. availability of several biodiesel feedstocks. Vegetable oils and greases can only replace a small fraction of transport fuel demand. With only 100,000 BPD of feedstock available for fuel consumption, even a 100 percent feedstock to fuel conversion would replace less than one percent of current U.S. foreign petroleum demand.[77]

Biorenewable Feedstock	Definition	Amount produced in the U.S. (BPD)	Amount available for fuel production in U.S. (BPD)
Vegetable Oils	Produced from soybeans, corn, canola, palm	194,000	33,500
Recycled Products	Yellow grease, brown (trap) grease	51,700	33,800
Animal Fats	Tallow, lard, fish oil	71,000	32,500
Pyrolysis Oil	Made from pyrolysis of waste biomass (cellulosic)	1,500	750
	Total:	**318,200**	**100,550**

Table 2. Availability of Biorenewable Feedstocks in the U.S.[78]

In order to gain wider public acceptance and use, biodiesel producers and researchers will have to overcome these drawbacks. An additional factor that must be overcome is cost, the primary raw materials for biodiesel cost between one and two dollars per gallon. After being processed into biodiesel, the current average wholesale price for a gallon of fuel is $2.63 per gallon. Although increased biodiesel production will likely cause this price to drop, it is not certain the price will drop below a two dollar per gallon threshold.[79]

Algae Fuel Production

Just like terrestrial plants, algae can be grown to produce oil. The National Renewable Energy Laboratory has extensive experience cultivating and manipulating microalgae to produce lipids or oils.[80] According to the NREL, “The recipe for getting microalgae to produce lipids sounds like a daydream for using underutilized resources: put them in salty water unfit for other use, expose them to the sun in areas unsuitable for growing crops, feed them power plant or other exhaust gas that threatens the world climate, and deny them certain vital nutrients.”[81]

Microalgae naturally store oil when denied nutrients used for growth and energy. “By manipulating nutrients and other growth conditions and by selecting and genetically engineering algae strains to increase oil production, NREL researchers were able to attain remarkably high lipid production levels.”[82] An advantage of producing oil with algae is that unlike terrestrial-based plants, algae do not require precipitation or good soil, all they require is carbon dioxide, sunlight and saline water in which to grow. Figure 9 illustrates the two-step process by which algae can be used to produce hydrocarbon jet fuel. NREL is proposing to work with U.S. petroleum refiners and the USAF to: 1) genetically engineer strains that can achieve the required lipid yields to meet DoD's needs, and 2) develop the downstream processing technology for converting the lipids to energy dense hydrocarbon jet fuel in a conventional petroleum refinery. It is also possible to refine the lipids to diesel and gasoline for use in other military or civilian vehicles.[83] These refined finished products would contain near-zero oxygen, and would have a

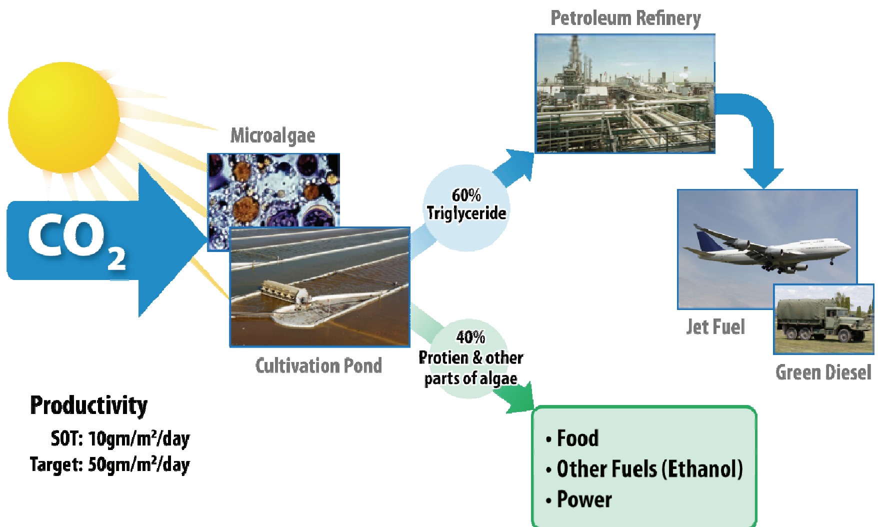


Figure 9. Jet Fuel From Algae Process[84]

chemical composition more like a petroleum product than a biomass-derived product. While it is technically possible to carry out the second step (lipid refining) with plant-based lipids, e.g. soybean oil or rapeseed oil, the quantity of oil feedstocks required to meet DoD's need exceeds the available supply of these plant-based oils. Algae oil offers a solution since they can produce oil under conditions that are unsuitable for traditional agriculture. Although areas like the desert Southwest or seashore are unsuitable for typical crop growth, by making use of man-made cultivation ponds, algae can flourish in these otherwise sparse environments.[85]

It was originally believed that inexpensive shallow ponds provided the most cost-effective way to grow algae. Table 3 shows a comparison of oil production from traditional biological sources. With the research NREL is proposing, it may be possible to achieve lipid productivities per acre that far exceed terrestrial plants. Algae oil production of more than 50 times that per acre of traditional oilseed crops may be achievable, yielding as much as 15,000 gallons of oil per year.[86] In addition to closed ponds, the low cost of plastic containers offers the possibility of growing algae in closed systems such as transparent tubes with even greater yield rates possible.[87]

Production Feedstock	Gallons of Oil per Acre/Yr
Corn	18
Soybeans	48
Safflower	83
Sunflower	102
Rapeseed	127
Oil Palm	635
Micro Algae	5,000 – 15,000

Table 3. Oil Yield Comparison of Available Feedstocks[88]

In order to produce high yields of oil, algae require a huge supply of carbon dioxide. One potential solution is placing algae pools next to coal burning power plants. According to Isaac Berzin, founder of Greenfuel, “just one 1,000 megawatt power plant using this system could produce more than 40 million gallons of biodiesel and 50 million gallons of ethanol a year. That would require a 2,000-acre “farm” of algae-filled tubes near the power plant. There are nearly 1,000 power plants nationwide with enough space nearby for a few hundred to a few thousand acres to grow algae and make a good profit.”[89]

