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Energy Content and Alternative Jet Fuel Viability

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This paper examines the chemical composition and energy content of several fuel options that could hypothetically be used with the existing fleet of aircraft. Fuel specific energy (energy per unit mass) is an important consideration in determining alternative-fuel viability, because aircraft must travel fixed distances before refueling. Since most aircraft fly with excess tank capacity, fuel energy density (energy per unit volume) is of secondary concern relative to specific energy. A first-order approach using the Breguet-range equation shows that the fleet-wide use of pure synthetic paraffinic kerosene fuels, such as those created from Fischer–Tropsch synthesis or hydroprocessing of renewable oil sources, could reduce aircraft energy consumption by 0.3%. Conversely, fuels with reduced specific energy, such as fatty acid methyl esters (biodiesel and biokerosene) and alcohols, will result in increased fuel volume usage and also a decrease in fleet-wide energy efficiency. No penalty in energy efficiency would occur were these fuels used in ground transportation; thus, fatty acid methyl esters and alcohols are better suited to use in ground-based applications.

Nomenclature

OEW	=	operating-empty weight
MTOW	=	maximum takeoff weight
R	=	range
R_1	=	range with maximum payload
R_2	=	range with maximum fuel
R_3	=	range with zero payload and maximum fuel
W_F	=	fuel weight
W_P	=	payload weight
W_R	=	reserve fuel weight

I. Introduction

WITH environmental concerns, economic pressure, and the need for energy supply diversification, interest in alternatives to conventional petroleum are once again high. Alternative fuels offer an opportunity to reduce the environmental impact of aviation while expanding the supply of energy. To understand the viability of a given fuel to augment our supplies of petroleum, one needs to consider 1) the finished fuel composition and 2) the economic and environmental sustainability of the processes used to create the finished fuel. Such effects must be considered on a life-cycle basis and include, but are not limited to, global climate impacts from greenhouse gases, local air quality impacts, the efficient usage of water and land resources, technical feasibility, and the cost of fuel production. The aforementioned perspectives must be considered in parallel.

The fuel options herein are being considered for their potential to serve as a direct replacement for conventional jet fuel, requiring little or no modification to existing infrastructure or aircraft, and therefore being "drop-in" compatible. Cryogenic fuels are not considered, because they require radically different aircraft fueling systems from today's fleet. This work considers only the implications from specific energy (energy per unit mass) and energy density (energy per unit volume) in examining the feasibility of a potential alternative jet fuel (both are based on net heat of combustion). Environmental and economic constraints are not assessed. Properties determining the safety of a fuel type for aircraft operations (e.g., freeze point, flash point, and thermal stability) are discussed form a qualifying viewpoint but the focus of the numerical analyses is on energy content per unit mass and unit volume.

The generic weight buildup of any aircraft is given by Eq. (1):

$$\mathrm{MTOW} = \mathrm{OEW} + W_P + W_F + W_R \tag{1}$$

where MTOW is the maximum takeoff weight of the aircraft, OEW is the operating-empty weight, W_P is the payload weight, W_F is the fuel weight, and W_R is the weight of any reserve fuel. The OEW consists of the structure, powerplant, furnishing systems, unusable fuel and other unusable propulsion agents, and other items of equipment considered an integral part of a particular airplane configurations, excluding usable fuel and payload.

The use of a fuel with lower specific energy than that of conventional jet fuel would lead to a flight efficiency penalty for aviation. The lower specific energy results in more fuel mass to carry the same quantity of energy. All else being equal, an aircraft carrying more weight in fuel will require additional energy to complete a given mission. A fuel with reduced energy density will reduce the range of an aircraft when its tanks are full, though these limits apply to a small percentage of actual flights, as will be shown. To compensate for this, the payload on the aircraft would have to be reduced or a longer-range aircraft will have to be used to fly a given route. A higher energy density fuel would increase the range and payload capacity of an aircraft operating with a full tank.

The remainder of this paper is broken out as follows. Section II considers a range of potential alternative fuels in terms of composition, energy content and fuel properties. Section III presents an analytical framework based in the Breguet-range equation to examine the impact of specific energy and energy density on the payload-range operability of select aircraft types. This framework is then used in Sec. IV to examine specific aircraft types and to more generally examine the fleet in Secs. V and VI. In Sec. V, surrogate relationships are created for existing aircraft configurations to show the change in fuel consumption as a function of specific energy and distance flown, and in Sec. VI these relationships are used to examine the change in fleet-wide fuel energy usage under varying fuel compositions. Section VII provides concluding thoughts on the subject with discussion of the viability of potential alternative fuels in terms of their energy content.

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II. Fuel Composition and Energy Content

A. Conventional Jet Fuel

Jet fuel, like all petroleum products, varies in chemical composition; it is required to meet specifications based on its use. Depending on the user, jet fuel must meet slightly different specifications. JP-8 and Jet A-1 are essentially identical in their specification, while Jet A has a higher freeze point. The specification for Jet A provides a minimum specific energy (42.8 MJ/kg), whereas that of JP-5 and JP-8 are based on a minimum fuel hydrogen content (13.4%). The specification for JP-5 differs in that it has a higher flash point to enhance safe operations on aircraft carriers.

The distribution shown in Fig. 1 is based on a broad worldwide sampling of Jet A, Jet A-1, and JP-8 jet fuels [1]. Jet fuel consists of roughly 60% paraffinic hydrocarbons (also known as alkanes), 20% naphthenes (also known as cycloparaffins or cycloalkanes), and 20% aromatic compounds, including both monocyclic hydrocarbons such as benzene and polycyclic hydrocarbons such as naphthalene (also known as poly aromatic hydrocarbons). Between 1 and 2% of the fuel hydrocarbons are naphthalenes. Jet A and Jet A-1 specifications allow up to 25% aromatic compounds and 3% naphthalenes by volume. Olefins (also known as alkenes) occur in trace quantities.

The Defense Energy Support Center (DESC) conducts surveys of the quality of jet fuel for the U.S. military and publishes their findings in their annual Petroleum Quality Information System (PQIS).§ The DESC survey data come from U.S. military bases distributed around the globe, including Europe and the Pacific. Based on a comparison of their survey and the DESC survey of JP-8, Shafer et al. [1] concluded that the average hydrocarbon compositions of JP-8, Jet A, and Jet A-1 are similar. Because of the gross similarities in jet fuel for civil and military applications as observed by Shafer et al. [1], it is assumed here, unless otherwise noted, that the PQIS data on JP-8 are representative of the hydrocarbon composition and energy density of commercial jet fuel (Jet A or Jet A-1). Consistent with the information presented in Fig. 1, the average aromatic compound content of JP-8 as reported by PQIS in 2007 was 17.9% and the minimum and maximum of the range of values that were sampled was 10.4 and 25.0%. The average JP-8 naphthalene content in 2007 was 1.2% (see footnote §). A statistical analysis of the DESC PQIS data indicates that 90% of fuel samples have a specific energy within 1% of the mean 43.2 MJ/kg.

Sulfur contained in jet fuel is combined in molecules with hydrogen and carbon that are termed heterocyclics (they could also contain oxygen or nitrogen). The sulfur content in jet fuel has implications both for air quality and fuel lubricity. Sulfur impacts air quality through sulfur oxide emissions reacting with gaseous ammonia in the atmosphere to form ammonium sulfate, a pollutant that contributes to atmospheric $PM_{2.5}$ concentrations, which are regulated under the National Ambient Air Quality Standards. Jet fuel specifications allow up to 3000 ppm (0.3%) sulfur content, by mass; however, the sulfur content of jet fuel is generally much lower, as seen through an analysis of the PQIS database, a survey of U.K. jet fuel, and a study by the Coordinating Research Council. A lower bound on fuel sulfur content is not defined in the jet fuel specifications for commercial or military jet fuel.

The Coordinating Research Council sponsored a voluntary survey of the sulfur content of jet fuel leaving U.S. refineries to determine the impact of the U.S. ultra-low-sulfur (ULS) diesel standard on jet fuel sulfur content [2]. The survey, a portion of which is shown in Fig. 2, shows that eastern U.S. refineries produced reduced sulfur jet fuel concurrently with the incorporation of the ULS diesel standard. The data also show strong regional variation in the sulfur content of jet fuel. The highest sulfur contents were recorded in the Gulf coast, and the lowest were recorded on the west coast.

