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Energy and Environmental Viability of Select Alternative Jet Fuel Pathways

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This paper analyzes alternative jet fuels in terms of how they could change emissions from military and civil aircraft and in terms of the challenges in meeting future energy goals. Estimations of the continental United States (CONUS) conventional jet fuel energy usage for the civil and military aviation fleets were used to inform the magnitude and logistics of where the fuels would be needed. To adequately meet military goals, the U.S. Air Force (USAF) and U.S. Navy (USN) would need to supply roughly 47,500 bpd and 18,800 barrels per day (bpd) of alternative jet fuels by 2016, respectively. The total amount of fuel for both military and civil goals would reach nearly 132,000 bpd within the next decade if tentative goals become actual policy. Quantifications of the emissions affecting surface air quality from CONUS civil, USAF and USN aircraft, as well as 50% and 100% synthetic paraffinic kerosene (SPK) combustion emissions normalized by conventional jet fuels were also provided. Although a 50% blend of SPK has been permitted, additional testing and analysis is needed for approval of higher blend percentages. It was found that NO_X emissions from military aircraft tend be lower while primary $PM_{2.5}$, CO and UHC emissions tend to be higher than their civilian aircraft counterparts. This is indicative of military aircraft being less efficient at lower power settings than civil aircraft during the LTO cycle. Emissions reductions with 50% and 100% SPK use could provide military and civil aviation planners with more options when locating aircraft in nonattainment areas within the CONUS. For some emissions, the introduction of SPK fuels could allow for additional aircraft for the same environmental impact or decreased overall air quality footprint for a particular location. SPK fuels from Fischer-Tropsch Biomass-to-Liquid (BTL) and Hydroprocessed Renewable Jet (HRJ) processes were examined for their ability to meet future alternative fuel and environmental goals. BTL facilities were found to have larger capital costs and HRJ required large land area. Lifecycle analysis (LCA) of greenhouse gas (GHG) emissions for select F-T BTL and HRJ were found to potentially meet or exceed organizational goals in the near term. High yield crops like algae could provide the energy and environmental goals, but additional constraints must be considered, such as water and CO_2 requirements; furthermore, these technologies need to be translated from the lab to commercial production. Additional research is required to provide an in-depth geographic analysis of the CONUS commercial and military demand centers and resource constraints to better understand the challenge in meeting future alternative fuel goals.

I. Introduction

The current interest from the commercial and military aviation sectors in alternative jet fuel stems from multiple factors including high conventional fuel prices, price volatility, lack of energy diversity, global climate impacts, and potential air quality benefits. Civil and military jet aircraft require a near-term fuel replacement to conventional petroleum based jet fuel that is a “drop-in” hydrocarbon substitute that functions with the existing aircraft infrastructure while meeting rigorous safety and quality standards. Such drop-in alternative jet fuel pathways

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Table 1: U.S. alternative fuel and GHG goals

Arena	Entity	Date	Alternative Fuel Use	Life Cycle GHG
Civil	ATA	Tentative	---	Encourage fuel providers to provide a fuel that will have lower GHG than conventional jet fuel[1]
	FAA	Tentative	1 billion gallons per year (65,200 bpd) by 2018[2]	---
	EPA*	2007	36 billion gallons per year (2.3 million bpd) of ground and air transportation fuels by 2022[3]	Reductions from 2005: corn ethanol (20%), advanced biofuel (50%), Biomass-based diesel (50%), Cellulosic biofuel (60%)[3]
Military	USAF	2010	50% of USAF domestic aviation via alternative fuel blend; cost competitive acquisition from domestic sources by 2016[4]	Alternative fuels produced in a manner that is "greener" than fuels produced from conventional petroleum[3]
	USN	2010	By 2020, half of the Navy's total energy consumption afloat will come from alternative sources [5]	

*EPA provides GHG thresholds for both aviation and traditional ground transportation alternative fuel feedstocks based on the Renewable Fuel Standard (RFS2) as a part of the Energy Independence and Security Act (EISA) of 2007.

can be broken into five broad categories: jet fuel from unconventional sources of petroleum such as oil sands, very heavy oils, and oil shale; synthetic jet fuel from thermochemical processes involving natural gas, coal, and/or lignocellulosic biomass such as Fischer-Tropsch (F-T) synthesis and pyrolysis; advanced fermentation, catalytic, and other means of converting sugars to jet fuel; hydroprocessing of conventional oils to synthetic jet fuel; and conversion of calorific liquids from micro-organisms to synthetic jet fuel.[6] Through both ground and flight tests, the USAF has already approved a 50% blend of F-T fuels with conventional jet fuels and the certification of a 50% blend of hydroprocessed renewable oils with conventional jet fuel should be complete in the near future.[7]

Commercial and military aviation have set ambitious alternative fuel and environmental targets for the next half century. The International Air Transport Association has set a goal of 10% alternative fuel use by 2017, carbon neutral growth in 2020, and a 50% decrease in aviation CO_2 emissions by 2050, relative to 2005 levels.[8] Table 1 provides a summary of U.S. civil and military goals and regulations regarding both alternative fuel production and lifecycle GHG emissions.[1-5] Each entity in Table 1 holds an interest in both alternative fuels as an energy source and as a potential means of reducing the environmental impacts of aviation. One aim of this work is to assess the extent that current alternative fuel technology can meet these energy and environmental goals.

Conventional jet fuel is composed mostly of n-, iso-, and cyclo- paraffins with up to a quarter of the fuel consisting of aromatics and naphthalenes. Small amounts (~700 ppm) of sulfur are also present in conventional jet fuels.[6,9] Synthetic paraffinic kerosene (SPK) fuels lack aromatics and sulfur that, as will be discussed in this paper, lead to a decrease in surface air quality emissions. These emissions are loosely defined as particles under 3,000 feet that are associated with direct or indirect impacts on plant life and human health through acid rain, ozone, and other forms of air pollution. There are two types of standards surrounding air quality: those directed at engine emissions and those aimed at regional ambient pollutant concentrations. Engine emissions of smoke, unburned hydrocarbons, carbon monoxide and nitrogen oxides from the commercial fleet must meet the internationally agreed upon ICAO Annex 16 Volume II standards.[10] Regional ambient air pollutant concentrations in the United States must meet the EPA National Ambient Air Quality Standards (NAAQS) standards, which are defined in the Appendix in Table A-1, as set forth under the Clean Air Act of 1990.[11] Both civil and military airports within the United States must comply with NAAQS, and regions that do not meet the NAAQS are said to be in nonattainment. Although the United States military does not have specific engine standards, they must complete an Environmental Impact Statement (EIS) whenever new aircraft are deployed and the EIS includes an evaluation of ambient air quality impacts.

This paper focuses on SPK fuels derived from F-T synthesis and hydroprocessing of renewable oils to make Hydroprocessed Renewable Jet (HRJ) fuel. Other pathways will be discussed in future publications by the research team. The F-T process involves steam reforming or gasification of carbonaceous feedstocks such as natural gas, coal, or biomass to synthesis gas (syngas) consisting of hydrogen and carbon monoxide. Prior to gasification, biomass would need to be pre-treated and this analysis assumes that torrefaction was used. An iron or cobalt catalyst converts the syngas into paraffinic hydrocarbons through F-T synthesis. The resulting hydrocarbon waxes are then hydroprocessed to produce jet, diesel, and naphtha fuels. This paper considers a F-T biomass-to-liquid (BTL) pathway that uses switchgrass as the fuel feedstock. HRJ fuels are processed via treatment with hydrogen gas to deoxygenate oils from various triglyceride feedstocks including animal fats and oils such as those from soybeans, palm, rapeseed, algae, jatropha, salicornia, and camelina. The deoxygenated oils are then hydroprocessed in a similar manner as F-T fuels to create hydrocarbons that have a distillation range similar to conventional jet fuel.[12]

The major objective of this study is to compare to what extent SPK produced from these two feedstocks and processes could meet civil and military energy and environmental goals. This paper is comprised of the following sections: estimating the CONUS conventional fuel energy usage for the civil and military aviation fleets to compare with alternative fuel goals, quantifying the emissions affecting surface air quality from civil, USAF and USN fleets, using 50% and 100% SPK combustion emissions normalized by conventional jet fuels, and examining the capital cost and land requirements needed to meet the civil and military alternative fuel goals with F-T BTL and HRJ fuels.

II. Energy Usage & Alternative Fuel Goals

In order to assess the extent to which alternative fuel pathways could reach the aforementioned goals for civil and military aviation, one must first assess the energy demand for jet fuel. For the purposes of this investigation, the generic term “jet fuel” could refer to JP-5, JP-8, or Jet A. Fig. 1 and Table 2 provide the relative distributions in barrels per day (bpd) for CONUS jet fuel purchases in 2010 for various institutions and fuel types. Fig. 1 also provides USAF energy utilization and civil fuel use by aircraft type from the 2010 USAF energy plan and 2009 BTS database, respectively. As expected, the civil sector dominates the market with Jet A. It is interesting to note the large amount of energy and fuel used by specific aircraft types for both the USAF and civil markets. For example, aviation mobility and single aisle aircraft use nearly half the total fuel for USAF and civil markets, respectively. This figure shows that the majority of the operational energy utilization (52%) is being used by a relatively low number of aircraft representing the Air Mobility Command (AMC) fleet. This is captured by the large fuel usage in Fig. 1 as compared to the relatively small number of AMC aircraft as conveyed in the Appendix in Fig. A-1, which illustrates the number and year of initial operation capability (IOC) for the USAF inventory.[13] The other command considered in Fig. A-1 is the Air Combat Command (ACC), which consists of fighter/bomber military aircraft.