In addition to thriving under conditions unsuitable for other crops, and thereby preserving arable land for food production, the properties of algae produced oil are superior to oil produced by terrestrial means. According to NREL, using hydroprocessing technologies already used by oil refineries to remove impurities, “algae oils could be made into a kerosene-like fuel very similar to petroleum-derived… commercial and military jet fuels.”[90]

With algae fuel production capacity using existing refineries, the logical question is what it would require to produce 5 billion gallons of jet fuel. According to Dr. Michael Pacheco, Director of the National Bioenergy Center, current technology is capable of producing 1,000 to 1,200 gallons of algae oil per acre suitable for jet fuel refining. Therefore, a pond capable of producing 5 billion gallons of jet fuel would consume 6,500 square miles.[91] Although currently capable of producing as much as 15,000 gallons of oil per acre, NREL scientists have yet to succeed in producing 15,000 gallons of oil suitable for jet fuel refinement.[92] Dr. Pacheco is convinced it will require two to three more years before production volumes of high-quality algae oil suitable for jet fuel refinement increase to the 10 to 15 thousand gallon per acre goal. Once achieved, the current 6,500 square mile requirement will be reduced to 830 square miles.[93] Figure 10 illustrates the size of these ponds as they would relate to the state of Arizona.

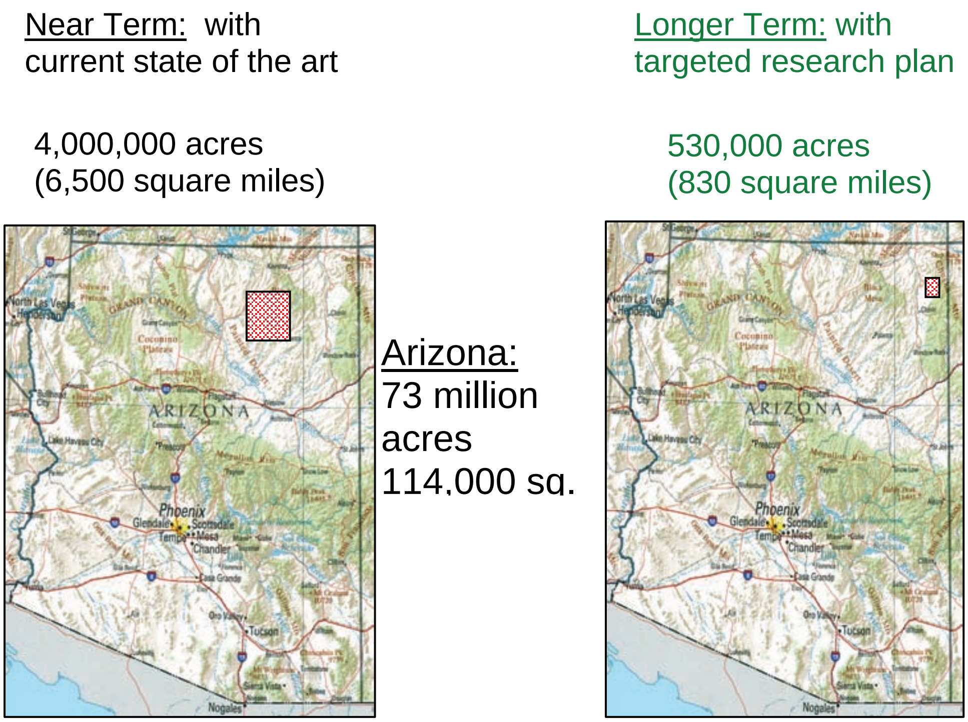


Figure 10. Algal Oil Needed for 5 Billion Gal/Yr Jet Fuel[94]

Biobutanol

The fourth and final type of biological fuel this paper discusses is biologically produced butanol. Biobutanol is not a new discovery. During the Battle of Britain when petroleum supplies were cut off by the German blockade, England relied on the fermentation of butanol to power its aircraft, jeeps and tanks.[95] Just like ethanol, biobutanol is produce by the fermentation of biomass. In fact, the feedstocks required to produce butanol are the same as those required to produce ethanol.[96]

When compared to ethanol, butanol has several superior properties. These include:

- Biobutanol contains 30 percent more energy than ethanol.[97] Butanol contains 110,000 BTUs per gallon versus 84,000 BTUs per gallon for ethanol. In comparison, gasoline contains 115,000 BTUs per gallon[98]
- Butanol is six times less evaporative than ethanol, and 13.5 times less evaporative than gasoline making it safer to use[99]
- Butanol can be shipped through existing pipelines, whereas ethanol must be transported via barge, rail or truck

- Butanol can be substituted for unleaded gasoline in mixtures approaching 100 percent without engine modification.[100] Ethanol can only be used as an additive to gasoline up to 85 percent, and then only with significant engine modifications[101]

A logical question is that if biobutanol is superior to bioethanol why do we not see biobutanol proliferating on the market as is ethanol. According to Environmental Energy Incorporated (EEI), production of butanol from corn and other biomass has been limited due to the higher cost of producing biobutanol. The lack of technological advance in biobutanol production produced low yields and low concentrations of biobutanol when compared to bioethanol.[102] The historical method of producing fuel through biomass used bacteria to produce acetone, butanol and ethanol with a yield ratio of 6:3:1 of butanol, acetone and ethanol. This means that for each bushel of corn one would produce 1.3 gallons of butanol, 0.7 gallons of acetone, and 0.13 gallons of ethanol. In comparison, the yeast fermentation process produces 2.5 gallons of ethanol from each bushel of corn making this process a much more cost effective alternative.[103]

Recent advances in biobutanol production now make it a cost effective venture. Environmental Energy Incorporated reports it is able to produce 2.5 gallons of butanol from each bushel of corn making biobutanol an economic alternative to ethanol.[104] With biobutanol's higher energy content, Environmental Energy Incorporated can produce 25 percent more energy than that produced from a bushel of corn.[105] When comparing the cost involved in producing biobutanol and bioethanol, biobutanol becomes even more attractive. Preliminary cost estimates suggest Environmental Energy Incorporated can produce biobutanol from corn for about $1.20 per gallon easily competing with Ethanol production costing about $1.28 per gallon. Additionally, by comparing energy content, biobutanol becomes even more cost effective. With corn currently costing $2.50 per bushel, biobutanol produces 105,000 BTUs per dollar compared to 84,000 BTUs per dollar for ethanol.[106] The effect is a more efficient fuel at a lower price.