There is considerable regional and international variability in the sulfur content of jet fuel. Jet fuel from the west had a minimum weighted monthly mean value of 116 ppm and a maximum value of 573 ppm. These findings have implications to air quality analyses

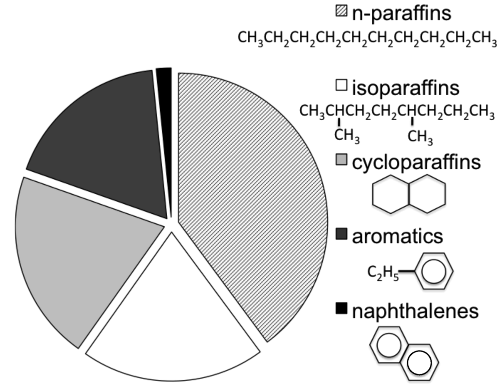
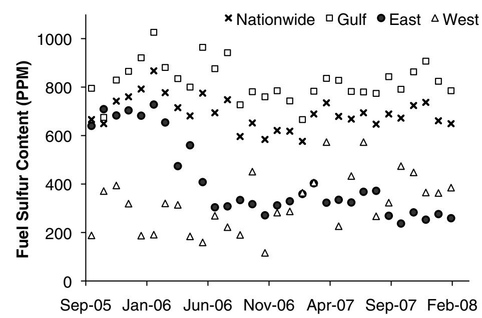


Fig. 1 Typical jet fuel composition from Shafer et al. [1]. Some typical molecular compositions are given for each type of hydrocarbon listed.



Weighted Mean Fuel Sulfur Content (PPM)		
	2006	2007
US East	446	321
US Gulf	858	800
US West	240	395
Nationwide	709	677

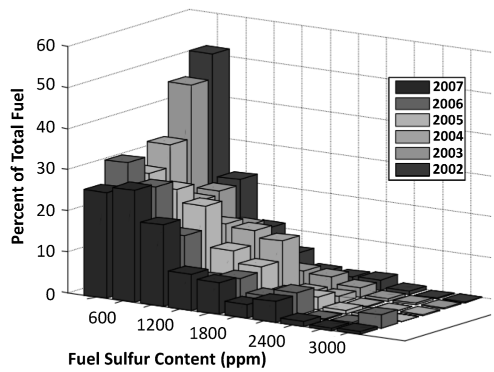
Fig. 2 Jet A average fuel sulfur content in the United States [2].

based upon a single nationwide value. The air quality analysis of Ratliff et al. [3], using a nationwide jet fuel sulfur content of 680 ppm indicated that approximately 30% of the national health impacts of aviation were due to operations in southern California. Lower fuel sulfur contents for this region could change this result considerably. Individual samples within the Taylor survey [2] varied from a low of 2 ppm to a high of 2200 ppm, thus showing the regional variability of jet fuel sulfur content and indicating that some refineries are already producing what would qualify as a ULS jet fuel (ULSJ) with fuel sulfur content less than 15 ppm. The sulfur content of JP-8, as gathered by DESC in the PQIS and shown in Fig. 3, is similar to that of Jet A within the Coordinating Research Council survey. Average fuel sulfur contents have been increasing slightly over time to recent values of roughly 750 ppm (see footnote §). The United Kingdom has seen mean jet fuel sulfur content fluctuate between 360 and 640 ppm over the past 20 years. In 2007, the mean for the United Kingdom was 500 ppm, with a standard deviation of 600 ppm [4].

B. Ultra-Low-Sulfur Jet Fuel

Reducing or eliminating sulfur from jet fuel could reduce the environmental impact of aviation on air quality. ULS standards are currently in place for diesel fuel refiners, retail stations, and wholesalers in the United States. Highway diesel fuel has met an ultra-low-sulfur specification since 2006 (at or below 15 ppm). Nonroad diesel engines will be required to use ULS diesel in 2010, and locomotives and marine engines will be required to use it in 2012 [5]. The sulfur level for ULS diesel was chosen because it enables the use of particulate-matter capture technologies that are poisoned by sulfur compounds.

§Data available online at http://www.desc.dla.mil/DCM/DCMPage.asp?pageid=99 [retrieved 2010].



Weighted Fuel Sulfur Content (PPM)		
	Mean	Std Dev
2002	530	514
2003	580	525
2004	666	504
2005	668	581
2006	754	648
2007	762	590

Fig. 3 JP-8 fuel sulfur content as reported by PQIS (see footnote §).

The hydrodesulfurization (HDS) process required to produce ULS diesel fuel (less than 15 ppm of sulfur) results in roughly a 1% loss in fuel energy density [6–8]. HDS removes sulfur by reacting sulfur-containing hydrocarbons with hydrogen gas to create hydrogen sulfide (H_2S), which can then be separated. The HDS process should also result in the conversion of a portion of the aromatic compounds to paraffins or naphthenes. The change in fuel composition is likely tied to the observed changes in fuel energy density.

Because of the similarities in diesel and jet fuels, it is assumed for the purposes of this paper that a transition to ULS jet fuel could result in a similar reduction of energy density. Before the implementation of ULS diesel, the fuel sulfur content of diesel fuel was approximately 300 ppm, or half that observed with conventional jet fuel (roughly 700 ppm); thus, the loss in volumetric energy density for jet fuel could be twice as high as that for diesel fuel. Future research is needed to confirm this hypothesis. The mean energy density of jet fuel is 34.8 MJ/L; a 1% loss in energy density corresponds to a decrease from the JP-8 mean of 34.4 MJ/L, and a 2% loss would result in an energy density of 34.0 MJ/L. The mean energy density for a ULS jet fuel would therefore likely fall between 34.0 and 34.8 MJ/L (the higher value corresponds to no change in energy density).

Existing jet fuel data were used to relate changes in energy density of ULS jet fuel to anticipated changes in specific energy and density. This is appropriate because the energy density of ULS fuel is still within the jet fuel specification (as determined by the specific energy and fuel density) and compositional changes are likely small. In a manner similar to that of Martel and Angello [9], linear relationships of energy density, specific energy, and density as a function of fuel hydrogen content were created based on PQIS data. The U.S. military specification for jet fuel uses hydrogen content as a surrogate for energy density; both JP-5 and JP-8 have minimum hydrogen contents of 13.4%. PQIS entries with nonzero values for sample volume, aromatic content, density, and specific energy were binned by hydrogen content and the average was determined for each bin; the binned average values are presented in Table 1. As it is likely that much of the hydrogen content data in PQIS are estimated using test specification D3343 [10], not measured directly by D3701 [11], the results may be influenced by previously estimated relationships between hydrogen content and other fuel properties.

A linear fit was applied to the values in Table 1, representing more than 1% of the total fuel volume:

$$y = m \times (\text{percent hydrogen}) + b \tag{2}$$

where y can be specific energy, energy density, or density and m and b are estimated through a least-squares fit of the data points. Table 2 captures these relationships.

Based on the relationships within Table 2, a 1% decrease in energy density is accompanied by an increase in mean hydrogen content from 13.8 to 14.0% and roughly a 0.3% increase in mean specific energy. Desulfurizing jet fuel from ~700 ppm to below 15 ppm could result in twice the fuel energy content change as converting diesel from ~300 ppm to below 15 ppm. A 2% change would further increase the mean hydrogen content to 14.2%, with a 0.6% increase in mean specific energy.

Because of the reduced complexity of the molecules comprising jet fuel, it is also conceivable that changes in jet fuel energy content with desulfurization will be negligible. Hence, the nominal mean specific energy of ULS jet recommended for analysis purposes within this paper is 1% below that of conventional jet fuel, but could lie within a range of 43.2 and 43.5 MJ/kg (a 0 to 0.6% increase from the mean JP-8 specific energy).

C. Hydrocarbon Jet Fuels with Reduced or Zero Aromatic Compounds

Synthetic fuels (not derived from petroleum) can be created from a wide array of feedstocks using methods such as gasification and Fischer–Tropsch (F-T) synthesis of coal, natural gas, or biomass (F-T jet) and hydroprocessing of renewable oils [hydroprocessed renewable jet (HRJ)]. The key characteristic of synthetic fuel pathways is that the resulting fuel is composed of paraffinic compounds similar to kerosene. Such fuels are referred to as synthetic paraffinic kerosene (SPK), and they differ from conventional jet fuel in that they are composed solely of paraffinic hydrocarbons. These fuels contain neither aromatic compounds nor sulfur [12].