Table 2 also provides the various fuel usage goals for both civil and military aviation. *To adequately meet the previously mentioned goal applied to the 2010 CONUS data below, the USAF and USN would need to supply roughly 47,500 bpd and 18,800 bpd of alternative jet fuels by 2016* (although this number will fluctuate based on a future demand in 2016). These fuel values are 73% and 29% of the tentative FAA goal of 1 billion gallons of alternative jet fuels for the commercial fleet by 2018. *If the FAA goal of 65,200 bpd of alternative jet fuel becomes official policy, then the combined alternative jet fuel goal would be at least 132,000 bpd by the end of this decade.*

To understand where this fuel would be used, Fig. 2 provides a spatial mapping of the CONUS active and reserve USAF, Air National Guard (ANG), and USN fuel sales between April 2010 and March 2011 and CONUS civil fuel usage in 2008, as reported by ATA.[14] It must be noted that the USAF and USN data are *fuel sales* that might be transported to locations other than those specified by DLA. The majority of the fuel sold is to ANG as an aggregation of many locations, however, Plant 42 and Vance AFB represent the two largest fuel sales areas. Plant 42 is an Air Force Material Command (AFMC) aerospace facility in Palmdale, California that tests the majority of classified USAF aircraft. Vance AFB is located near Enid, Oklahoma and operates as one of the USAF flight training bases under Air Education and Training Command (AETC). Nearly a quarter of the USN fuel purchased is located in the Naval Support Activity Panama City (NSA PC) in Florida. This location is one of the major research and development locations for the USN. Lastly, the majority of civilian fuel use in 2008 was at Los Angeles (LAX), Atlanta (ATL), John F. Kennedy (JFK), Chicago O’Hare (ORD), and San Francisco (SFO) international airports. The top ten largest commercial airports in the United States accounted for over half of the total fuel use. The civil fuel use at any large airport is on average an order of magnitude more than the military fuel airbase purchases for a similar timeframe. In future work by the authors, meta-analyses will be conducted to assess alternative supply scenarios and logistical concerns to both military and civilian demand centers.

Table 2: Military 2010 and civil 2009 CONUS jet fuel use

	Fuel Use (bpd)					
	Jet-A	JP-8	JP-5	Other	Total	Alternative Fuel Goal
Civil	1,160,000	-	-	-	1,160,000	65,200
USAF	-	91,600	-	3,460	95,100	47,500
Navy	316	11,800	25,000	-	37,500	18,800
Army	-	52,400	-	938	53,300	---
Total	1,160,000	156,000	25,000	4,700	1,350,000	132,000

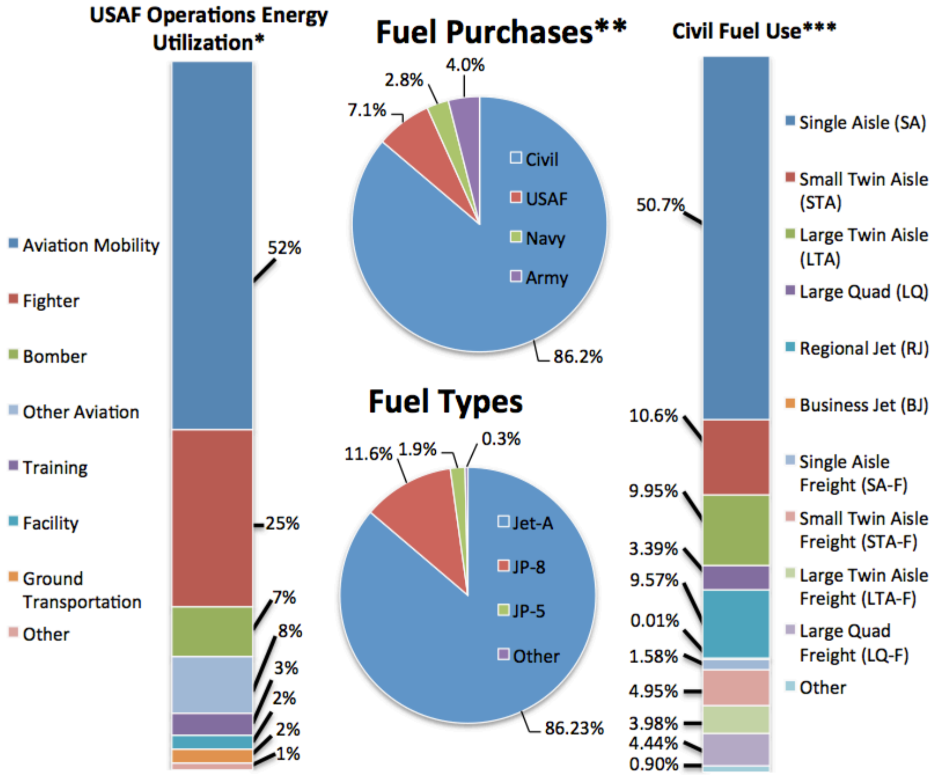

Fig. 1: 2010 CONUS military and commercial jet fuel energy use, purchases, and fuel types

*Operations energy utilization from the Air Force Energy Plan 2010[4]

**Military jet fuel purchases/types from the Defense Logistics Agency (DLA) continental United States (CONUS) sales April 2010 through March 2011[**]; civil jet fuel use/type from Bureau of Transportation Statistics (BTS) Form 41 and 298C, T2: U.S. Air Carrier Traffic and Capacity Statistics by Aircraft Type for 2009[15]

***Civil jet fuel use percentages from Bureau of Transportation Statistics (BTS) Form 41 and 298C, T2: U.S. Air Carrier Traffic and Capacity Statistics by Aircraft Type for 2009; aircraft categories assigned to BTS data using FAA Aviation Environmental Design Tool (AEDT) conventions based on aircraft size and mission

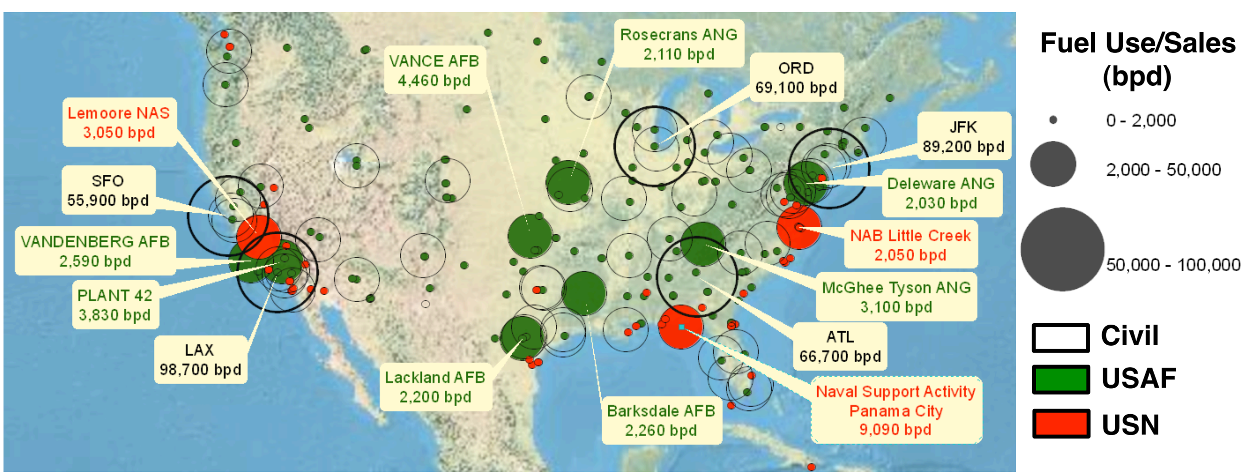

Fig. 2: CONUS fuel use of jet fuel by the USAF, US Navy, and civilian airports. The military data span the time period between April 2010 and March 2011 while the commercial data is for 2008. All data are in barrels per day (bpd). Note that AFB denotes Air Force Base, ANG denotes Air National Guard, NAS denotes Naval Air Station, NAB denotes Naval Amphibious Base, and airport codes denote civilian airports (e.g., SFO denotes San Francisco International Airport). The top eight USAF, three USN, and five civil fuel use/sales are labeled.

[**] Baniszewsk D., Personal Communication, Total fuel sales from April 2010 through March 2011, Defense Logistics Agency Database, 2011.

III. Combustion Emissions and Surface Air Quality

A. Emissions Terms and Definitions

As outlined in the introduction, civil and military aviation must both meet regulations on engine emissions and regional ambient air quality. The primary emissions of concern to aviation are nitrogen oxides (NO_X consisting of NO and NO_2), sulfur oxides (SO_X consisting of SO_2 and SO_3), and particulate matter.[16] Particulate matter are regulated in the NAAQS by average particle; the notation PM_{10} and $PM_{2.5}$ are used to describe particles with diameters of 10 and 2.5 micrometers or less, respectively. It is important to note the difference between primary and secondary particulate matter as the NAAQS regulate the combination of primary particular matter from sources such as aircraft engines as well as secondary particulate matter that forms from the chemical reaction and transport of emissions such as NO_X and SO_X in the atmosphere. Primary particulate matter consists of both volatile and nonvolatile (PM_{NV}) components. The later is also known as black carbon or soot emissions. An additional class of species of interest is volatile organic compounds (VOCs) that consist of unburned hydrocarbons (UHCs) and various aldehydes. Emissions affecting surface air quality are usually assessed over a standard landing-takeoff (LTO) cycle with an assumed combination of power settings and times in mode, as seen in Table 3. Although there have been studies showing variation of current fleet operations and the ICAO assumptions,[17] this investigation will use Table 3 for consistency with the current regulatory framework.