This chapter presented a synopsis of four biologically derived fuels. Each fuel has advantages and disadvantages. Each fuel has different flow characteristics, production methods and energy content. But, how do these characteristics impact the ability of each of these fuels to replace petroleum-based JP-8 as a fuel source for U.S. Air Force aircraft?

Chapter 3
Analysis

In order to replace JP-8 as the Air Force fuel of choice by 2025, a biological replacement must meet several important criteria. The paper established three criteria that must be satisfied in order for a biological fuel to replace JP-8:

- The fuel must be able to meet current JP-8 energy density standards

- The fuel must not require major engine modifications or prevent the use of petroleum-based JP-8

- Fuel production must meet Air Force fuel demand in terms of quantity, transportability and stability

The ideal biological fuel would be a direct replacement for JP-8. This means that any biological alternative must provide the same amount of energy. Energy content is assessed by comparing the energy of the fuel per unit volume, but must also be assessed by comparing the energy per unit weight. In order to meet JP-8 fuel density standards, a biological alternative must meet both criteria. A discussion of how this criterion impacts aircraft design and mission accomplishment will be presented in detail.

The second criterion, linked to the first, is compatibility with aircraft systems. Not only is energy content a critical fuel attribute, but also lubricity, cold weather performance/viscosity, and heat absorption must be taken into account. Any biofuel alternative must closely approximate all JP-8 characteristics in order to be considered a viable alternative. If the selected fuel requires substantial engine or aircraft modification in order to be used in existing aircraft, the cost of modifying the entire aircraft fleet may make the biofuel alternative cost prohibitive. Additionally, the U.S. Air Force mission is global, and in order to operate around the world fuel must be available worldwide. Switching to a fuel that is not in use globally would place a severe logistical constraint on USAF operations and negatively impact mission accomplishment. Therefore, in order to replace JP-8, a biological replacement must allow the aircraft to continue to operate with commercially available fuel supplies.

The final criterion is quantity available, transportability and storage requirements. A viable replacement to JP-8 must be able to meet the USAF fuel demand, must be capable of using existing USAF fuel delivery systems to include pipelines and must not degrade during storage thereby preventing its use months after its purchase. With these three criteria satisfied, the USAF would be able to replace dependency on foreign procured oil, provide stability in the budgeting process, and maintain operational flexibility for worldwide missions.

Energy Density

The first criterion that must be satisfied is energy density. The primary function of fuel is to provide energy to propel the aircraft forward. The aircraft's turbine engine transforms chemical energy stored in the fuel into thrust that pushes the aircraft forward thus resulting in flight. When burning hydrocarbon fuels such as JP-8, the fuel energy is released during combustion, a rapid reaction with oxygen at a high temperature.[107] Combustion is described by the following equation:

$$C_xH_y + (x + y/4)\ O2 \rightarrow x\ CO_2 + y/2\ H_2O + \text{heat}$$

The energy released during this reaction is called the heat of combustion. The combustion process produces energy by breaking the carbon-hydrogen bonds and converting them to carbon-oxygen and hydrogen-oxygen bonds. Some alternative fuels, such as alcohols, contain oxygen, resulting in lower energy content because the oxygen in the fuel molecule does not contribute energy during the combustion process. By starting the combustion process with carbon-oxygen molecules, these molecules reform, do not create additional heat energy and therefore add nothing to the combustion process. The result is a lower energy content in alcohol-based fuels than hydrocarbon fuels.[108] Figure 11 shows energy content of various fuels as they compare to jet fuel.

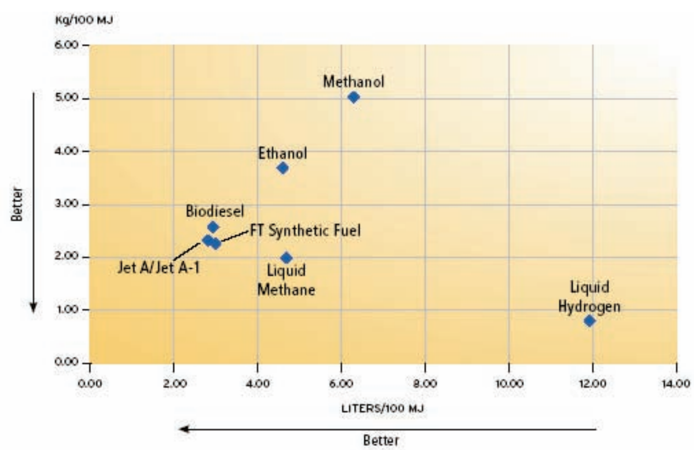


Figure 11. Mass of Fuel vs. Volume of Fuel per Unit Energy[109]

The ideal aircraft fuel would minimize both mass and volume for a given energy content. Aircraft are rated to takeoff at a specific maximum takeoff weight (MTOW) that includes the weight of the aircraft, passengers, cargo, weapons and fuel. If an aircraft reaches MTOW before its fuel tanks are full, a fuel with a higher energy per pound (gravimetric energy content) will allow the aircraft greater range. Accordingly, a fuel with low gravimetric energy content would force a shorter range or require additional aerial refueling in order to accomplish a similar mission.