For a given number of carbon molecules, aromatic compounds have a higher *energy density* than paraffinic compounds, and paraffinic compounds have a higher *specific energy* than aromatic

Table 1 Mean JP-8 properties for PQIS data (see footnote §) that have been binned according to fuel hydrogen content

Fuel hydrogen content, %	Specific energy, MJ/kg	Energy density, MJ/L	Density, kg/L	Aromatic compound, % of total	Fuel volume, % of total
13.19	43.2	35.0	0.810	13.3	0.02
13.27	43.1	35.2	0.818	15.5	0.02
13.40	43.0	35.2	0.818	20.1	4.6
13.50	43.1	35.1	0.815	20.2	9.9
13.60	43.1	34.9	0.809	20.1	12.6
13.68	43.2	34.8	0.805	18.6	6.9
13.78	43.2	34.6	0.801	18.0	9.3
13.88	43.3	34.4	0.795	17.6	16.8
13.97	43.3	34.3	0.793	16.6	10.8
14.06	43.3	34.4	0.795	16.1	3.9
14.16	43.6	34.4	0.789	14.3	1.2
14.27	43.4	34.3	0.791	14.5	0.5
14.38	43.5	35.0	0.804	16.1	0.4
14.46	43.3	34.6	0.799	18.1	0.2

Table 2 Linear fit coefficients to the PQIS JP-8 database

Physical property y	Slope m	y-intercept b	R^2
Specific energy, MJ/kg	0.572 MJ/kg/%H	35.3 MJ/kg	0.88
Energy density, MJ/L	−1.23 MJ/L/%H	51.6 MJ/L	0.92
Density, kg/L	−0.039 kg/L/%H	1.34 kg/L	0.96

compounds. These properties result from the molecular structure for these two classes of hydrocarbons, as shown in the data of Fig. 4. Also shown in Fig. 4 are the mean jet fuel properties from Table 1, a JP-8 sample from oil shale that was extracted using the Shell in situ conversion process (ICP), and a range of SPK samples. Plotting the energy density and specific energy as a function of hydrogen content facilitates a comparison of the compositional relationship of these various fuels. The individual data that were used in the creation of Fig. 4 are summarized in Table 3.

Wide ranges of hydrocarbons, including aromatic compounds, have specific energies that follow the trends of Eq. (2) and Table 2. As such, Eq. (2) and Table 2 should hold for a wide range of fuels that meet the distillation range of jet fuel. Logically, SPK fuels also follow the specific energy trends of Eq. (2) and Table 2. Because they are composed solely of paraffinic compounds, the SPK fuels have higher hydrogen content and specific energy than conventional jet fuel.

The energy density of aromatic and paraffinic compounds follows two distinctly different relationships. Aromatic compounds have a slightly increasing energy density with increasing hydrogen content, which is opposite to the trend for paraffinic compounds. Paraffinic hydrocarbons follow the trend of JP-8 in that increasing hydrogen content corresponds to decreasing energy density, but the slope is steeper than that of the jet fuel trend line. The jet fuel trend line appears to be a combination of these two trends; this is expected because jet fuel contains between 15 and 20% aromatic content regardless of the hydrogen content of the sample. Based on these observations, fuels that differ markedly in aromatic composition

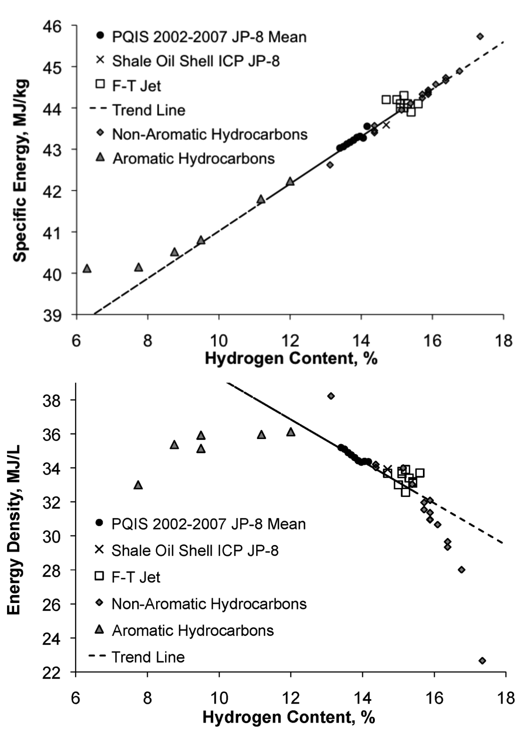


Fig. 4 Comparison of observed trends in specific energy and energy density for the individual hydrocarbon compounds that typically compose hydrocarbon fuels. The hydrocarbons vary in carbon number from 6 to 16. The JP-8 mean data are from Table 1, but only values that correspond to more than 1% of the total fuel volume are plotted.

from jet fuel will not follow the energy density trends of Eq. (2) and Table 2. Because they lack aromatics, SPK fuels have lower energy density relative to conventional jet fuel.

A fuel with 3% aromatic compounds was recently produced from oil shale using the Shell ICP technique [13]. It is not known if the relatively low aromatic compound and fuel sulfur contents are a result of the ICP recovery technique or of the postextraction processing to refine the fuel. Because the fuel properties fall between those of conventional jet fuel and SPK fuels, the fuel energy density also fell between these extremes.

D. Fatty Acid Methyl Esters (Biodiesel and Biokerosene)

The chemical composition of a biodiesel or biokerosene depends on the feedstock that is used in its creation. Specifically, the fatty acid content of the feedstock determines the chemical composition of the fatty acid methyl esters (FAMEs) that comprise the biodiesel or biokerosene. This is because the transesterification process used for FAME production is composed of a triglyceride (three fatty acids bonded to a glycerol molecule) reacting with an alcohol, generally methanol, in the presence of a base chemical to create FAME molecules and glycerol. The chemical composition of the FAME (RCO_2CH_3) is tied to the fatty acid (RCOOH) in that both contain an alkyl chain, R, between 7 and 21 carbon molecules in length with 0 to 3 carbon–carbon double bonds.

The majority of fatty acids in animal or vegetable oil contain either 16 or 18 carbon molecules. Some feedstocks such as coconut oil, palm kernel oil, and babassu oil have fatty acids composed of 10 to 14 carbon molecules. Fatty acids can either be saturated (all of the carbon bonds are saturated with hydrogen atoms) or unsaturated (double carbon bonds exist within the molecule). If the fatty acid is saturated, then the FAME has a chemical formula of $C_nH_{2n+1}CO_2CH_3$; the number of hydrogen molecules of unsaturated fatty acids will decrease by twice the number of double carbon bonds. Bacha et al. [8] and Hasenhuettl [14] present fatty acid distributions for select vegetable oils and animal-fat feedstocks. Variation in fatty acid type leads to variability in the properties of biodiesel. Based on the distribution of fatty acids that comprise raw vegetable oil, the ratio of carbon–hydrogen–oxygen, by weight, in biodiesel derived from soybeans is 77%–12%–11%, respectively. Palm-oil-derived biodiesel has a similar C–H–O ratio of (76%–13%–11%). For a biodiesel derived from coconut oil, referred to as biokerosene herein, the ratio changes to 74%–12%–14%. Biodiesel properties presented in this paper are based on a FAME derived from soybean oil, whereas biokerosene properties are based on a FAME derived from coconut oil.

The chemical composition of FAME molecules and their fuel properties lead to concerns regarding their use as a transportation fuel. The relatively high freeze point of biodiesel would require that it be used in a blend for jet aircraft use. The pour point of pure biodiesel can vary from −3 to 12°C [15], which is sufficiently high to freeze under normal aircraft cruise operating conditions. According to Bacha et al. [8], the pour point is that at which "wax just begins to precipitate and the fuel becomes cloudy." The fuel will no longer flow approximately 3 to 5°C (6 to 10°F) below the cloud point [8]. Corporan et al. measured freeze points of −50 and −27°C for biodiesel blends of 2 and 10% with conventional jet fuel, respectively [16]. Assuming that the freeze point scales linearly within this range of blending percentages, a 5% biodiesel blend would have a freeze point of approximately −41°C, and may meet the Jet A freeze-point specification of −40°C. However, other measurements indicate that blends containing only 1% biodiesel may not meet freeze-point requirements [17]. As demonstrated by the Virgin flight test in February 2008, higher blend percentages are possible with the use of lower-carbon-number feedstocks such as babassu and coconut oil.