Table 3: ICAO LTO modes, power settings and times in mode[17]

ICAO Stage	Power Setting (%)	Time in Mode (min)	Time Weighting (%)
Takeoff	100	0.7	2.1
Climb Out	85	2.2	6.7
Approach	30	4.0	12.2
Taxi/Idle	7	26	79.0

B. USAF Landing and Takeoff (LTO) Emissions

1. Methodology

USAF LTO emissions from JP-8 use were computed using emissions rates for various aircraft/engine combinations from the Air Conformity Applicability Model (ACAM) database, which is maintained by the Air Force Center for Engineering and the Environment.[18] The model consists of multiple databases that sum mass based emissions species E_m (NO_X, CO, VOC, Primary PM_{10}, Primary $PM_{2.5}$, SO_X) from ground support equipment and aircraft to provide analyses for EIS scenarios. The USAF aircraft emissions tests were conducted on static stands at various facilities.[19] Primary PM_{10} and $PM_{2.5}$ emissions were tested using the EPA methods 5 and 202 that account for PM_{NV}, organic, and inorganic condensable particulate matter (CPM).[20] LTO emissions were calculated from Equation 1 using tested emissions rates $\dot{m}$ (lb_m/s) for each species, LTO time in mode t_i, and a given number of engines n_{eng}. Aircraft with multiple engine types were accounted for in this analysis.

$$E_m = \sum_{i=1}^{4} \dot{m}_i t_i n_{eng} \tag{1}$$

2. Air Mobility Command and Air Combat Command LTO Emissions

Table A-2 and Table A-3 present the ACAM baseline AMC and ACC aircraft, IOC, engine, and emissions per LTO cycle assuming ICAO times in mode for each aircraft from Table 3. For ACC fighter and bomber aircraft with afterburner, the takeoff mode included afterburner emissions rates that far exceed traditional takeoff emissions rates. The C-5A/B/C and VC-25 aircraft produce the most emissions per LTO cycle in the AMC fleet while the B-1B creates the most primary particulate matter emissions in the ACC fleet. Fig. 3 and Fig. A-2 portray the AMC and ACC emissions compared to one another and compared to average civil fleet LTO emissions, which are further analyzed in the US Civil LTO section below.

C. Civil LTO Emissions

1. Methodology

Commercial LTO emissions were estimated using a combination of the ICAO emissions databank for major engines in the civil fleet and aircraft types from the aforementioned BTS database for 2009. This type of assignment structure has various problems upon implementation: many of the engines in the ICAO database have different types of combustors, the majority of aircraft in the BTS fleet have multiple engines types, and the number of operations vary for each reported BTS aircraft. To address the first two issues, a range of engines and combustors were used. The minimum, average, and maximum of all assigned combinations of engines and combustors were evaluated for each aircraft and these data represent the bounding bars in Fig. 3. The last concern was dealt with by weighting these emissions averages by the number of operations for each aircraft class. Every BTS aircraft was binned by the aircraft classes from Fig. 1 based on aircraft size and mission type. Additionally, the civil fleet primary $PM_{2.5}$ emissions were estimated from the ICAO databank smoke number, fuel sulfur content, and UHC emissions using the first order approximation method (FOA3) which aggregates approximations of the primary volatile and nonvolatile $PM_{2.5}$ from the engine exit plane.[21]

2. US Civil LTO Emissions

Fig. 3 and Fig. A-2 depict the approximate USAF AMC, ACC and US civil LTO emissions and fuel burn ranges per aircraft and class previously described for NO_X, $PM_{2.5}$, CO, UHC, and fuel burn. When comparing between civil aircraft classes, one notices that both the first and last four categories result in higher LTO emissions. This trend is linked to the aircraft size and weight differences as well as the engine and combustor technologies for each class. For the majority of LTO emissions in Fig. 3, the AMC fleet matches favorably with the civil categories. The larger AMC aircraft (C-5/C-17) LTO emissions and fuel burn are similar to the corresponding LTA and LQ civil classes. However, the ACC fleet NO_X emissions tend be lower while the $PM_{2.5}$, CO and UHC emissions tend to be higher than their civilian counterparts. This is indicative of less efficient aircraft at lower power settings in the LTO cycle. Likewise in Fig. A-2, the majority of particulate matter emissions from the ACC fleet are greater than that of the AMC due to afterburning aircraft upon takeoff. This is especially evident with the larger afterburning four-engine B-1B emissions, which are nearly an order of magnitude larger than the AMC fleet.

D. SPK Emissions Relative to Conventional Jet Fuel

1. Methodology

To understand how SPK fuel use changes air quality emissions, documented NO_X, SO_2, PM_{NV}, CO, and UHC emissions from multiple engine types operating on conventional jet fuel, 50% and 100% SPK fuels were organized and compared at various power settings.[22-29] Table 4 lists the compiled engine combustion tests using fuel blends up to 100% SPK. Although a 50% blend of SPK has been approved, additional testing and analysis is needed for approval of higher blend percentages such as a 100% SPK fuel. Fig. A-3 stratifies the test engines by bypass ratio on an energy normalized fuel flow versus percent thrust chart where blue, red, and green correspond to turboshaft, low bypass turbofan, and high bypass turbofan engines, respectively. The engine types span a wide spectrum of engine technologies for both civil and military fleets. The mass-based emissions indices (EI_m) are in units of grams of pollutant per kilogram of fuel. Each EI was energy normalized by the fuel specific energy using the lower heating value provided in each test document. In cases where raw data were obtained, EI were humidity corrected and temperature normalized between fuel types. Data uncertainties were used in each test to match bounds for upper and lower percent changes between fuels. For example, the lowest SPK emissions were compared to the highest conventional fuel emissions to represent the highest percent reduction for a particular fuel blend. In future analysis of this data, uncertainty bounds will be calculated using a stochastic process assuming a normal distribution range for each test fuel.

Each of the SPK emissions changes could be used to scale the USAF AMC, ACC, and civil aircraft fleets as a means of approximating the emissions if these aircraft were operating on SPK. For many of the aircraft, the test engines do not match the baseline engines. Therefore, a surrogate engine could be chosen based on engine thrust or bypass ratio and type as illustrated in Fig. 4. The next subsections outline the emissions differences for 50% and 100% SPK compared to conventional jet fuels.

2. Compiled SPK LTO Emissions Reductions

The assembled energy normalized SPK emissions changes from conventional jet fuel are quantified in Fig. A-4. The 100% SPK PM_{NV} EI_m experience reductions between 80% and 98% at midrange power settings and between 32% and 92% at higher power settings depending on the engine type. This decreased reduction at higher power settings could be due to a thermal mechanism of PM_{NV} overshadowing the reduction seen from the scarce aromatics in SPK fuels. The 50% SPK PM_{NV} reductions vary between 0%-50%, 31-60%, and 36-96% for low bypass turbofan, turboshaft, and high bypass turbofan engines depending on power setting, respectively. The variation of the reductions based on engine type is statistically significant. Therefore, it appears that at 50% SPK blends, the effect of technology levels on PM_{NV} emissions formation is more apparent than at 100% SPK. UHC and CO reductions are both most pronounced at near idle power settings with values of 13-40%, 4-27%, 5-25%, and 0-40% for UHC 100%

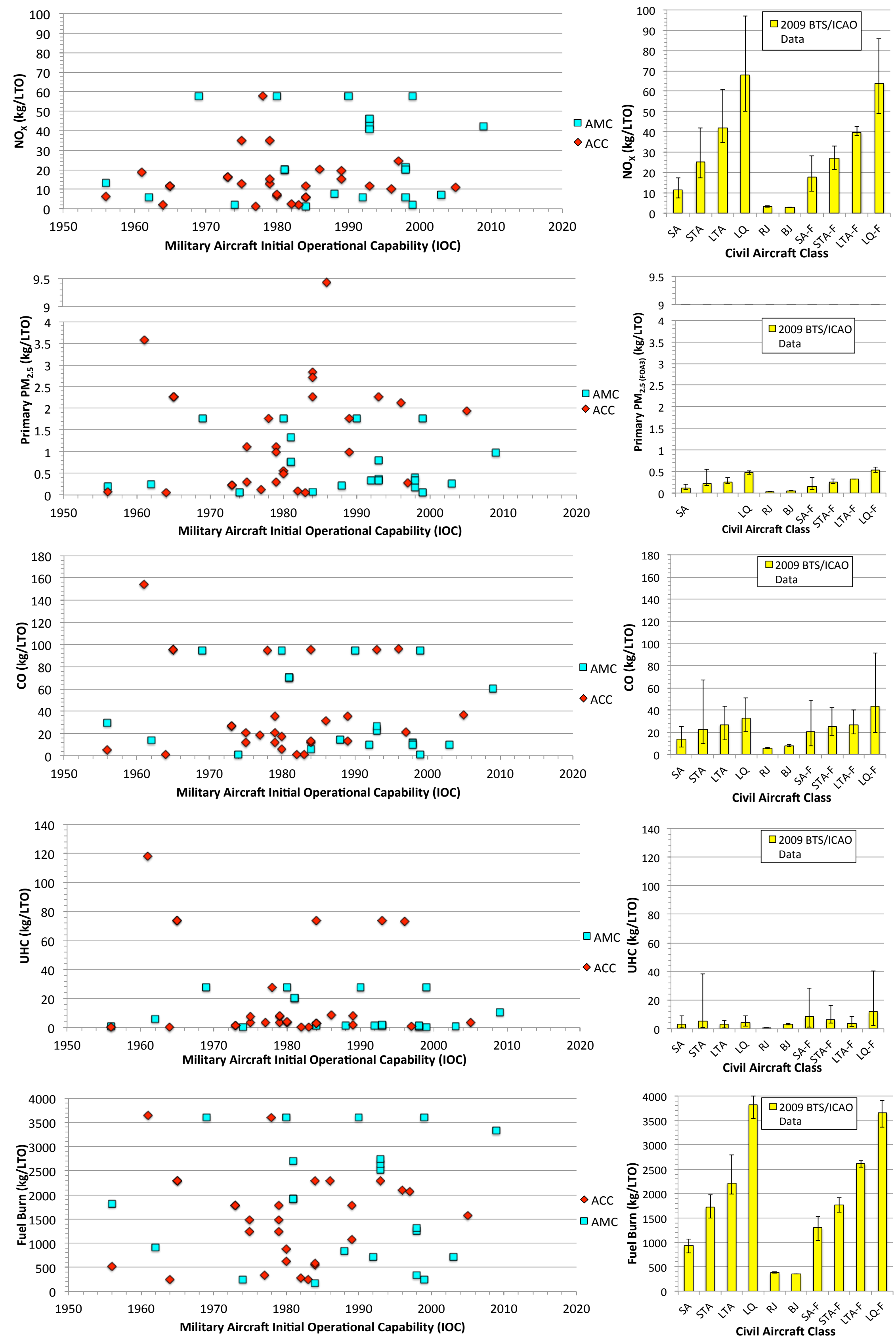

Fig. 3: USAF AMC, ACC, and civil aircraft NOX, Primary PM2.5, CO, and UHC LTO emissions and fuel burn. The error bars in the civil data represent the range of values from the current fleet.