Energy per gallon (volumetric energy content) is just as important. Once an aircraft reaches full fuel capacity, its unrefueled range is set. A lower volumetric energy content fuel reduces combat range and in turn reduces combat capability. The only solution is to either accept limited flight range, or to spend increased time flying to and from a tanker in order to accomplish the same mission as an aircraft fueled with a high volumetric energy content fuel.[110] Table 4 compares performance characteristics of the four biofuels and jet fuel.

Fuel	Specific Energy MJ/kg	Energy Density MJ/l	Boiling Point °C	Freezing Point °C	Viscosity
Jet Fuel	43.2	34.9	150 - 300	<-40	1.2**
Algae Jet Fuel	#	#	#	#	#
Biodiesel*	38.9	33.9	>400[111]	0	4.7**
Ethanol	27.2	21.6	78	-183	1.52***
Butanol	36.0	29.2	118	-89	3.64***

*Separate values unavailable for algae produced biodiesel. **At 40°C.[112] ***At 20°C
Algae jet fuel exhibits properties similar to jet fuel.[113]

Table 4. Biofuel to Jet Fuel Comparison[114]

According to an October 2006 NASA study; bio-diesel has nearly the same weight, volume, and performance characteristics of current oil-derived jet fuel.[115] But ethanol and butanol fall far short of energy content requirements due to oxygen resident in the fuel. In order to fully understand the impact of operating an aircraft on an alcohol based fuel such as ethanol, NASA's study explains:

> Ethanol powered airplanes would have to be specifically designed. Figure [12] shows one such Boeing 737-sized airplane.… [Ethanol's] performance is much worse than…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 twenty 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 fifteen percent more energy for a 500 [nautical mile] mission.

As ethanol 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 [nautical mile] mission.[116]

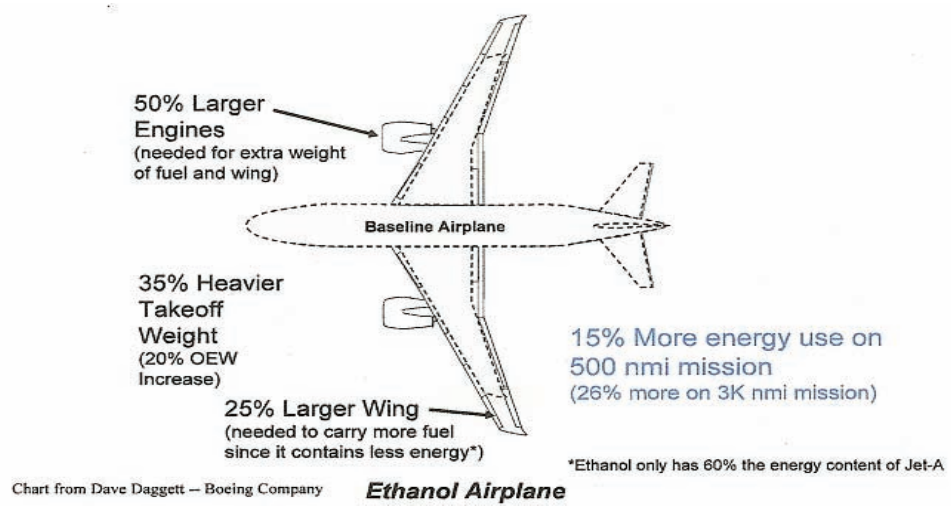


Figure 12. Ethanol Powered Airplane vs. Jet-A Powered Airplane[117]

Alternative Fuel and Aircraft Compatibility

Although the primary function of jet fuel is as a source of energy, fuel is also used to cool avionics and serves as a lubricant in engine systems and pumps.[118] Therefore, in order to prevent fleet-wide engine modifications, a suitable alternative fuel must not only meet energy density requirements, but must also meet this secondary performance specification in order to adequately replace JP-8. The fuel must also be compatible with various other aircraft fuel system component materials including various metals, epoxy-type coatings and elastomeric seals.[119] In order to evaluate each biofuels ability to perform these secondary fuel functions, we must examine three qualities: heat absorption capability, viscosity and engine component compatibility.

Heat absorption capability

The ability of a liquid to absorb heat is limited by its boiling point. Once a liquid reaches its boiling point, the liquid transforms into a gas and can no longer absorb energy at standard temperature and pressure. According to Chevron Global Aviation, the maximum boiling point for aviation fuel is set at 300°C.[120] A fuel that boils at a lower temperature would have a reduced capability to absorb heat from avionic equipment and engine components.

Table 4 summarizes boiling point characteristics for biofuel alternatives. Biodiesel has a superior boiling point exceeding the boiling point of typical jet fuel by over 100°C and therefore meets the jet fuel standard. Algae-produced jet fuel also meets jet fuel heat absorption criteria.[121] Ethanol and butanol boil at much lower temperatures with ethanol boiling at 78°C and Butanol boiling at 118°C.[122] Ethanol and butanol fail the 300°C jet fuel criteria, and therefore do not meet this standard.

Viscosity

A second criterion for jet engine compatibility is the ability of the fuel to flow throughout an aircrafts operational temperature range. Table 4 summarizes viscosity and freezing point values for select fuels. A higher viscosity fuel can be advantageous since higher viscosity provides more hydrodynamic lubrication than a fuel with lower viscosity. According to Chevron Global Aviation, "while jet fuel specifications do not place an explicit lower limit on viscosity…Jet engines are designed to work with jet fuels within a normal viscosity range."[123]

Biodiesel has superior lubricity properties due to its higher viscosity, but the primary concern with biodiesel is its low temperature properties. The maximum freezing point for jet fuel is -40°C. Fuel exposed to very low temperatures at an aircraft's cruise altitude must remain fluid in order to be pumped to the engines.[124] A high viscosity rating makes it harder to pump the fuel and with a freezing point of 0°C, biodiesel is incapable of flowing at the very cold temperatures experienced by an aircraft during high altitude flight. According to Chevron Global Aviation, "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."[125]

Ethanol and butanol both remain fluid well below the -40°C jet fuel requirement and therefore satisfy the requirement to flow at extremely cold temperatures. Lubricity properties of both ethanol and butanol demand further study in order to determine their ability to adequately lubricate engine components.