Jet fuel is an important medium for heat exchange within aircraft engines and systems, leading to thermal stresses that may cause biodiesel to decompose and leave deposits in fuel-system lines. These deposits can accrue over time and degrade system performance and safety. Testing indicates that some biodiesel blends, even when blended at 1%, could lead to unacceptable thermal stability

Table 3 Select properties of alternative jet fuel samples derived from Fischer-Tropsch synthesis, hydroprocessing of renewable oils, and oil shale via the Shell ICP process

Hydrogen, wt %	Density, kg/L	Specific energy, MJ/kg	Energy density, MJ/L	Sulfur	Aromatics, vol%	Source[a]
			Fischer–Tropsch jet fuel samples			
15.4	0.755	43.9	33.1	——	0	Average Syntroleum F-T value [40]
15.0	0.747	44.2	33.0	——	0	SASOL F-T value [40]
15.3	0.757	44.1	33.4	<0.01 wt%	<0.1	Corporan et al. [41]
15.1	0.767	44.1	33.8	——	——	Freerks and Muzzell [42]
——	0.759	44.2	33.6	——	——	Hemighaus et al. [43]
15.6	0.765	44.1	33.7	<0.0001 wt%	0.9	Muzzell et al. [44]
15.4	——	43.9	——	0.00	0	Chang et al. [13]
15.1	0.765	44.0	33.7	<0.001	0.5	Sasol IPK [12]
15.4	0.756	43.9	33.2	0.002	0.0	S-8 [12]
——	0.736	44.2	32.5	<0.01	0.2	Shell GTL [12]
15.2	0.735	44.3	32.6	<0.01	0	Sasol GTL-1 [12]
14.7	0.762	44.2	33.7	<0.01	0	Sasol GTL-2 [12]
Mean	0.755	44.1	33.3	——	——	——
			HRJ fuel samples			
——	0.751	44.4	33.3	0.00009 wt%	0	UOP-jatropha [45,46]
——	0.755	44.2	33.4	0.0003 wt%	0	UOP-coconut [45,46]
——	0.749	44.3	33.2	<0.0	——	UOP-jatropha [45,46]
——	0.753	44.0	33.1	<0.0	——	UOP-camelina [45,46]
——	0.748	44.2	33.1	<0.0	——	UOP-jatropha/algae [45,46]
——	0.762	44.2	33.7	——	0	Syntroleum R-8 from waste animal fats and grease [47]
——	0.762	44.2	33.7	——	0.4	Syntroleum R-8x from salicornia oil [47]
——	0.769	44.2	34.0	——	0.8	Company A from palm oil [47]
——	0.767	44.2	33.9	——	0.2	Company B from canola oil [47]
Mean:	0.758	44.1	33.5	——	——	——
			JP-8 sample created from shale oil using the Shell ICP process			
14.7	0.778	43.6	33.9	0.00	3.2	Chang et al. [13]

[a]IPK is isoparaffinic kerosene, GTL is gas-to-liquids, and UOP is United Oil Products.

degradation [18]. Because of concerns about thermal stability of jet fuel with residual biodiesel contamination, biodiesel is currently not being transported in U.S. petroleum pipelines. The concern is that trace quantities of biodiesel will trail back to jet fuel traveling in the same pipeline, and this contamination will lead to an unacceptable degradation in the jet fuel thermal stability. In Europe, biodiesel is currently transported as a blend with conventional diesel fuel, but there is ongoing research to determine the effect on jet fuel quality and an acceptable level of biodiesel contamination of jet fuel [19,20]. Considering the research is focused on determining a maximum FAME contamination, as measured in parts per million, it appears unlikely that any biodiesel or biokerosene blend would be considered for certification in current jet aircraft applications.

Further complications arise because the energy content (both energy density and specific energy) of biodiesel and biokerosene are less than conventional jet fuel. This occurs because the molecules that comprise these fuels are partially oxidized. The energy content of biodiesel derived from soybean oil, canola oil, and many animal fats is similar, due to the similarity in the fatty acid methyl esters comprising the finished biodiesel products. Biokerosene derived from coconut oil, babassu oil, or other lower-carbon-number oils will have energy content that is lower than that derived from soybean oil.

The specific energy of FAME molecules increases with increasing carbon chain length. As an example, methyl caprylate ($C_9H_{18}O_2$), methyl caprate ($C_{11}H_{22}O_2$), and methyl laurate ($C_{13}H_{26}O_2$), components of coconut-oil-based biodiesel, which are not in soy-based biodiesel, have gross specific energy of combustions between 34.7 and 38.0 MJ/kg (methyl laurate has the highest value), whereas methyl stearate ($C_{19}H_{38}O_2$), methyl oleate ($C_{19}H_{36}O_2$), and methyl linoleate ($C_{19}H_{34}O_2$), which are components of soy-based biodiesel but not of coconut-based biodiesel, have gross heats of combustion between 39.7 and 40.1 MJ/kg. The result is that biokerosene has lower specific energy than biodiesel. As an example, coconut ethyl ester (biodiesel created from ethanol transesterification of coconut oil) has specific energy that is 4% lower than a soy methyl ester, whereas the measured energy content of the fuel used in the Virgin Atlantic flight tests (a coconut methyl ester) had specific energy that is 9% below a typical biodiesel [21,22].

E. Summary of Energy Content

The properties for the fuels that were discussed in this section are listed in Fig. 5 and Table 4. The statistical information about jet fuel is based on the specification for Jet A and the DESC PQIS database for JP-8. The range of values from the DESC database is reflected in the volume-weighted values denoted as JP-8 low and JP-8 high. The JP-8-low value has fuel hydrogen content that is larger than 5% of the samples, and the JP-8-high value has fuel hydrogen content that is larger than 95% of the fuel samples. Unlike Table 1, which required that all values in the fuel sample be nonzero, this analysis only required that the fuel sample data have a nonzero value of fuel

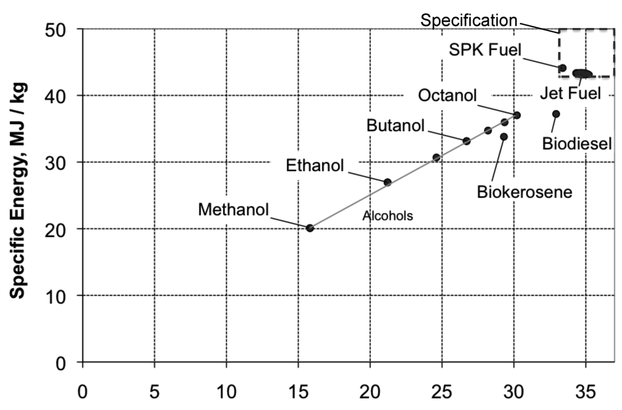


Fig. 5 Energy density and specific energy for a wide range of fuels. The lines denote a range of alcohol fuels. The variations in JP-8 properties from Table 1 were used to create the range of values surrounding the jet fuel data entry. The box marked specification corresponds to the specific energy and density range within ASTM D1655.

Table 4 Properties for a wide range of fuels

Fuel	Chemical composition	Carbon mass fraction	Specific energy, MJ/kg	Energy density, MJ/L	Density, kg/L	CO_2 emissions, gCO_2/MJ
Jet fuel (JP-8 mean)[a]	C_mH_n	86.2	43.2	34.7	0.802	73.1
JP-8 low[a]	C_mH_n	86.6	43.0	35.1	0.829	73.9
JP-8 high[a]	C_mH_n	85.9	43.4	34.3	0.791	72.6
Jet A min specification[b]	C_mH_n	——	42.8	33.2	0.775	——
ULSJ nominal value[c]	C_mH_n	86.0	43.3	34.3	0.792	72.7
SPK (F-T jet and HRJ)[d]	C_mH_n	84.7	44.1	33.4	0.757	70.4
Biodiesel[e]	$C_mH_nCO_2CH_3$	77	37.2	32.9	0.885	76
Biokerosene[f]	$C_mH_nCO_2CH_3$	74	33.8	29.3	0.867	80
Methanol[g]	CH_3OH	37.5	20.1	15.8	0.787	68.4
Ethanol[g]	C_2H_5OH	52.1	27.0	21.2	0.787	70.9
Butanol[g]	C_4H_9OH	64.8	33.1	26.7	0.806	71.7
Octanol[g]	$CH_3(CH_2)_7OH$	73.8	37.0	30.2	0.816	73.0

[a]Based on statistical analysis of DESC PQIS (see footnote §). Low and high refer to specific energy.
[b]Based on ASTM D1655 [23] using minimum density and maximum specific energy.
[c]Nominal mean value for ULS jet fuel; potential range of values discussed in Sec. II.B.
[d]Based on average of HRJ and F-T jet fuel data presented in Table 3.
[e]Based on a soybean-oil-derived ester [8,14]. Energy content data are from the National Renewable Energy Laboratory [24].
[f]Based on a coconut-oil-derived ester [8,14]. Energy content data are from Whitefield [22].
[g]Yaws [25].

hydrogen content. Therefore, the range of JP-8 values in Table 4 should capture 90% of the fuel volume. The values in Fig. 5 for specific energy, energy density, and density were created using these hydrogen mass contents with the relationships defined in Table 2.