Table 4: Experimental SPK emissions tests

Experiment	Engine	Representative Military Aircraft	Representative Civil Aircraft
Bulzan et al. (2010)[22]	CFM56-2C1	Boeing KC-135R	Douglas DC-8-70
Lobo, Hagen, Whitefield (2011)[23]	CFM56-7B	Boeing C-40	Boeing 737-600 to 900
Corporan and DeWitt (2010)[24]	F117-PW-100 (PW2000 series)	Boeing C-17	Boeing 757
Timko et al. (2008)[25]	PW308	Hawker C-29A	Hawker 4000
Bester and Yates (2009)[26] Corporan et al. (2008)[27]	RR-Allison T63-A-700	Sikorsky S-75	Bell 206, MD 500, MBB Bo 105
Moses, Wilson III, Roets (2003)[28] Coproran et al. (2009)[7]	T700-GE-701 T700-GE-701C	Boeing AH-64, Sikorsky UH60/SH60	Saab 340
Corporan et al. (2007)[29]	TF33 P-103 (JT3D)	B-52H Stratofortress Boeing KC/NKC/RC/OC/RE-135E/U/N/V/X	Boeing 707

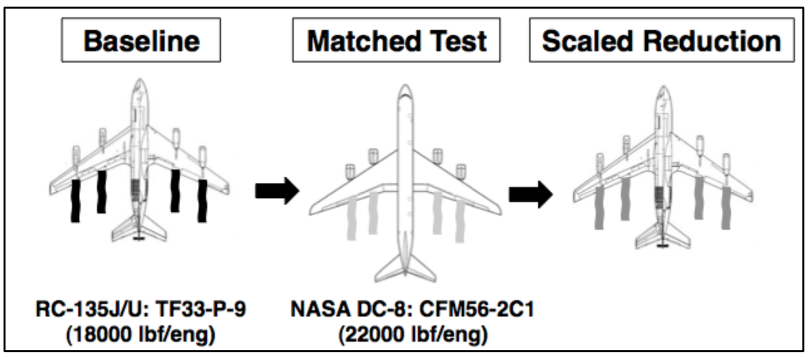

Fig. 4: Military and civil aircraft SPK surrogate engine method to estimate scaled emissions

Table 5: Assumed times and fuel flows for each ICAO mode and engine type considered in Table 6[18]

ICAO Mode	ICAO Time in Mode (min)	Fuel Flow (kg/s)				
		CFM56-2B (CFM56-2C1)	CFM56-7 (CFM56-7B)	F117-PW-100	TFE731-2-2B (PW308)	TF33-P-103
Taxi/Idle	26	1,070	847	1,210	209	986
Approach	4	2,600	2,100	4,360	542	3,880
Climb Out	2.2	6,730	5,740	11,060	1,390	6,320
Takeoff	0.7	8,030	6,840	14,110	1,640	7,510

Table 6: Turbofan 50% and 100% average SPK LTO emissions normalized to conventional jet fuels

		Experiment	Bulzan et al. (2010)	Lobo, Hagen, Whitefield (2011)	Corporan and Dewitt (2010)	Timko et al (2008)	Corporan et al. (2007)
		Test Engine	CFM56-2C1	CFM56-7B	F117-PW-100	PW308	TF33-P-103
NO_X	100% SPK	Taxi/Idle	0.91			1.04	
		Approach	0.92			0.89	
		Climb Out	0.92			0.93	
		Takeoff	0.94			0.93	
		ICAO time wt. avg.	**0.91**			**1.01**	
		ICAO fuel wt. avg.	**0.92**			**0.97**	
PM_{NV}	50% SPK	Taxi/Idle	0.28	0.35		0.78	0.57
		Approach	0.22	0.37		0.51	0.64
		Climb Out	0.18	0.64		0.64	0.61
		Takeoff	0.20	0.60		1.01	0.66
		ICAO time wt. avg.	**0.27**	**0.38**		**0.74**	**0.58**
		ICAO fuel wt. avg.	**0.24**	**0.46**		**0.72**	**0.61**
	100% SPK	Taxi/Idle	0.09	0.33		0.02	
		Approach	0.05	0.11		0.11	
		Climb Out	0.11	0.41		0.42	
		Takeoff	0.13	0.36		0.67	
		ICAO time wt. avg.	**0.09**	**0.31**		**0.07**	
		ICAO fuel wt. avg.	**0.09**	**0.31**		**0.72**	
CO	50% SPK	Taxi/Idle	0.92		0.67	0.79	
		Approach	0.80		0.76	1.00	
		Climb Out	0.82		1.00	1.00	
		Takeoff	1.20		1.00	1.00	
		ICAO time wt. avg.	**0.91**		**0.71**	**0.83**	
		ICAO fuel wt. avg.	**0.90**		**0.82**	**0.90**	
	100% SPK	Taxi/Idle	0.87			0.67	
		Approach	0.77			1.00	
		Climb Out	0.90			1.00	
		Takeoff	1.30			1.00	
		ICAO time wt. avg.	**0.87**			**0.74**	
		ICAO fuel wt. avg.	**0.90**			**0.85**	
UHC	50% SPK	Taxi/Idle	0.86			0.70	
		Approach	0.83			1.00	
		Climb Out	0.89			1.00	
		Takeoff	0.85			1.00	
		ICAO time wt. avg.	**0.86**			**0.76**	
		ICAO fuel wt. avg.	**0.86**			**0.86**	
	100% SPK	Taxi/Idle	0.73			0.60	
		Approach	0.73			1.00	
		Climb Out	0.89			1.00	
		Takeoff	0.85			1.00	
		ICAO time wt. avg.	**0.75**			**0.68**	
		ICAO fuel wt. avg.	**0.78**			**0.82**	

SPK, UHC 50% SPK, CO 100% SPK, and CO 50% SPK, respectively. High uncertainties are present particularly for the change in UHC with 50% SPK use at low power settings. Neat SPK NO_X reductions varied most at lower power settings but were nearly constant at higher power settings with reductions between 2-11%. It is important to note that the reductions are within instrument noise for some of the data and will need further stochastic analysis to understand the uncertainty range. The time and fuel weighted averages from Table 5 were used to calculate the 50% and 100% SPK jet fuel LTO NO_X, PM_{NV}, CO, and UHC emissions in Table 6 with normalization by conventional jet fuel. The normalized emissions do not change significantly between ICAO time or fuel burn weighted averages. These emissions reductions with the use of 50% or 100% SPK could potentially provide military and civil aviation planners with more options in terms of locating aircraft in nonattainment areas within the CONUS. For some emissions, the introduction of SPK fuels could provide for additional aircraft for the same environmental impact or decrease the overall air quality footprint for an existing location.

IV. Life Cycle GHG Emissions and Production Potential of HRJ and F-T Fuels

Lifecycle assessment provides an analysis framework for estimating GHG emissions directly from a product and from the material, energy flows, or services through the supply-chain. Because plants absorb CO_2 from the atmosphere during growth, biofuels (where the fuel feedstock is derived from biomass or plant oils) present an opportunity to reduce the life cycle GHG emissions from aircraft; thus, there is a CO_2 "biomass credit" that is generally equal to the CO_2 emissions from combustion. However, the life cycle GHG emissions for a biofuel can be higher than those of conventional jet fuel depending on the details of how the fuel is produced. The conversion of land for biofuel production represents the largest potential source of emissions for biofuels. As an example, if land use change emissions were avoided, then a hydroprocessed biofuel from palm oil could have emissions of 30 g CO_2e/MJ (34% of conventional jet fuel), but if the land that was being used for palm cultivation had previously been a peatland rain forest, then the life cycle GHG emissions could be 698 g CO_2e/MJ (800% of conventional jet fuel).[30] Table 7 illustrates the life cycle GHG emissions for camelina HRJ and switchgrass F-T BTL in gCO_2e/MJ and normalized to a 2005 baseline for conventional jet fuel (87.5 gCO_2e/MJ). Compared with the goals in Table 1, these two biomass processes have the potential to reduce the life cycle GHG emissions by 60-80% from 2005 conventional jet fuel levels.[12,31,32] In addition to meeting the environmental performance goals, this section considers whether these fuels could meet the military and civil alternative fuel use goals.