According to Dr. Michael Pacheco, algae-produced jet fuel exhibits temperature characteristics similar to JP-8 and would meet temperature range qualities demanded by high altitude flight. Since algae oil is has the carbon content of jet fuel, it would not require mixing in order to meet viscosity or lubricity qualities required for turbine engine operation.[126]

Compatibility with Engine Components

The final criterion for determining an alternative fuels ability to replace JP-8 is its compatibility with the various metals, epoxy-type coatings and elastomeric seals inside the engine. One way of determining a fuel's compatibility is by examining the fuels aromatic hydrocarbon content.

Jet fuels with high aromatic content will not burn as cleanly as fuels with low aromatic content, so jet fuel specifications dictate a maximum aromatic content. There has never been a need to specify a minimum jet fuel aromatic content since conventionally refined petroleum-derived kerosene has aromatic concentrations between eight and 22 percent by volume.[127] While aromatic hydrocarbons are partially responsible for the smoke and soot produced by turbine engines, aromatics also cause elastomeric engine seals to swell. According to Mike Farmery, Shell Aviation Global Fuel Technical and Quality Manager, "Without [aromatic hydrocarbons], the seals will shrink and cause leakage.[128]

Alcohols such as ethanol and butanol and terrestrial produced biodiesel do not contain any aromatic hydrocarbons.[129] The impact of zero aromatic content was seen in California when the state required all automobile fuel be mixed with an alcohol based additive, MTBE. The intent was to reduce airborne pollutants resulting from combustion of fossil fuels by mixing gasoline with a fuel containing no aromatic hydrocarbons. The unintended consequence was engine fuel seals cracking and causing fuel leaks. In order to burn these biofuels in an aircraft, engine fuel seals would have to be replaced with a resistant material.

Two more concerns with ethanol are the fact it is a strong solvent and its affinity for water. Ethanol is known to corrode lead-plated fuel tanks; as well as magnesium, copper, zinc, and aluminum parts. Therefore, ethanol vehicles require special material fuel lines, hoses and valves that resist corrosion.[130] Secondly, unlike petroleum-based fuels that do not mix with water, ethanol and water are highly miscible.[131] The addition of water in the fuel that cannot be removed causes additional corrosion of fuel system components. Corrosion inhibiting additives may provide a solution but must be fully studied to determine the effect of ethanol on aircraft fuel system materials.

One-hundred-percent biodiesel presents some of the same challenges as ethanol. As stated earlier, biodiesel has a high water content. Some of the water is a byproduct of the production process, and some comes from storage tank condensation.[132] Like ethanol, the addition of water causes corrosion of vital fuel system components such as fuel pumps, injector plugs, and fuel lines. Since biodiesel does not mix with water, the water can be removed during the refinement process.

A second problem with the presence of water in biodiesel is the possibility of biological contamination. Water in biodiesel needs to be controlled since aerobic fungus and bacteria can easily grow at the fuel-water interface. Products used to control microbial growth in diesel fuels will work equally well with biodiesel, so with proper monitoring biological contamination can be controlled.[133]

A third concern is that 100 percent biodiesel will degrade, soften, or seep through some hoses, gaskets, seals, and elastomers with prolonged exposure. Additionally, brass, bronze, copper, lead, tin, and zinc may accelerate the oxidation of biodiesel fuels and potentially create fuel insolubles or gels when reacted with some fuel components. In order to prevent fuel system problems such as fuel filter clogging, materials such as Teflon, Viton, fluorinated plastics and Nylon can be used without issue.[134] As with Ethanol, extensive testing to determine jet engine components compatibility must be conducted prior to using biodiesel derivatives as a jet fuel.

Unlike ethanol, biobutanol has a very low affinity for water. In fact, with an affinity of only 7.8 percent, biobutanol has a lower affinity for water than gasoline and is much lower than ethanol's 100 percent water affinity.[135] Additionally, biobutanol is less corrosive than ethanol and can be used in internal combustion automobile engines without modifying fuel system components.[136] Although less corrosive, extensive testing must occur before biobutanol is introduction into an aircraft fuel system.

Algae produced jet fuel is believed to be nearly identical to the fuel currently in use by the U.S. Air force. However, as with other biofuels under consideration, algae jet fuel would have to undergo thorough testing prior to in-flight use.

Production Capacity, Transportability and Stability

The final set of criteria a biologically produced fuel must meet is production capacity, transportability and fuel stability. The USAF does not produce its own fuel, and will likely continue to depend on civil production to meet jet fuel requirements. Therefore, alternative fuel production must not only be able to meet USAF requirements of nearly five billion gallons per year, but must also continue to meet growing consumer demands. Secondly, the USAF already has a fuel distribution system in place consisting of railroads, tanker trucks, barges and pipelines. An alternative fuel would be cost prohibitive if it forced the establishment of a new fuel distribution system. Therefore a biological replacement fuel must be capable of using the existing USAF fuel distribution infrastructure. Finally, the fuel must be storable. If a military operation requires a sudden surge in fuel use, the fuel must be on hand or risk to mission success is possible. Limited "shelf life" may not rule out a fuel, but it certainly makes a fuel less attractive for USAF use.

Production Capacity

All biological fuels considered are capable of supplying the current USAF 3.2 billion gallon fuel requirement. Analysis of production capacity must not only look at the ability to replace fuel volume, but must also explore the second-order impacts of adopting a new fuel standard. Each fuel will be examined in turn.