The JP-8 mean values from Table 4 also match those reported for Jet A-1 in the United Kingdom for 2007 [4]; thus, the entry should fairly represent both commercial jet fuel and military JP-8. The Jet A minimum specification entry reflects the minimum specific energy, 42.8 MJ/kg, and an allowable density range, 0.775 to 0.840 kg/L, for Jet A as provided by ASTM D1655 [23].

Figure 5 and Table 4 also include information for alcohols and fatty acid esters. The box marked Specification within Fig. 5 shows the full range of specific energy and energy density that correspond to the ASTM D1655 [23] specification. Combining the minimum specific energy with the maximum density gives the minimum energy density listed in the table.

III. Analytical Methodology

As discussed in the introduction, specific energy and energy density are both critical factors in determining aircraft performance. This section presents a first-order analysis of the change in aircraft operating performance that would accompany a change in alternative-fuel energy content as estimated through the Breguet-range equation:

$$R = \frac{H_g}{g}\eta\frac{L}{D}\ln\left(1+\frac{W_F}{\mathrm{OEW}+W_P+W_R}\right) \tag{3}$$

where η is engine efficiency, L/D is the lift/drag ratio for the aircraft, H_g is the specific energy, W_F is the weight of the fuel, W_P is the weight of the payload, and OEW is the empty weight of the aircraft. The reserve fuel, W_R, is estimated as 4.5% of maximum takeoff weight (MTOW) for all ranges [26]. The analysis presented herein assumes that fuel type has a negligible effect on aircraft empty weight, efficiency, and lift/drag ratio and the amount of alternative reserve fuel must have energy equivalent to the conventional jet fuel reserve fuel.

Some recent results have indicated that the thermodynamic efficiency of a gas turbine may not be independent of fuel type. Bester and Yates [27] conducted experiments on a RR-Allison T63-A-700 turboshaft gas turbine burning 100% SPK fuel and concluded that the lack of aromaticity and increased hydrogen-to-carbon (H/C) ratio of SPK fuel could lead to a 1.2% increase in engine efficiency. Aromatic compounds promote soot formation in the combustion chamber and the H/C ratio is directly related to the heat capacity of the combustion products. Soot contained in the exhaust represents a loss of potential heat release within the combustion chamber and higher heat capacity of combustion products leads to more energy being available for extraction from the turbine [27]. As there is only one study with these data, η was assumed to be unchanged; however, future analyses expanding on this paper should reexamine the state of knowledge in this field.

The amount of conventional jet fuel required to carry a given payload a given range can be estimated from the aircraft payload-range diagram. These aircraft-specific relationships capture the complex relationship between aircraft weight, distance flown, and fuel use. A schematic of a payload-range diagram is shown in Fig. 6. For ranges at which the payload is limited by structural constraints ($R < R1$), fuel is added to fly longer distances. At longer ranges ($R1 < R < R2$), the total aircraft weight is limited by the MTOW and payload must be reduced to allow for added fuel and increased range. At the longest ranges ($R > R2$), the aircraft tanks are full and payload must be reduced to increase range. The majority of commercial flights have ranges below $R1$; however, some flights do exceed $R2$. All aircraft in this analysis are assumed to operate at full payload capacity.

By solving Eq. (3) for a given range and payload, the mass of alternative fuel required to fly a mission can be written as a function of the ratio of $H_{g,J}$ to $H_{g,A}$ and values available from a payload-range diagram. The subscripts J and A refer to baseline values for jet fuel and the alternative fuel, respectively, as shown in Eq. (4):

$$W_{F,A} = \left(\mathrm{OEW}+W_P+\left(\frac{H_{g,J}}{H_{g,A}}\right)W_{R,J}\right)\cdot\left[\exp\left(\left(\frac{H_{g,J}}{H_{g,A}}\right)\ln\left(1+\frac{W_{F,J}}{\mathrm{OEW}+W_P+W_{R,J}}\right)\right)-1\right] \tag{4}$$

If the specific energy of the alternative fuel exceeds that of conventional jet fuel, then additional fuel and/or payload can be carried without exceeding either the MTOW or maximum structural payload. For the level of fidelity sought in this paper, the added

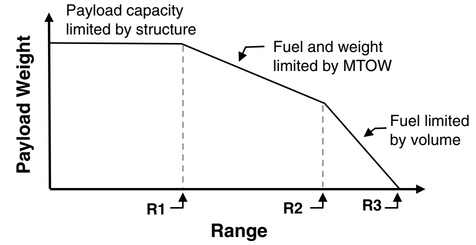


Fig. 6 Typical payload-range diagram.

Table 5 Aircraft and parameters used for energy content analysis[a,b]

	Embraer 145-LR	Boeing 737-300	Boeing MD87	Boeing 737-800	Boeing 757-200	Boeing 767-300ER	Boeing MD11 Freighter	Boeing 777-200LR	Boeing 747-400	Airbus A380
MTOW, kg	22,000	63,277	63,503	79,016	115,650	186,880	273,294	347,450	396,894	560,000
OEW, kg	12,114	32,904	33,237	41,413	59,350	90,011	112,748	157,079	179,015	270,281
MZFW, kg	17,900	48,308	50,802	62,732	85,300	133,810	204,710	209,100	246,074	361,000
W_F, kg	5,187	19,131	17,764	20,894	34,260	73,364	117,356	162,636	174,093	247,502
$R1$, km	2,114	3,931	2,627	3,910	5,740	7,540	7,025	14,057	10,702	11,022
$R2$, km	2,973	5,477	4,453	5,522	7,010	11,906	11,912	17,483	13,153	21,170
$R3$, km	3,555	6,662	5,628	7,112	8,663	13,725	15,141	19,446	14,816	24,520
Avg range May 2006, km	717	932	802	1,458	2,061	3,737	4,597	4,852	5,547	——

[a]Payload-range data are from airport planning guides from Embraer [28], Airbus [29], and Boeing [30–36].
[b]Average distances flown in May 2006 are provided by G. Baker of Volpe National Transportation Systems Center; data are part of those used to create the annual Federal Aviation Administration's emissions inventory [37].

payload, $\Delta W_{P,A}$, and fuel weight, $\Delta W_{P,A}$, can be estimated according to the following:

$$\Delta W = \min[\mathrm{MTOW} - (\mathrm{OEW} + W_{P,A} + W_{F,A} + W_{R,A}), \times \mathrm{MZFW} - (\mathrm{OEW} + W_{P,A})] \tag{5}$$

$$\Delta W_{F,A} = \Delta W\left(\frac{W_{F,A}}{\mathrm{OEW} + W_{P,A} + W_{R,A}}\right) \tag{6}$$

$$\Delta W_{P,A} = \Delta W - \Delta W_{F,A} \tag{7}$$

where the increased aircraft weight ΔW is constrained by either the MTOW or maximum structural payload, and MZFW is the maximum zero-fuel weight. This modification to Eq. (4) is only observed for flight distances between $R1$ and $R2$.

If a fuel with reduced specific energy is used, an aircraft will reach its MTOW with less energy in the fuel tanks. If a fuel of reduced specific energy fuel is used and the estimate of gross takeoff weight exceeds MTOW, the payload and alternative-fuel weight are determined iteratively. This is accomplished via iteration of Eq. (4) with

$$W_P = \mathrm{MTOW} - (\mathrm{OEW} + W_{F,A} + W_{R,A}) \tag{8}$$

This modification is only observed for flight distances between $R1$ and $R2$.

If a fuel with reduced energy density is used, an aircraft will reach its tank capacity with less energy in the fuel tanks. The result is a reduction in $R2$, denoted as $R2_A$. For each distance examined, tank capacity is compared to the volume of alternative-f uel and reserves. For distances exceeding $R2$, $W_{F,A}$ is held constant and $W_{P,A}$ is modeled by multiplying the slope of the payload-range diagram by the ratio of fuel specific energy:

$$W_{P,A} = W_{P,A,R2A} - \frac{H_{g,J}}{H_{g,A}}\left(\frac{R - R2_A}{R3 - R2}\right) \times (\mathrm{MTOW} - \mathrm{OEW} - W_{F,A} - W_{R,A}) \tag{9}$$

where $W_{P,A,R2}$ denotes the payload weight at $R2_A$ with the alternative fuel. This modification only affects flights in excess of $R2$ where the alternative fuel has an energy density that is less than conventional jet fuel.