While biofuels may have the potential to reduce aviation GHG emissions, there are constraints on biomass production to make these fuels. These constraints could come from economic costs, resource availability in terms of land and water, as well as the potential harm that could result from the introduction of invasive plant species into unprepared ecosystems. Biofuel yields (volume of biofuel per land area per year) were created for a range of biofuel pathways and are presented in Fig. 5. The top and bottom charts provide product slates for maximum distillate and maximum jet fuel, respectively.[33] Although aviation leaders would be drawn towards maximizing the jet fuel fraction of the fuel product slate, there is an additional associated cost. Many fuel feedstocks, such as jatropha and salicornia, have relatively low biofuel production per unit of land. This does not mean that they should not be cultivated for biofuel production; it simply indicates that these feedstocks cannot replace petroleum as a source of jet fuel. For example, camelina, which also has a relatively low yield, could be grown without irrigation in rotation with other crops in the upper plains of the United States and Canada, thus benefiting local farmers; further, the lessons learned in converting camelina oil to biofuels could be valuable if a higher yield crop, such as algae, becomes commercially available. Palm oil is the second highest yielding oil crop considered in Fig. 5. Increasing palm production would likely result in the conversion of high carbon stock land to palm plantations and as discussed previously, increased production could result in considerable GHG emissions from land use changes.

Table 7: Camelina HRJ and switchgrass F-T BTL life cycle GHG emissions by process stage and relative to conventional jet fuel

	Camelina HRJ (gCO_2e/MJ)			Switchgrass F-T BTL (gCO_2e/MJ)*		
	Low	Baseline	High	Low	Baseline	High
Biomass Credit	-70.5	-70.5	-70.5	-193	-223	-239
Recovery of Feedstock	3.6	12.7	10.5	3.8	6.4	11.4
Transportation of Feedstock	1.8	2.2	2.2	0.6	0.6	0.6
Processing of Feedstock	10.3	10.3	10.3	122	152	168
Transportation of Jet Fuel	0.6	0.6	0.6	0.5	0.5	0.5
Combustion CO_2	70.4	70.4	70.4	70.4	70.4	70.4
WTT N_2O	2.9	7.4	10.8	7.2	10.3	13.3
WTT CH_4	0.8	1.1	1.0	0.1	0.2	0.5
Total	**19.9**	**34.1**	**35.3**	**12.0**	**17.8**	**26.1**
Relative to Jet	**0.23**	**0.39**	**0.40**	**0.14**	**0.20**	**0.30**

*Scenario does not include carbon soil sequestration

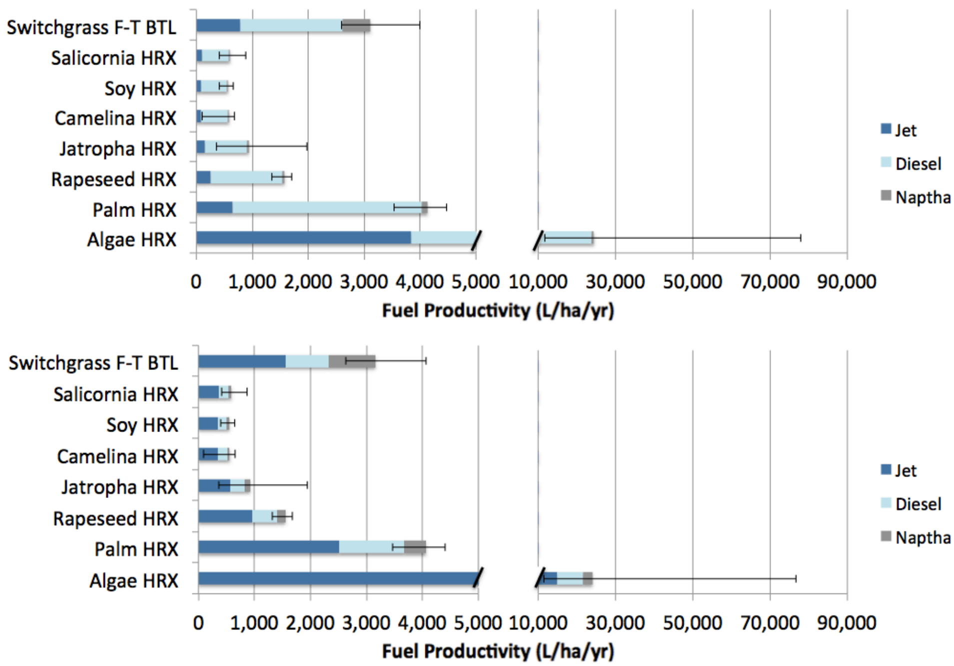

Fig. 5: Fuel production potential for various alternative jet fuels that could be derived from biomass: maximum distillate product slate (top) and maximum jet fuel product slate (bottom)[30]

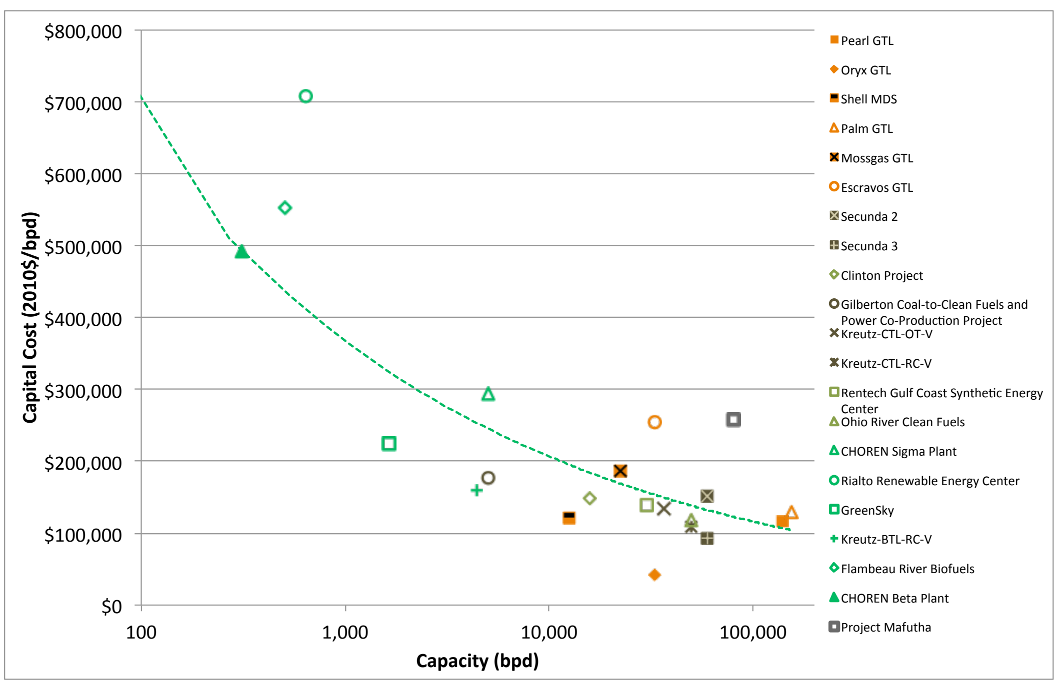

Fig. 6: Fischer-Tropsch facility capital cost as a function of capacity for proposed, cancelled and constructed Fischer-Tropsch facilities. Solid markers denote facilities that have been built while open represents proposed, cancelled, or original estimates for facilities. The dashed line is a curve fit to the CHOREN Beta BTL facility. Details for each facility are available in Table A-4.

Coal and biomass could be converted to jet fuel via F-T synthesis with carbon capture and sequestration (CCS), denoted as CBTL, with a 25% reduction in GHG emissions and considerable production of a reduced GHG diesel fuel (the volume of diesel fuel is roughly twice the volume of jet fuel produced). It is conceivable that natural gas could also be used instead of coal to make a GBTL fuel. Many biomass feedstocks could be used, such as agricultural residues like corn stover, forestry waste, or dedicated energy crops like grasses or salicornia; however, these feedstocks could also be used for generation of heat and power where their use may lead to greater carbon mitigation. The CO_2 emissions could also be fed to algae for fuel production. Furthermore, the capital costs of F-T facilities would be large and CCS has not been demonstrated on the scale that would be needed to support a large F-T industry.

A literature review of the capital costs of F-T facilities worldwide, including completed, proposed and cancelled projects, reveals the large capital costs involved with this technology as seen in Fig. 6. Because the first F-T commercial facilities were developed several decades ago, all capital costs were adjusted to 2010 dollars using the Nelson-Farrar Refinery Index.[34] In conjunction with the reported refinery size, the capital costs were normalized to a cost per barrel of daily capacity ($/bpd). Prior to F-T synthesis, GTL facilities often produce Natural Gas Liquids (NGL) directly from the natural gas feedstock. To determine the capital costs of F-T fuels, total GTL project costs were adjusted where needed using a reference NGL facility.

Due to logistical constraints of transporting biomass to a facility, the capacity limit of a BTL facility is on the order of 5,000 bpd. However, GTL facilities can be much larger as natural gas can be piped from the well to the F-T facility; as such, a facility size of 100,000 bpd is feasible. As facility size increases, costs per barrel come down due to economies of scale. Because of this, a 5,000 bpd BTL facility would likely cost on the order of $250,000 per bpd of capacity while a 100,000 bpd GTL facility could be on the order of $100,000 per bpd of capacity. For comparison, a 4,000 bpd hydroprocessing facility would cost roughly $23,000 per barrel per day of capacity.[35]

The quantities of CO_2 that would need to be transported if F-T synthesis is used with fossil resources coal could be large. As an example, Stratton et al. (2010) estimated that a CTL facility could have life cycle GHG emissions that are 1.11 times their 2005 conventional petroleum baseline. However, to achieve that level of GHG emissions, 3.7 barrels of supercritical CO_2 would need to be sequestered for every barrel of total CTL fuel produced. Similarly, GTL could have emissions comparable to the 2005 conventional petroleum baseline, but 0.6 barrels of supercritical CO_2 would need to be sequestered for every barrel of total GTL fuel produced. This CO_2 would need to either be used for Enhanced Oil Recovery (EOR) or sequestered geologically. EOR is a means of enhancing oil recovery from partially depleted oil reservoirs using CO_2 flooding. Assuming the logistics of transporting the CO_2 were overcome, the current EOR capacity of 30 to 40 million tons per annum of CO_2 would be saturated with three CTL facilities each having 75,000 barrels per day of capacity, or with 13 GTL facilities, each having 100,000 barrels per day of capacity.[36,37] If a larger F-T industry were desired, or if other sectors such as electricity were to use CCS to reduce their GHG footprint, then geological sequestration would have to be used.