The Air Force currently consumes over 3.2 billion gallons of fuel annually.[137] With U.S. ethanol production of four billion gallons in 2005, the Air Force would consume the entire year's production leaving nothing for other domestic use.[138] Additionally, the 2005 ethanol production run required 55 million tons of U.S. corn representing nearly one-sixth of the country's grain harvest. It is feasible to double ethanol production in order to meet current domestic as well as potential U.S. Air Force ethanol demand. But, the impact of diverting one-third of U.S. corn harvest to ethanol production could have unintended negative economic repercussions. For example, Brazil, the world's largest sugar producer and exporter, is now converting half of its sugar harvest into fuel ethanol. With just 10 percent of the world's sugar harvest going into ethanol, the price of sugar has doubled. With the U.S. supplying 70 percent of world corn exports, a similar rise in corn prices could have far reaching economical impact.[139]

As was discussed earlier, there have been substantial advances made with alternate feedstocks for ethanol production. Cellulosic biomass shows great promise as a biomass feedstock and will potentially enable the production of large quantities of ethanol without having a major impact on edible sources of biomass such as corn. NREL scientists forecast that by the year 2020, advances in enzymatic biotechnology will enable the production of 94 gallons of ethanol per ton of biomass. This is an increase of 30 gallons over current production yields of 64 gallons per ton.[140] Added to this, the findings of the joint Department of Energy and Department of Agriculture *Billion-Ton Study*, states 1.3 billion dry tons of biomass is available for ethanol production without impacting U.S. food, feed and export demands.[141] Based on these figures, it would be feasible to produce 122.2 billion gallons of ethanol by the year 2020 far exceeding USAF fuel demands and guaranteeing enough ethanol to meet growing consumer demands as well. Even if this figure is overly optimistic, and ethanol production technology does not advance as quickly as speculated, a modest increase in production of only 15 gallons per ton of biomass would still yield over 100 billion gallons of ethanol per year. This figure dwarfs current Air Force fuel requirements by a factor of twenty.

Biobutanol production has the same biomass limitation as ethanol. According to Environmental Energy Incorporated, the yeast fermentation process produces 2.5 gallons of ethanol from each bushel of corn and they are now able to realize yields similar to ethanol production.[142] One advantage ethanol has is public acceptance. Since it has been in use for over twenty years as an automotive gasoline additive, consumers already accept ethanol. The only means by which butanol can achieve ethanol production levels is by substituting ethanol as the biofuel of choice. With increased consumer demand the cost associated with building biobutanol production facilities could become economically feasible. It is feasible that enough biobutanol can be produced by 2025 to fill USAF fuel requirements, but it is too early to predict U.S. consumer demand for biobutanol.

Like biobutanol, terrestrial produced biodiesel production capacity is well below that of ethanol. But unlike biobutanol, biodiesel has an established market promoting biodiesel production and growth. The biodiesel industry continues to grow with production volume tripling from 25 million gallons in 2004 to 75 million gallons in 2005. The National Biodiesel Board expected biodiesel production to double again in 2006.[143] If biodiesel is able to make use of waste vegetable oils produced by restaurants, this volume could swell by an additionally 300 million gallons annually.[144] As with biobutanol, biodiesel will likely be plagued by a lack of consumer acceptance. With cold weather properties limiting its use to temperatures above freezing, biodiesel will likely be seen as an additive to diesel as opposed to a replacement. It is not likely that enough terrestrial biodiesel will be produced to meet the USAF 3.2 billion gallon requirement until the fuel properties of biodiesel are adequately addressed and consumer demand makes increased production profitable.

Algae produced oil offers a solution to production concerns presented by terrestrial produced biodiesel. Algae have the potential to out-produce all biofuels. With yields of 5,000 to 15,000 gallons per acre of algae, algae could produce 100 times the volume of other biological fuels each year. As Isaac Berzin of Greenfuel stated, "just one 1,000 megawatt power plant using his system could produce more than 40 million gallons of biodiesel and 50 million gallons of ethanol a year." With nearly 1,000 power plants nationwide algae has the potential to produce 10 times the amount of biodiesel required for USAF consumption.[145] As with biobutanol, the infrastructure does not exist for algae to produce jet fuel. In order for algae produced jet fuel to gain public acceptance, the price must be reduced from its current price of four dollars per gallon to a more competitive two dollars per gallon.[146] Once an economic pathway is established, algae produced jet fuel production could meet USAF and National biofuel demand.

Transportability and Storage

The final criteria that must be satisfied are transportability and fuel storage. The USAF has a robust fuel distribution that uses various forms of transportation in order to deliver fuel from the refinery to the aircraft. Figure 13 depicts the common means by which fuel is shipped to an Air Force base. In order to make use of an alternative fuel, it must fit the current Air Force distribution system comprised of trains, trucks, barges and pipelines and not require cost prohibitive infrastructure construction. All biofuel alternatives presented are easily containerized and shipped on trains, trucks, barges and pipelines with one exception: ethanol. Ethanol cannot be shipped in multi-fuel pipelines because the moisture in the pipelines and storage tanks is absorbed by the ethanol.[147] Because of this limitation, transportation costs will be higher for ethanol than for other biofuel alternatives. A study conducted by Downstream Alternatives, Inc., analyzed the logistics of supplying ethanol to California. The analysis concluded that the only viable method of transporting ethanol from Midwest ethanol production facilities to California would be by rail or barge. Landlocked Ethanol plants must use rail shipments at a cost of fourteen to seventeen cents per gallon.[148] Although this may be considered a small price to pay, if the USAF required five billion gallons of ethanol, the

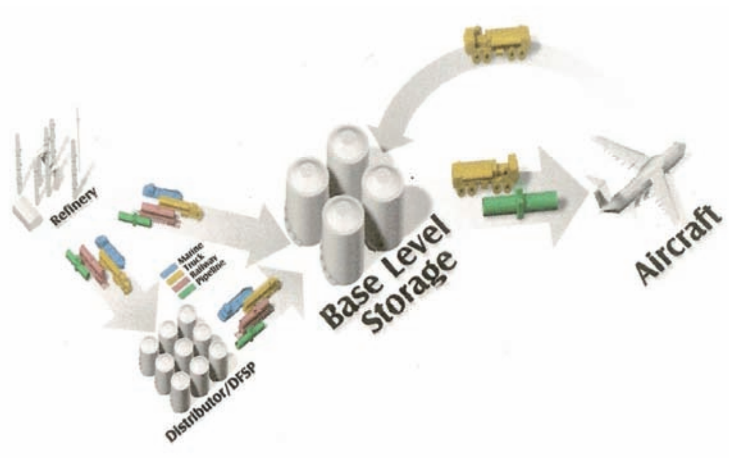


Figure 13. USAF Fuel Distribution System[149]

cost of shipping by rail would amount to over would amount to $850 million in additional transportation costs.