In the two sections that follow, a wide range of aircraft from regional jets to jumbo jets were examined to quantify how fuel energy density and specific energy could affect aircraft operability in terms of payload and range capability. The aircraft and the payload-range data that were used for this purpose are presented in Table 5.

IV. Fuel Energy Content and Operability

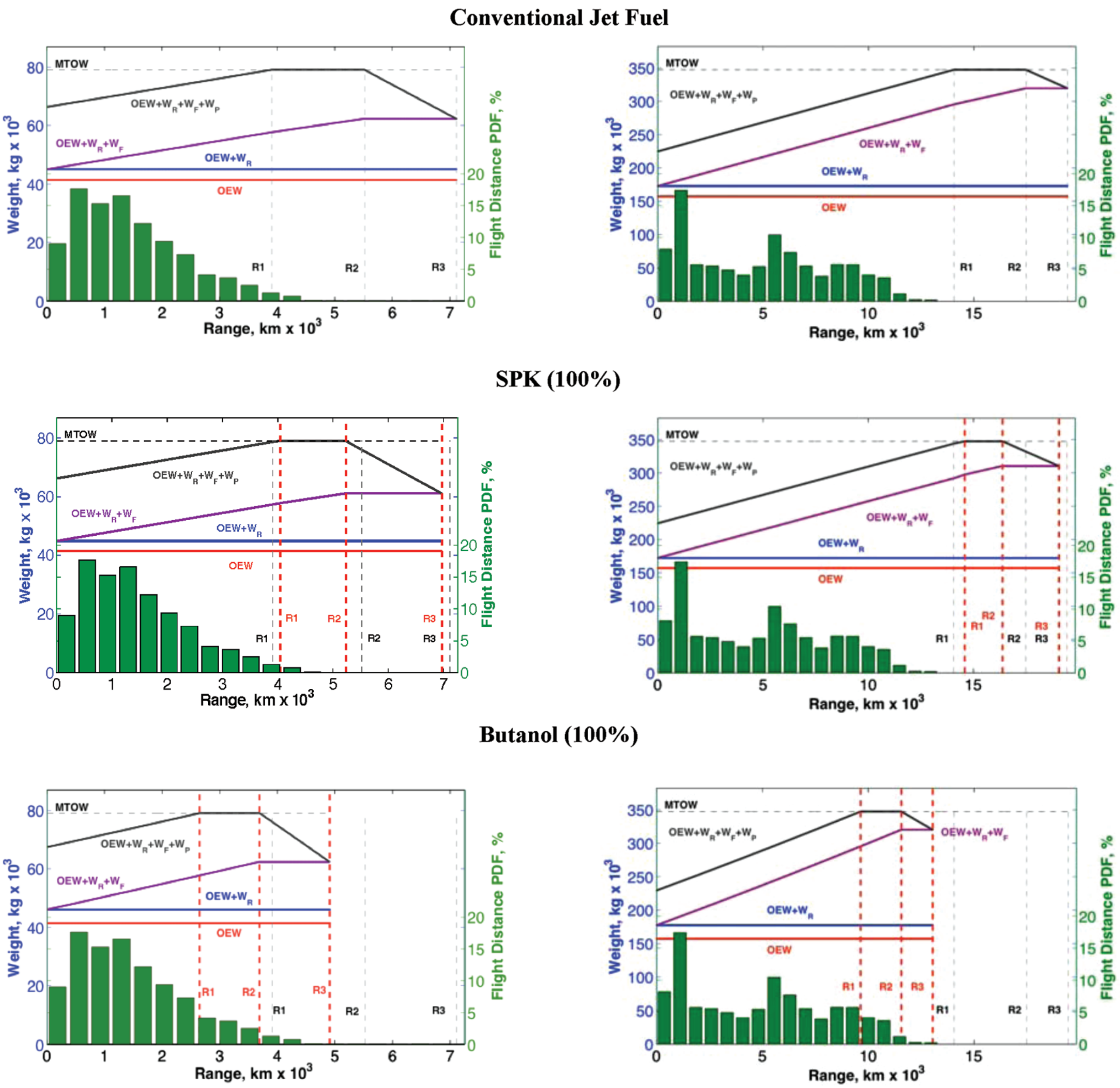
The impact of using alternative jet fuels on fleet-wide aircraft performance was estimated by combining Eqs. (4–9) with the payload-range diagram information for aircraft types spanning regional jets to jumbo jets. The data shown in Fig. 7, created for the Boeing 737-800 and the Boeing 777-200ER, demonstrate how SPK and butanol use would impact payload and range capability. The performance data for conventional jet fuel are based on the manufacturer payload-range data for these aircraft. Each plot shows the aircraft weight buildup versus range for each fuel with emphasis placed on $R1$, $R2$, and $R3$. These plots also show the relative number of flights that were flown for each distance worldwide during May 2006.

At ranges for which the payload is limited by structural constraints ($R < R1$), the aircraft simply adds fuel to fly longer distances. For fuels with reduced specific energy, such as butanol, the increased fuel weight leads to the aircraft reaching MTOW at reduced range and $R1$ is reduced. An increase in $R1$ is observed when fuels such as SPK are used as they have an increased specific energy relative to conventional jet fuel. At ranges where the combined mass of fuel and payload are limited by the maximum takeoff weight of the aircraft ($R1 < R < R2$), the aircraft trades payload for more fuel. For fuels with reduced specific energy, such as butanol, the increased fuel weight leads to a decrease in payload capacity for a given range between $R1$ and $R2$. Conversely, fuels with increased specific energy, such as SPK, allow for increased payload at a given range over these flight distances. At ranges limited by fuel volume ($R > R2$), the distance an aircraft can fly is limited by tank volume and payload must be considerably reduced to fly further. For fuels with reduced energy density, such as SPK and butanol, the aircraft reaches tank capacity at reduced range. The potential loss of operating range with fuels of reduced energy density and potential gain in payload capacity between $R1$ and $R2$ using fuels with increased specific energy indicates that two operating regimes must be considered in greater depth.

Tables 6 and 7 provide the percent *reduction* in $R1$ and $R2$, respectively, that would accompany the use of various fuels within each of the aircraft types. For example, the lowered energy density of SPK fuel causes the maximum fuel volume ($R2$) for a Boeing 737-800 to be reached at a nominal range of 5400 km instead of 5520 km: a reduction of 4%. The variability of JP-8 and Jet A specification are given for comparison. The energy density of SPK fuels is comparable to that of the lower end of JP-8-high fuel; hence, a comparable reduction in $R2$ is experienced with both of these fuels. This reduction is less than would be experienced with the use of a fuel meeting the minimum Jet A specification.

Boeing has internally considered the changes in aircraft operability arising from the use of SPK fuel.[¶] When examining the 777-200LR, Boeing found the use of SPK to result in a 2.2% increase in $R1$, a 5.6% decrease in $R2$, and a 2.0% decrease in $R3$. The model developed in Sec. III of this work predicted a 3.7% increase in $R1$, a 6.3% decrease in $R2$ and a 2.0% decrease in $R3$ given the same aircraft data and fuel properties; hence, this model can reliably

[¶]Private communication with T. Rahmes, The Boeing Company, September 2009.



NOTE: Weight buildup comprised of OEW, reserve fuel weight, fuel weight, and payload. Dashed range lines represent structural weight limit on payload (R < R1), MTOW limit on takeoff weight (R1 < R < R2), and tank capacity limit on fuel volume (R2 < R < R3). The gray dashed lines show the limits from the manufacturer's payload-range diagram. The histogram shows the probability density function of flight distances from all worldwide operation during May 2006.

Fig. 7 Illustrative weight buildup for the Boeing 737-800 (left column) and Boeing 777-200LR (right column) on conventional jet fuel, 100% SPK, and 100% butanol.

predict the trends, and to a lesser extent the magnitudes, of the changes in aircraft operability resulting from the use of fuel with different densities, specific energies, and energy densities.