Unconventional fossil-to-jet fuel pathways have large production potential, but they have comparable or higher emissions than conventional jet fuel; therefore, their use will not reduce GHG emissions. BTL fuels have low GHG emissions, but they also have limited fuel production potential due to the large capital costs for F-T production facilities. With the use of excess rapeseed, palm or soy (available after food needs are met) for Hydroprocessed Renewable Jet (HRJ) production, rapeseed to HRJ, soy to HRJ and palm to HRJ have low life cycle GHG emissions; however, there is little excess available and new cropland is required for additional production. Current global production of soy, palm and rapeseed oil translate to only 34%, 43% and 18% of US jet fuel demand, respectively.[38]

Table 8: Capital, land area, and fuel production required to meet 132,000 bpd of jet fuel via camelina HRJ and switchgrass F-T BTL

Fuel Product Slate	Process	Plants	Capital Investment (Billion $)	Land Area (Million ha)	Fuel Production (bpd) Jet	Diesel	Naphtha/ LPG	Total
Maximum Distillate	Camelina HRX	214	19.7	85.7	132,000	704,000	19,300	856,000
	Switchgrass BTL	106	133	9.9	133,000	311,000	85,900	530,000
Maximum Jet Fuel	Camelina HRX	54	5.0	22.4	134,000	63,100	19,100	216,000
	Switchgrass BTL	54	67.5	5.0	133,000	65,000	71,800	270,000

As such, expanded production of soy oil and palm oil for large-scale HRJ production could result in significant GHG emissions from land use change. Because of its low yield, jatropha is likely limited to small regional applications making it inappropriate to replace considerable quantities of conventional jet fuel. Hence, BTL fuels as well as HRJ fuels from soy, palm, and jatropha have limited potential for reducing GHG emissions. The production potential of F-T is largely dependent on the type of biomass being used, as there is much difference in the yields of crop residues such as corn stover and dedicated energy crops like switchgrass. Salicornia holds promise if it is used to make both HRJ and BTL (or CBTL) fuels as it could reduce life cycle GHG emissions by 25% compared to conventional jet fuel and has a production potential equivalent to one third of palm.

Of the options available to aviation, HRJ fuels from algae, cyanobacteria, or other microorganisms present an ideal combination of potentially low GHG emissions and high fuel yield per acre. There is a wide variety of oil producing microorganisms, and the oils they produce vary in chemical composition. The ideal situation for jet fuel production would be to cultivate an algal strain that produces an oil of carbon length similar to jet fuel (alkyl length with 12 carbons). As shown in Fig. 5, the use of algae fuels could lead to the largest yields. However, it remains to be seen if this is commercially possible. Algae are different from other oils, (e.g., palm, soybeans, camelina), in that they are fed CO_2 from an outside source, such as a power plant, instead of relying on the atmosphere. This enables the algae to achieve higher growth rates. Since algae need to be fed CO_2 from an outside source, the total amount of CO_2 available to produce algae is a production constraint. Work is ongoing by the research team to understand this constraint on algae production.

To meet the previously mentioned future alternative jet fuel goal of 132,000 bpd within the next decade, a considerable amount of investment and/or land area would be needed depending on the feedstock and process. Table 8 presents an estimate of the number of facilities, capital investment, and land area required to meet 132,000 bpd of alternative jet fuel production with two different fuel product slates. The capital investment estimates assume current 4,000 and 5,000 bpd facilities each costing \$23,000 and \$250,000 per bpd in 2010 for generic F-T and HRJ plants, respectively. Using the average maximum distillate and jet product slates for camelina HRX (X denoting diesel fuel, jet fuel or naphtha) and switchgrass BTL, one can estimate the amount of land required for each of the facilities. Although the HRX facilities have an order of magnitude less capital investment, the amount of land required to supply those facilities in camelina would need to cover between 22 and 86 million hectares depending on the fuel product slate. For comparison, in 2007 the U.S. northern plain states, which are a candidate location for camelina growth, had 34 million hectares of crop and pasture land being used for agricultural purposes.[39,††] As techniques improve and technologies develop, one may see decreases in facility number and capital investment, however, the land area requirements will hold as they are largely based on plant yield and oil content.

V. Conclusions

This paper analyzed the energy and environmental feasibility of some current alternative jet fuel technologies when compared to various organizational goals. Estimations of the CONUS conventional fuel energy usage for the civil and military aviation fleets were compared with alternative fuel goals. Quantifications of the air quality emissions from CONUS civil, USAF and USN fleets, as well as 50% and 100% SPK combustion emissions normalized by conventional jet fuels were also provided. Lastly, approximate F-T BTL and HRJ lifecycle GHG emissions and production metrics were compared to conventional jet fuels and alternative fuel goals. The following general conclusions were presented:

1. *To adequately meet the previously mentioned goal applied to the 2010 CONUS data below, the USAF and USN would need to supply roughly 47,500 bpd and 18,800 bpd of alternative jet fuels by 2016*
2. *Military aircraft NO_X emissions tend be lower while the CO and UHC emissions tend to be higher than their civilian counterparts. This is indicative of military aircraft tending to be less efficient at lower power settings in the LTO cycle when compared to their civil counterparts.*
3. *Emissions reductions with 50% and 100% SPK (assuming 100% SPK fuel use were to be approved) could provide military and civil aviation planners with more options when locating aircraft in nonattainment areas within the CONUS. For some emissions, the introduction of SPK fuels could provide for additional aircraft for the same environmental impact or decrease the overall air quality footprint for a particular location.*
4. *Alternative fuels from other fossil feedstocks (GTL and CTL) have higher production capabilities that those from bio-feedstocks at the cost of equal or greater GHG emissions to conventional petroleum based jet fuel.*

[††] The northern plain states were defined as Colorado, Idaho, Montana, North Dakota, South Dakota, and Wyoming.

5. *Switchgrass F-T BTL and camelina HRJ have the potential to reduce life cycle GHG emissions by 60-80%. However, these processes also have requirements of large capital costs and land area using current production technologies. F-T facilities tend to be more limited by capitol availability while HRJ facilities tend to be more limited by land requirements.*
6. *The potential for high yields from certain forms of algae or other fuel pathways like oil-excreting organisms make them interesting candidates to meet future energy and environmental goals; however, additional constraints need to be considered due to water and CO_2 requirements. Furthermore, these technologies need to be proven as being commercially viable.*

If aviation is to meet the alternative fuel use goals that have been set for this decade, tradeoffs among energy yield per land area, the environment, and overall cost need to be considered. The identification of a beneficial alternative fuel mix requires higher fidelity spatial analyses to address climate, resource, and logistical concerns. As a result, this work forms a step toward understanding how these goals will be met. The next phase will be an in-depth geographic analysis of the demand centers in CONUS and resource availability such that we better understand the potential of alternative jet fuels to meet future aviation energy and environmental goals.

Appendix

Table A-1: National Ambient Air Quality Standards[11]

Pollutant	Primary Standards	
	Level	Averaging Time
Carbon Monoxide (CO)	9 ppm (10 mg/m^3)	8- hour
	35 ppm (40 mg/m^3)	1-hour
Lead	0.15 µg/m^3	Rolling 3-Month average
Nitrogen Dioxide (NO_2)	53 ppb	Annual (Arithmetic Average)
	100 ppb	1-hour
Particulate Matter (PM_{10})	150 µg/m^3	24-hour
Particulate Matter ($PM_{2.5}$)	15.0 µg/m^3	Annual (Arithmetic Average)
	35 µg/m^3	24-hour
Ozone (O_3)	0.075 ppm (2008 std)	8-hour
	0.08 ppm	8-hour
	0.12 ppm	1-hour
Sulfur Dioxide (SO_2)	0.03 ppm	Annual (Arithmetic Average)
	0.14 ppm	24-hour
	75 ppb	1-hour