The second criterion is storability. The corrosive qualities of biofuel alternatives have already been discussed. In order to prevent undue damage to fuel storage tanks, all fuel alternatives must be tested to ensure they will not corrode and weaken the existing fuel storage system.

Biodiesel offers additional storage challenges. First, biodiesel "ages," that is to say viscosity increases with time. Already a highly viscous fuel, biodiesel becomes unusable in as little as six months. According to the National Biodiesel Board biodiesel must be used within six months of manufacture to guarantee fuel quality.[150] The second challenge already discussed is microbial growth. Biodiesel must be continuously monitored to ensure fuel purity.

Algae produced jet fuel can take advantage of the existing USAF fuel distribution and storage system. Once the oil is refined at existing petroleum refineries, it can make use of the existing delivery infrastructure and storage capacity.[151]

Determining each alternative fuel's compatibility with the established USAF fuel delivery and distribution system is crucial to meet USAF fuel needs. Although most transportation and storage problems can be overcome, the cost involved with solving these problems may cause adoption of a specific biofuel alternative to be economically infeasible.

Analytical Summary

This section began by establishing three general criteria that must be satisfied in order to replace JP-8 as the Air Force fuel of choice by 2025. The established criteria are:

- The fuel must be able to meet current JP-8 energy density standards
- The fuel must not require major engine modifications or prevent the use of petroleum-based JP-8
- Fuel production must meet Air Force fuel demand in terms of quantity, transportability and stability

Appendix A includes table 5, which summarizes the analytical findings. Although the ideal biological fuel would be a direct replacement for JP-8, it is apparent that no biological alternative currently affords a perfect solution for USAF fuel requirements.

Considering the potential of each biofuel to satisfy USAF requirements, ethanol is the least likely to meet Air Force fuel requirements. Although ethanol provides an affordable alternative to JP-8, its low energy density would either force a redesign of the entire USAF turbine aircraft fleet or risk severe mission degradation. Additionally, with ethanol's highly corrosive properties, intense testing must take place in order to determine aircraft system and fuel distribution system compatibility. Ethanol appears to be better suited for ground transportation and does not provide a viable jet fuel replacement.[152]

Biobutanol offers some of the same limitations presented by ethanol. Although butanol's energy density (29.2 megajoules per liter) is higher than that of ethanol (21.6 megajoules per liter), it is still well below the energy density of JP-8 (34.9 megajoules per liter). As with ethanol, the use of 100 percent biobutanol as an aircraft fuel would either reduce combat capability or mandate significant fuel and aircraft system modification.

It is possible that biobutanol could be used as an additive to petroleum-based jet fuel. The petroleum would provide aromatic hydrocarbons to the butanol preventing rubber seal deterioration. However, this approach would complicate current USAF logistics by adding another fuel requirement. Further, any engine or fuel system modifications would have to be thoroughly tested in order to determine an aircraft's ability to operate on the biobutanol blend as well as on pure JP-8 fuel. These limitations make biobutanol a poor replacement for USAF future fuel needs.

Biodiesel has the greatest potential to replace JP-8 as the USAF jet fuel of choice. Its energy density (33.9 megajoules per liter) is comparable to that of JP-8. The drawback of biodiesel is poor low-temperature properties. Scientists must find a solution to prevent biodiesel from freezing in cold weather experienced during high altitude flight. Unlike biobutanol, there is already an established market for biodiesel. With states like Minnesota mandating all diesel fuel sold contain biodiesel, biodiesel companies have financial incentive to develop fuel properties that expand the current market and make biodiesel useable year round in even cold climates.

There are limitations to terrestrial-based biodiesel production. First, it is estimated that only 300 million gallons of feedstock are available each year through animal fat conversion and restaurant waste. Therefore any production over 300 million gallons will be in direct feedstock competition with ethanol and other biomass based fuels. Basic supply-and-demand economics tells us that if supply remains constant and demand increases, then prices will increase. It is not likely that terrestrial-based biodiesel will offer a solution to USAF jet fuel requirements alone without employing alternative production methods that dramatically increase production capacity without creating a feedstock competition with other biological fuels.

Algae produced oil offers a solution to terrestrial-based biodiesel production limitations. Algae oil production is theoretically capable of producing enough fuel to eliminate USAF foreign oil dependency, and can dramatically reduce, if not eliminate U.S. foreign oil dependency as well.

Unlike ethanol and terrestrial biodiesel, which have been around for over 100 years, and biobutanol, which was used by the British over 60 years ago during World War II, algae produced oil is a relatively new science. Between 1978 and 1996, the National Renewable Energy Laboratory conducted research into using algae to produce oil. In conjunction with this study, scientists collected and screened over 3,000 strains of micro-algae and now have a solid understanding of algae oil production. According to the NREL, "NREL is now looking to reestablish its microalgal oil research in partnership with oil refiners, with a particular view towards jet fuel production. The program was discontinued at a time when diesel was less than $0.60 per gallon. Both diesel and jet fuel now cost far more. Military jet fuel also carries a very high added cost and logistic difficulty of transport around the world. To mitigate this, there is considerable refining capacity strategically located around the world that could be used for hydroprocessing microalgal oil into jet fuel, with both offshore and onshore locations highly suitable for microalgae growth nearby."[153]

Added to NREL's renewed interest in algae produced jet fuel, genetic engineering and screening technologies have advanced dramatically since 1996 when the original research program was closed out.[154] Current algae oil facilities produce only 1,000 to 1,200 gallons of oil per acre suitable for jet fuel refinement. Now that scientists understand the science involved with modifying algae to produce higher volumes of oil, it may require as little as another two to three years to achieve 10,000 gallon per acre production rates. Increased production will allow scientists to solve a primary obstacle that must be overcome: the current price-per-gallon. At over four dollars per gallon, algae-produced jet fuel is currently economically unattractive. In order to become competitive with current and projected petroleum fuels, the price of algae-produced fuel must be reduced to around a two dollar per gallon threshold. Once this is achieved, algae produced fuel will likely gain acceptance in the civilian sector and offers a cost effective alternative for USAF fuel needs.