Table 8 provides the potential decrease in fuel weight that would accompany the use of SPK fuel assuming the aircraft were flying the minimum distance that is fuel volume limited (denoted as *R*2). Only SPK were considered here, as they are the only fuel that has an increase in specific energy relative to conventional jet fuel. This decrease in fuel weight could be used to carry increased payload in the form of either passengers or revenue cargo. For comparison, the

Table 6 Percent reduction in *R*1 for a variety of aircraft operating on select alternative fuels

Fuel	E145-LR	B737-3	MD87	B737-8	B757-2	B767-3ER	MD11	B777-2LR	B747-4	A380
Jet A min spec	1.1	1.3	1.0	1.3	1.2	1.3	1.2	1.3	1.3	1.3
JP-8 low	0.7	0.8	0.6	0.8	0.7	0.8	0.8	0.8	0.8	0.8
Jet fuel (JP-8 mean)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JP-8 high[a]	−0.8	−0.5	−0.9	−0.5	−0.7	−0.7	−0.4	−0.6	−0.6	−1.4
SPK[a]	−3.6	−3.5	−4.3	−3.6	−4.2	−3.7	−2.3	−3.7	−3.9	−9.7
Butanol	33	32	32	32	31	31	31	31	31	31
Ethanol	52	50	51	51	49	49	50	49	49	49

[a]Negative values imply an increase in *R*1.

Table 7 Percent reduction in $R2$ for a variety of aircraft operating on select alternative fuels

Fuel	E145-LR	B737-3	MD87	B737-8	B757-2	B767-3ER	MD11	B777-2LR	B747-4	A380
Jet A min spec	7.2	5.8	6.4	6.0	7.3	6.1	4.6	6.2	6.5	11
JP-8 low[a]	−2.3	−3.3	−3.8	−3.4	−4.0	−3.3	−2.4	−3.1	−3.4	−6.8
Jet Fuel (JP-8 mean)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JP-8 high	2.8	1.6	1.6	1.5	2.0	1.7	1.3	1.8	1.8	2.4
SPK	6.5	5.4	5.9	5.3	6.6	5.9	4.6	6.3	6.5	11
Butanol	34	33	37	33	34	36	27	34	34	54
Ethanol	54	52	55	53	53	53	44	52	52	66

[a]Negative values imply an increase in $R2$.

Table 8 Approximate decrease in fuel weight for each aircraft type if it were operating on SPK fuel and flying the minimum fuel volume limited distance $R2$ (given relative to conventional jet fuel); maximum structural payload is given for comparison

Fuel	E145-LR	B737-3	MD87	B737-8	B757-2	B767-3ER	MD11	B777-2LR	B747-4	A380
Fuel weight decrease, kg	100	320	310	370	570	960	1,400	1,500	1,900	2,600
Maximum structural payload, kg	5790	15,400	17.,570	21,320	25,950	43,800	91,960	52,030	67,060	90,720

Table 9 Percent of operations in May 2006 that exceeded various ranges

Distance[a]	E145-LR	B737-3	MD87	B737-8	B757-2	B767-3ER	MD11	B777-2LR	B747-4
$0.5 \times R1$	17.0	4.7	14.0	24.0	26.9	46.5	64.7	28.4	55.0
$0.7 \times R1$	3.4	0.7	5.0	10.1	7.3	35.9	49.0	9.5	37.2
$R1$	0.4	0.0	0.3	1.7	0.8	9.6	21.4	0.0	5.4
$0.75 \times R2$	0.0	0.0	0.1	1.0	1.8	1.5	4.2	0.2	11.5
$0.95 \times R2$	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.4
$R2$	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0

[a]The distances assume that the aircraft is operating on conventional jet fuel.

Bureau of Transportation Statistics accounts for passenger weight with luggage as 91 kg.**

Most aircraft generally fly distances below $R1$; therefore, the impacts outlined above are negligibly small for SPK fuels, but could be large for alcohols. The data in Fig. 7 indicate that 12.6% of 737–800 operations and 9.5% of 777-200LR operations exceed $R1$ when butanol is used as the fuel compared to 1.0 and 0.0% when SPK is used as the fuel. Table 9 presents the percent of operations for the previously considered aircraft types that exceed various fractions of $R1$ and $R2$ when burning conventional jet fuel. It can be seen that the majority of aircraft operations do not require full tanks when using conventional jet fuel (i.e., most flown distances are less than $R2$).

As shown in Table 6, the use of pure butanol could have a dramatic affect on aircraft operability, as it would lead to over a 30% decrease in $R1$; ethanol use would lead to roughly a 50% decrease. As shown in Table 9, for the Boeing 747-400 the reduction in $R1$ would reduce the payload capacity for nearly a third of the flights (difference between $R1$ and $0.7^{*}R1$) if butanol were used. The payload capacity of half of the Boeing 747-400 flights would be affected if ethanol were used (difference between $R1$ and $0.5^{*}R1$). Even regional jets would be impacted with the use of alcohols, over 16% of Embraer 145-LR flights would have reduced payload capacity with ethanol use. Not all of these flights would actually be affected, since aircraft operate at roughly 60% of their full capacity, but modifications would be necessary in many flights and operating capability would decrease.

Pure SPK fuel use would not affect $R1$, and based on Table 7, their use would lead to roughly a 5% reduction in $R2$. As shown in Table 9, a 5% reduction in $R2$ may not be noticed by the airlines, as few aircraft fly this distance. The exception is the Boeing 747-400, which would have 0.4% of flights affected; some of these flights may have to take off with reduced payload to be able to fly the same distance. If using pure SPK fuels, some flights (specifically, those having a range between $R1$ and $R2$) would be able to take advantage of some fraction of the payload increase shown in Table 6. The Boeing 747-400 would have this potential increase on 5% of its flights.

All distances presented in this section were great circle distances, not the actual distance flown by the aircraft. For most operations, this would not affect the conclusions from this section, because as shown by Reynolds [38], the actual distances flown on intra-U.S., intra-Europe, and transatlantic flights are typically only 3% longer than the great circle distance with some individual flights having actual distances that exceed great circle distances by 10%. However, some long haul operations between Europe and eastern Asia have actual distances that exceed the great circle distance by over 20%, due to inefficient routing [38]. These inefficient routings could be a concern for the MD11 and the Boeing 747-400 as 4.2 and 11.5% of their respective operations had a great circle distances greater than $0.75 \times R2$, which roughly approximates the combined effect of a 20% increase in actual distance relative to great circle distance and a 5% reduction due to the decreased energy density of SPK fuels. Inefficient routings would not, in general, be a concern for the other passenger aircraft types listed in Table 9, because less than 2% of the operations for the other aircraft types considered have great circle distances in excess of $0.75 \times R2$.

V. Alternative Jet Fuel Surrogate Usage Curves

For each aircraft type presented in Table 5, the weight of alternative fuel was estimated for increasing range and this was normalized by the amount of conventional jet fuel required to fly the same range (based on the mean JP-8 entry in Table 4). As shown by the curve of Fig. 8 for the mean SPK specific energy from Table 4, the amount of aircraft fuel weight required to fly a given range is largely independent of aircraft type. The data are plotted up to the range at which tank capacity is reached, $R2$, using conventional jet fuel. With the exception of the Airbus A380, the large data points within Fig. 8 represent the average distances flown by each of the analyzed aircraft

**Data available online at http://www.bts.gov/programs/airline_information/air_carrier_traffic_statistics/airtraffic/annual/1981_present.html [retrieved 27 July 2010].

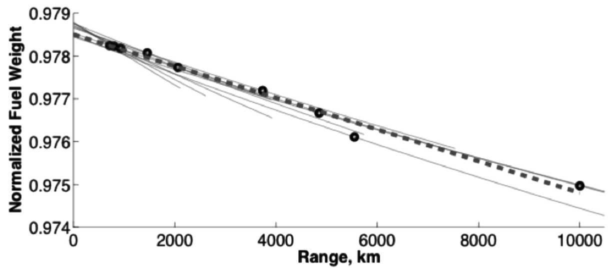


Fig. 8 Fuel weight ratio for a variety of aircraft operating on SPK. The thin lines represent individual aircraft, and the thick dotted line is a least-squares fit through these aircraft.

types (see Table 5). The Airbus A380 was not in operation in 2006; hence, a distance of 10,000 km was chosen for comparison purposes. These typical distances were then used to create normalized fuel weight curves. Surrogate fuel trend lines for each fuel type were used to estimate the impact of alternative-fuel use on the existing aircraft fleet.