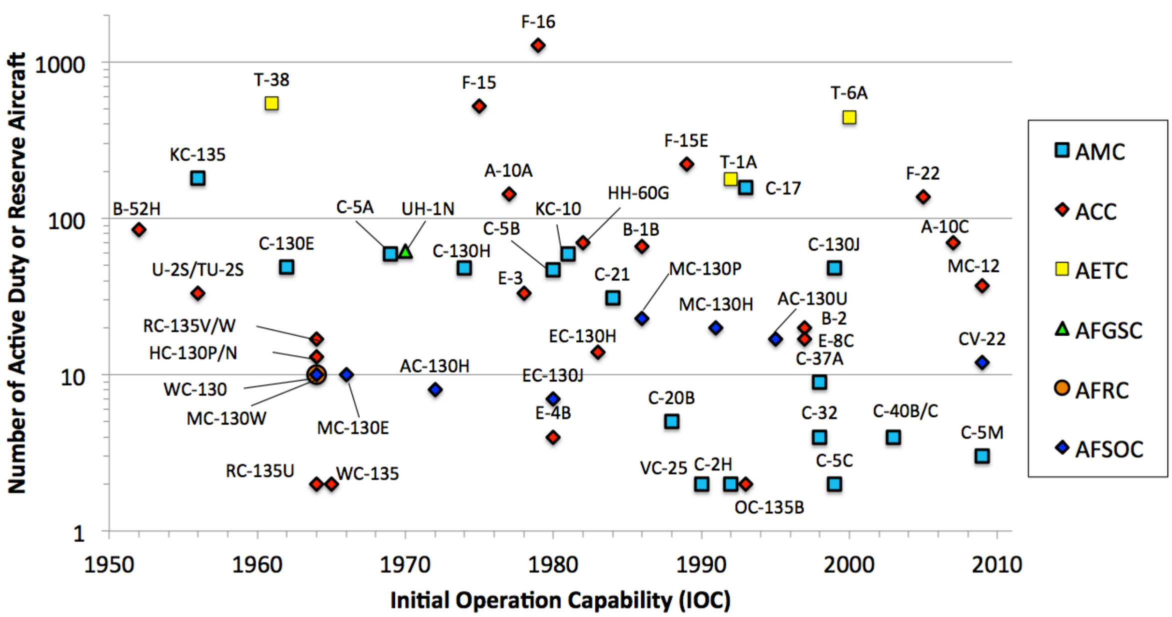

Fig. A-1: USAF 2010 inventory for the Air Mobility Command (AMC), Air Combat Command (ACC), Air Education and Training Command (AETC), Air Force Global Strike Command (AFGSC), Air Force Reserve Command (AFRC), and Air Force Special Operations Command (AFSOC)[13]

Table A-2: AMC aircraft, engines, and JP-8 LTO emissions[18]

			Emissions (kg/LTO)					
Aircraft	IOC*	Engine	NO_X	CO	VOC	PM_{10}	$PM_{2.5}$	SO_X
C-130E	1962	T56-A-7B	5.74	13.9	6.8	0.275	0.249	1.19
C-130H	1974	T56-A-15	2.15	1.26	0.503	0.0606	0.054	0.33
C-130J	1999	RRAllison AE2100D (T56-A-15)	2.15	1.26	0.503	0.0606	0.054	0.33
C-17 (F17-PW-100)	1993	F117-PW-100	42.9	23.8	2.22	0.403	0.365	3.27
C-17 (PW2040)	1993	PW2040	40.8	22.8	1.77	0.884	0.799	3.44
C-17 (PW2041)	1993	PW2041	46.2	26.6	2.43	0.367	0.34	3.57
C-20B	1983	Spey Mk511	7.6	14.3	1.57	0.238	0.214	1.09
C-20H	1983	Spey Mk611	5.76	9.69	1.43	0.373	0.336	0.94
C-21A	1984	TFE731-2-2B	1.29	6.07	1.65	0.0824	0.0741	0.232
C-32A (F117-PW-100)	1998	F117-PW-100	21.4	11.9	1.11	0.202	0.183	1.64
C-32A (PW2040)	1998	PW2040	20.4	11.4	0.886	0.442	0.399	1.72
C-37A	1998	BMW-RR BR710A1-10 (Spey Mk 611)	5.76	9.69	1.43	0.373	0.336	0.94
C-40B/C	2003	CFM56-7	7.13	9.99	1.14	0.286	0.26	0.94
C-5A	1969	TF39-GE-1C (CF6-5DC2)	58	94.5	31.9	1.96	1.77	4.68
C-5B	1980	TF39-GE-1C (CF6-5DC2)	58	94.5	31.9	1.96	1.77	4.68
C-5C	1999	TF39-GE-1C (CF6-5DC2)	58	94.5	31.9	1.96	1.77	4.68
C-5M	2009	CF6-80C281	42.4	60.2	12.3	1.07	0.965	4.34
KC-10 (CF6-50C2)	1981	CF6-50C2	20.3	70.9	23.9	1.47	1.33	3.51
KC-10 (F103-GE-100)	1981	F103-GE-100	20.3	70.5	23.7	0.855	0.772	2.49
KC-10 (F103-GE-101)	1981	F103-GE-101	20.3	70.5	23.7	0.855	0.772	2.49
KC-135R	1956	F108-CF-100	13.3	29.3	0.892	0.22	0.202	2.36
VC-25	1990	CF6-50C2	58	94.5	31.9	1.96	1.77	4.68

*Initial Operational Capability

Table A-3: ACC aircraft, engine, and JP-8 LTO emissions[18]

			Emissions (kg/LTO)					
Aircraft	IOC	Engine	NO_X	CO	VOC	PM_{10}	$PM_{2.5}$	SO_X
A-10A/B	1977	TF34-GE-100A	1.08	18.4	3.82	0.147	0.132	0.438
B-2	1997	F118-GE-100	24.6	21.3	0.917	0.307	0.277	2.7
B-1B	1986	F101-GE-102	20.4	31.8	9.89	10.5	9.43	2.98
B-52H	1961	TF33-P-103	18.6	154	137	3.97	3.58	4.74
E-3B/C	1984	JT3D-3B	11.8	95.4	85.4	2.51	2.26	2.97
E-4B	1978	CF6-50E2	58	94.5	31.9	1.96	1.77	4.68
E-8C	1996	TF3-102C	10.1	96.1	84.8	2.36	2.13	2.73
EC-130H	1983	T56-A-15	2.15	1.26	0.503	0.0606	0.054	0.33
F-15A/B (F100-PW-100)	1975	F100-PW-100	34.8	20.5	4.02	0.338	0.306	1.92
F-15A/B (F100-PW-200)	1975	F100-PW-200	12.9	12.2	8.52	1.23	1.1	1.62
F-15C/D (F100-PW-100)	1979	F100-PW-100	34.8	20.5	4.02	0.338	0.306	1.92
F-15C/D (F100-PW-200)	1979	F100-PW-200	12.9	12.2	8.52	1.23	1.1	1.62
F-15C/D (F100-PW-220)	1979	F100-PW-220	15.1	35.2	9.6	1.11	0.991	2.31
F-15E (F100-PW-220)	1989	F100-PW-220	15.1	35.2	9.6	1.11	0.991	2.31
F-15E (F100-PW-229)	1989	F100-PW-229	19.4	13.6	2.04	1.97	1.77	1.4
F-16A/B (F100-PW-200)	1980	F100-PW-200	6.44	6.08	4.26	0.615	0.551	0.809
F-16A/B (F100-PW-220)	1980	F100-PW-220	7.54	17.6	4.8	0.553	0.496	1.16
F-16C/D (F110-GE-100)	1984	F110-GE-100	5.74	11.6	3.44	3.14	2.83	0.717
F-16C/D (F110-GE-129)	1984	F110-GE-129	5.91	13.5	3.38	3.01	2.71	0.763
F-22A	2005	F119-PW-100	10.8	36.7	3.82	2.15	1.94	2.05
HC-130H/P/N	1964	T56-A-15	2.15	1.26	0.503	0.0606	0.054	0.33
HH-60G	1982	T700-GE-700	2.22	1.37	0.376	0.108	0.097	0.361
OC-135B	1993	TF33-P-5	11.8	95.4	85.4	2.51	2.26	2.97
RC-135V/W	1973	CFM56-2B	16.1	26.6	1.4	0.242	0.225	2.31
RC-135U	1973	CFM56-2B	16.1	26.6	1.4	0.242	0.225	2.31
U-2S/TU-2S	1956	F118-GE-101	6.15	5.32	0.229	0.0769	0.0693	0.674
WC-135C	1965	TF33-P-9	11.8	95.4	85.4	2.51	2.26	2.97
WC-135W	1965	TF33-P-5	11.8	95.4	85.4	2.51	2.26	2.97