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Chapter 4
Recommendations and Conclusion

This paper explored the ability of biofuels to replace petroleum jet fuel in Air Force aircraft and specifically examined the feasibility of current and potential biofuels to achieve this goal by the year 2025. The President acknowledged the need to reduce foreign fuel dependency during his 2006 State of the Union Address. The USAF, hurt by budgeting volatility caused by fluctuating fuel prices and spurred by the Presidents mandate "to replace more than 75 percent of our oil imports from the Middle East by 2025," is aggressively pursuing alternative jet fuels.[155]

The current F-T Syntroleum program has the greatest probability of achieving short-term success in reducing USAF foreign fuel dependency. It is estimated a facility that could produce 10,000 barrels of synthetic jet fuel per day would cost approximately $1 billion to build, and a plant that could produce 80,000 barrels a day would cost at least $6.5 billion and five to seven years to build. The National Mining Association says it is feasible that the United States could produce at least 300,000 barrels (15 million gallons) of coal-derived fuel a day by 2015.[156] In order to provide the USAF 3.2 billion gallons of jet fuel, 240 such facilities would have to be built at a cost of over $1.5 trillion.[157] Even with aggressive funding, it appears unlikely that synthetic fuel production capacity will expand another 240-fold by the year 2025 and completely satisfy USAF jet fuel demand.

A key advantage of fossil-fuel based synthetic fuel is that it is already proven to work in USAF aircraft and initial tests indicate no aircraft modifications are required to operate on an equal blend of syntroleum and JP-8. Therefore, pursuing fossil fuel based synthetic kerosene is the best solution to meet USAF jet fuel needs in the near future.

This paper examined the ability of biologically produced fuels to meet USAF fuel demand by 2025. In order to replace JP-8 as the USAF fuel of choice, a biological alternative fuel must meet certain basic criteria. Although not all inclusive by any stretch, this paper established the following criteria:

- The fuel must be able to meet current JP-8 energy density standards

- The petroleum fuel alternative must not require major engine modifications or prevent the use of petroleum-based JP-8

- Fuel production must meet Air Force fuel demand in terms of quantity, transportability and stability

By comparing the properties of ethanol, biobutanol, terrestrial produced biodiesel and algae produced oil, it is evident that ethanol and biobutanol will not meet USAF fuel requirements primarily due to low energy density characteristics. Terrestrial produced biodiesel meets jet fuel energy density requirements, but exhibits poor cold weather characteristics that are incompatible with high altitude flight. Additionally, terrestrial produced biodiesel production capacity is limited due to feedstock availability. Of the four fuels examined, only algae produced oil, refined into jet fuel, offers a long-term environmentally friendly and permanent solution to USAF foreign fuel dependency.

Algae jet fuel offers the Air Force a secure energy source and has the potential to stabilize future fuel costs. With fuel currently costing the Air Force $3.7 billion annually and foreign oil prices uncontrollably driving this cost even higher, biofuels have the potential to offer a domestically controlled alternative that will add predictability to operating costs. The National Renewable Energy Laboratory anticipates it will require three to five more years of research to validate the algae to jet fuel concept with an ability to produce 10,000 to 15,000 gallons of high quality jet fuel per acre of algae fields.

Algae jet fuel production offers advantages not presented by F-T jet fuel. First, algae oil production can take place anywhere onshore or offshore and only requires sunlight, water and a carbon dioxide supply. Therefore, production can be dispersed and located so as to increase security of fuel production facilities as well as minimize product transportation requirements. Second, algae oil refinement takes advantage of existing refinery capacity and does not require the construction of multi-billion dollar F-T facilities in order to produce jet fuel. Therefore, costs associated with expanding production will be less than the F-T option. Finally, algae produced fuel is an environmental zero-sum venture. Since the algae take carbon dioxide already present in the atmosphere to produce its oil, it does not add additional carbon dioxide when burned. It only releases what was already present.

Algae-produced jet fuel should be the long-term objective of the USAF alternative fuels program. In order to succeed, the USAF must continue to partner with NREL and industry to develop algae-based jet fuel production requirements. By fostering this partnership, the USAF can reduce its dependency on foreign procured oil, and do so with a renewable, environmentally friendly jet fuel alternative.

APPENDIX A
Summary of Analytical Findings

Fuel	Production Capacity Current	Production Capacity 2025 Potential	Cost/Gallon 2007	Cost/Gallon 2025	Energy Density MJ/l	Freezing Point °C	Aircraft Mod Required	Transport Limitations	Storability
Jet Fuel	5B gal+	5B gal+	$1.79	Unknown	34.9	<-40	No	None	Normal use
Biodiesel (Terrestrial)	75M Gal	300M gal potential	$2.63	~$2.00	33.9	0	Seals	None	6 months
Algae Jet Fuel	N/A	5B gal+	>$4.00	<$2.00	*	*	Seals	None	Normal use
Ethanol	5B gal+	8B gal+	$1.28	<$1.00	21.6	-89	Entire Aircraft	No Pipeline	Normal use
Biobutanol	N/A	8B gal+	$2.50	<$1.00	29.2	-183	Entire Aircraft	None	Normal use

* Algae produced jet fuel exhibits characteristics that are very similar to jet fuel.[158]

Table 5 Summary of Analytical Findings

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