Up to the range at which tank capacity is reached, Fig. 9 shows the change (relative to conventional jet fuel) in fuel energy and fuel weight as a function of range for varied fuel specific energies. Fuels with reduced specific energy require additional fuel mass to fly a given distance, leading to increased total energy use. Oxygenated fuels fall within the range of roughly 50 to 90% of the specific energy of conventional jet fuel; therefore, these fuels require increased energy to complete a flight between two fixed points. Conversely, SPK fuels have 1.6 to 2.6% higher specific energy than conventional jet fuel; therefore, their use results in a decrease in the energy requirement to fly a given distance (relative to conventional jet fuel).

Recent results from the Delft University of Technology and Shell Global Solutions agree well with the surrogate fuel usage curves developed in this work. Their analysis considers an Airbus A320 flying missions of various lengths with different payloads using SPK fuel. For a distance of 2500 km at 80% capacity, an overall flight efficiency increase of 0.2% was found [39]. When the results from Fig. 9 are applied to SPK fuel for a range of 2500 km, a 0.2% decrease in fuel energy is obtained, which corresponds to a 0.2% increase in efficiency.

VI. Fleet-Wide Fuel Usage

In the previous sections, surrogate fuel use curves were developed for a variety of potential fuel options to demonstrate the change in fuel consumption accompanying changes to the fleet fuel consumption. These fuel use curves were then applied to all of the operations within the Federal Aviation Administration's database of flight operations for a typical day in 2005 to determine the change in fuel usage that would accompany a change in fuel composition, assuming it were technically feasible. The resulting change in fleet-wide fuel consumption, on a volume and energy basis, is presented in Fig. 10.

The range in values for conventional jet fuel represents the bounds presented in Table 4. Blending percentages of 5% biodiesel and 20% biokerosene represent theoretical points that could potentially meet freeze-point concerns. The 20% biokerosene blend matches that used in the February 2008 Virgin Atlantic flight test. It must be noted that the aviation fuel industry is currently determining a maximum acceptable contamination level in terms of parts per million of FAME in jet fuel, because of the concerns regarding thermal decomposition of FAME in engine fuel lines. Pure ethanol and butanol were also considered even though their flash points exceed those currently allowed in the ASTM D1655 [23] jet fuel specification. The examination of FAME blends and alcohol fuels is merely an academic exercise to understand the tradeoffs of using these fuels in aircraft.

Fleet-wide use of biodiesel, biokerosene, or alcohols requires more total energy compared to the amount needed if conventional jet fuel were in the tank. If it were possible to deploy ethanol throughout the global commercial aviation fleet, roughly 9% more energy would be required than if conventional kerosene-based conventional jet fuel were used. Butanol, if it were commercially available, would require 4% more energy. Assuming freeze-point and thermal stability concerns could be overcome, the use of the biodiesel or biokerosene

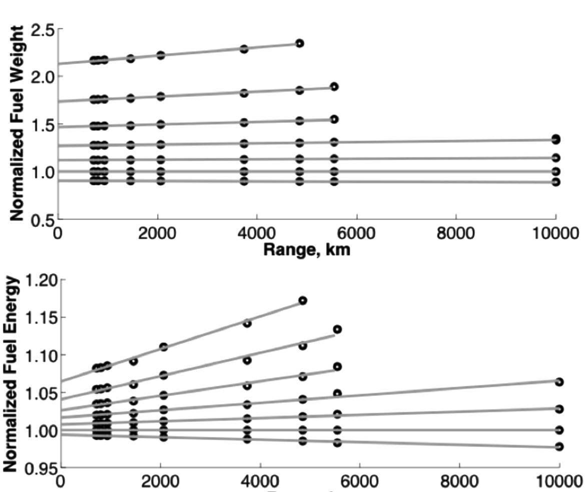


Fig. 9 Fuel weight and fuel energy ratios (relative to conventional jet fuel) for aircraft operating on fuels with varied specific energy. The specific energy ranges from 50% (top line) to 110% (bottom line) in increments of 10% of the specific energy of conventional jet fuel.

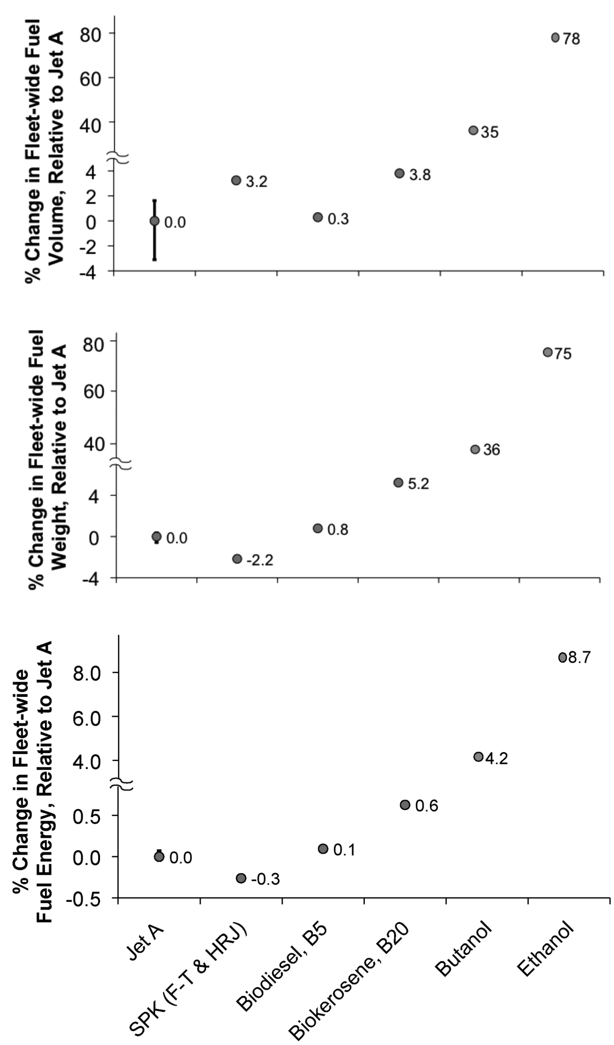


Fig. 10 Change in fleet-wide fuel volume and energy consumption for varied fuel composition.

blend would also result in increased energy consumption. The use of a 20% biokerosene blend would increase the fuel volume consumption of the worldwide fleet by roughly 4% and would decrease the energy efficiency by 0.6%. Only the use of SPK fuels results in a net improvement of fleet-wide energy efficiency. Although their use would increase the total volumetric consumption of jet fuel, the use of pure SPK fuels could improve the overall fleet efficiency by 0.3%.

VII. Conclusions

Alternative fuels that could hypothetically be used with the existing fleet of aircraft were examined from the perspective of chemical composition and energy content. Through the use of a first-order approach based in the Breguet-range equation, the influence of energy content on aircraft performance was examined. The analysis shows that the use of fatty acid methyl esters (biodiesel and biokerosene) and alcohols will not only result in increased fuel volume usage, but it will also result in a decrease in fleet-wide energy efficiency.

Ground transportation does not suffer a significant penalty for reduced specific energy, because fuel constitutes a relatively small percentage of the vehicle weight and because a ground vehicle does not expend large amounts of energy overcoming gravity. Cars operating on alcohol- and petroleum-derived gasoline require comparable amounts of energy to travel a given distance, because they can refill as needed, compensating for the reduced energy being carried in their fuel tanks. Aircraft, however, must carry enough energy to travel between two fixed points without refilling en route. Therefore, because biomass-based alcohol, biodiesel, and biokerosene fuels are a limited resource, the public receives a larger greenhouse-gas benefit, to the extent that such a benefit is present, when these fuels are used in ground transportation relative to their use in aviation.

Economic considerations further complicate the use of alcohols in aviation. Unless alcohol fuels were considerably less expensive per gallon than conventional jet fuel, their use would be prohibitively expensive. Butanol would need to be more than 30% less expensive than jet fuel on a volumetric basis in order for it to be economic for use in aircraft, and ethanol would need to be 80% less expensive to overcome increased volumetric fuel consumption.

SPK fuel use (F-T and HRJ fuels) would reduce the fuel energy consumed by aviation, thus improving aviation energy efficiency. The use of pure SPK fuel would increase energy efficiency by 0.3% on average. However, aviation is not the only available user for the resources that are used to create SPK. In some instances, using these resources for SPK results in less fuel volume than if they had been used to create high-performance diesel fuels. It remains to be seen if the benefit in reduced energy consumption through SPK use in aviation can merit a premium for these resources relative to their use for diesel. Further research should be devoted to better understanding the societal benefits of using limited resources in the production of fuels for diesel and jet engines.

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