*Initial Operational Capability

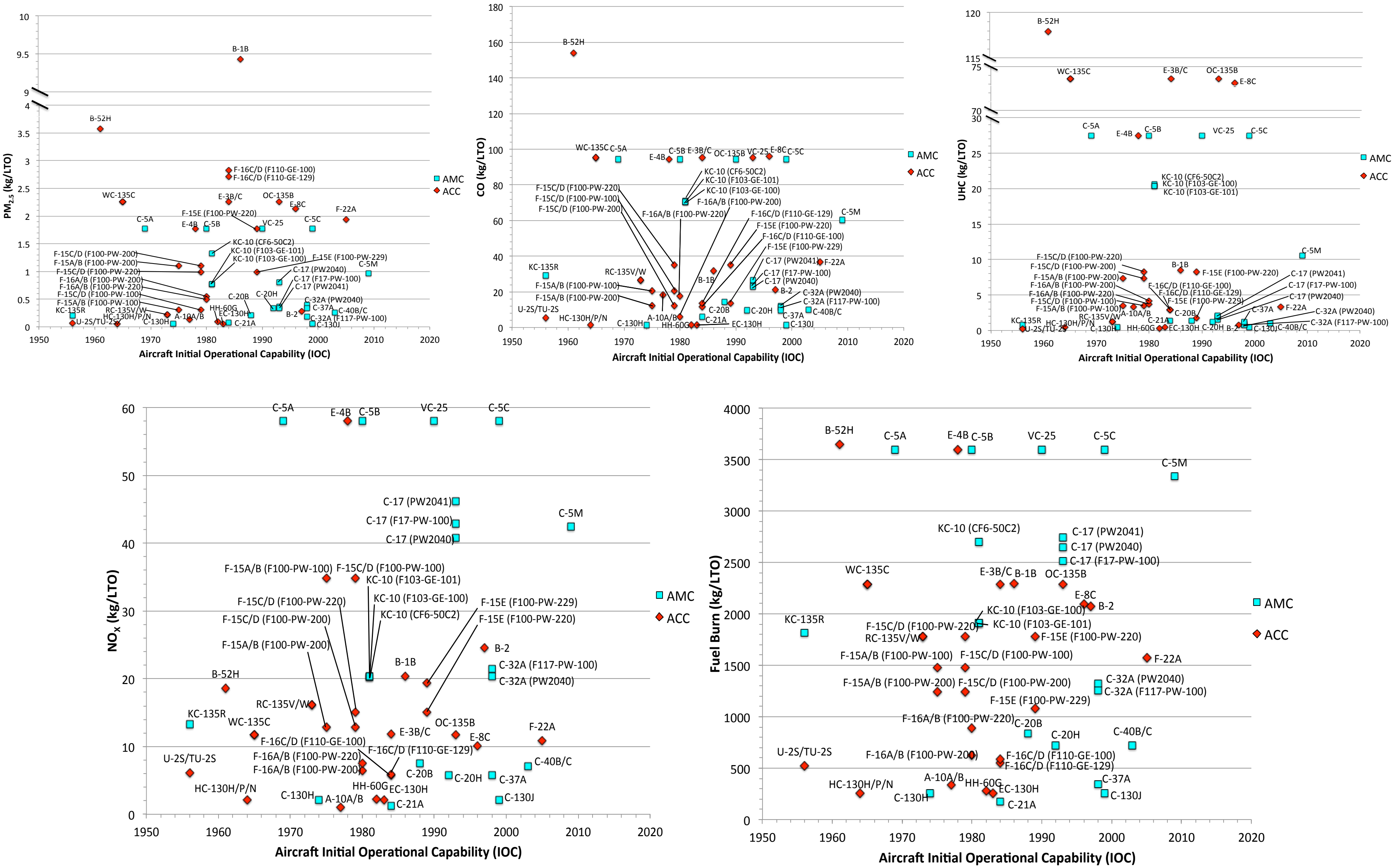

Fig. A-2: USAF ACC and AMC aircraft NO_X, $PM_{2.5}$, CO, and UHC LTO emissions and LTO fuel burn

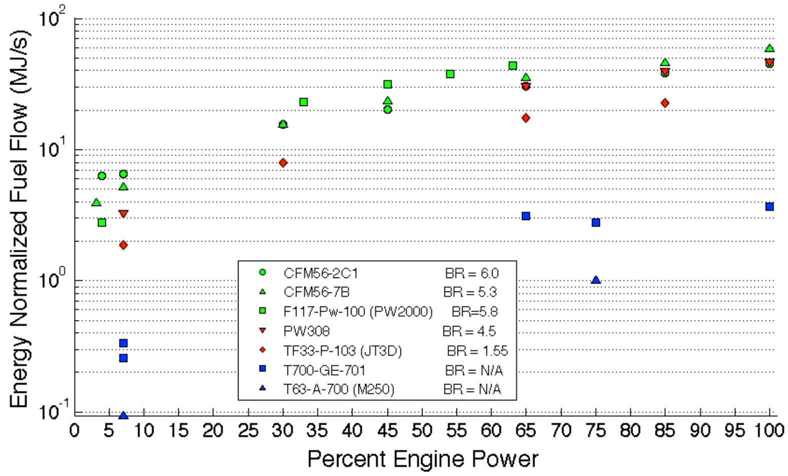

Fig. A-3: Fuel flow range for SPK engine tests

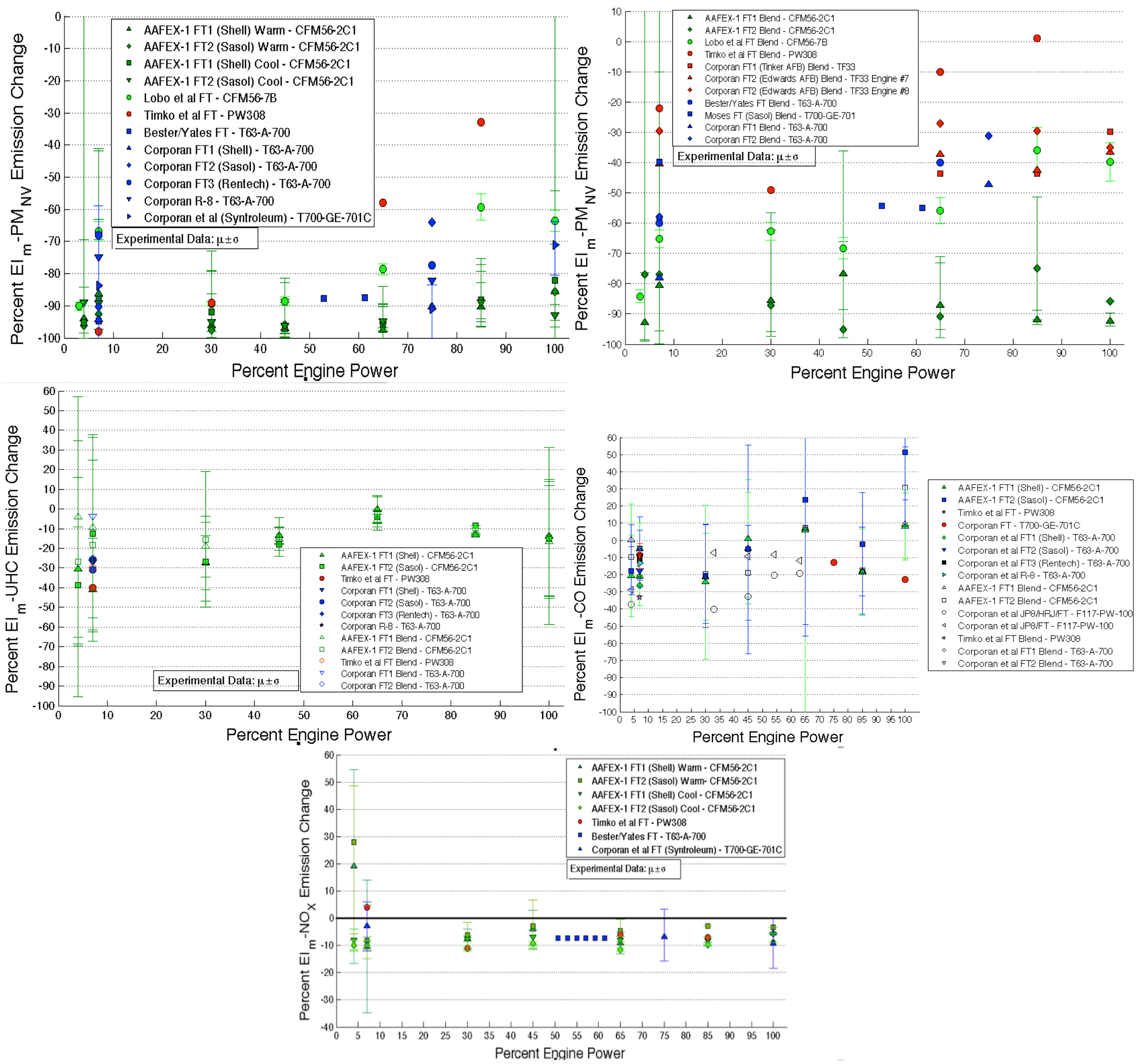

Fig. A-4: Energy normalized percent change in 50% and 100% SPK PM_{NV}, UHC, CO, and NO_X emissions

Table A-4: Location, Status, Capacity and Cost of Fischer-Tropsch Facilities

Project	Country	Plant Type	Status	Completion Year [Proposed]	Total Construction Cost (Billions 2010 USD)	F-T Liquids Capacity-Original (bpd)	F-T Liquids BPD Capital Costs (2010 USD/bpd)	Reference
Pearl GTL	Qatar	GTL	Completed	2010	$18.5B	140,000	$115,985	40
Oryx GTL	Qatar	GTL	Completed	2006	$1.42B	33,000	$42,564	41
Shell MDS	Malaysia	GTL	Completed	1993	$1.51B	12,500	$121,267	42
Palm GTL	Qatar	GTL	Cancelled	N/A	$20.0B	154,000	$129,694	43
Mossgas GTL	South Africa	GTL	Completed	1992	$4.39B	22,500	$186,415	44
Escravos GTL	Nigeria	GTL	Under Construction	[2013]	$8.40B	33,000	$254,545	45
Secunda 2	South Africa	CTL	Completed	1980	$9.10B	60,000	$151,522	46
Secunda 3	South Africa	CTL	Completed	1984	$5.60B	60,000	$92,535	46
Clinton Project	Australia	CBTL	Proposed	[2015]	$2.35B	15,800	$148,515	47
CHOREN Beta Plant	Germany	BTL	Completed	2008	$0.153B	310	$492,312	42
CHOREN Sigma Plant	Germany	BTL	Proposed	N/A	$1.47B	5,000	$294,038	48
Rialto Renewable Energy Center	USA	BTL	Proposed	[2012]	$0.45B	640	$708,200	49
Rentech Gulf Coast Synthetic Energy Center	USA	CBTL	Proposed	[2014]	$4.15B	30,000	$138,438	50
Gilberton Coal-to-Clean Fuels and Power Co-Production Project	USA	CTL	Proposed	N/A	$0.887B	5,000	$177,536	51
Flambeau River Biofuels	USA	BTL	Proposed	[2013]	$0.281B	510	$551,834	52
Ohio River Clean Fuels	USA	CBTL	Proposed	[2013]	$6.00B	50,000	$118,869	53
GreenSky	UK	BTL	Proposed	[2014]	$0.366B	1,631	$224,289	54
Kreutz-CTL-RC-V	Model	CTL	Theoretical	2007	$5.41B	50,000	$108,262	55
Kreutz-CTL-OT-V	Model	CTL	Theoretical	2007	$4.89B	36,655	$133,414	55
Kreutz-BTL-RC-V	Model	BTL	Theoretical	2007	$0.705B	4,409	$159,933	55
Project Mafutha	South Africa	CTL w/CCS	Proposed	N/A	$20.6B	80,000	$258,065	56

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