

An Overview of the NASA Alternative Aviation Fuel Experiment (AAFEX)

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ABSTRACT: The NASA Alternative Aviation Fuel Experiment (AAFEX) was conducted at NASA's Palmdale, CA aircraft facility in January-February, 2009 to investigate the effects of synthetic fuels on: 1) engine performance; 2) engine and auxiliary power unit (APU) gas and particle emissions and characteristics; and 3) volatile aerosol formation in aging exhaust plumes. The NASA DC-8, which has CFM-56 engines, was used as the test platform and the test fuels included standard JP-8 along with two synthetic fuels produced from natural gas and coal feedstocks using the Fischer-Tropsch (FT) process. AAFEX included participants from the Air Force Research Lab at Wright-Patterson, Arnold Engineering Development Center, Aerodyne Research Inc., Carnegie-Mellon, the EPA, Harvard, Missouri Science and Technology, Montana State University, NASA, the University of California, and United Technologies. During AAFEX, the aircraft was parked in an open-air run-up facility and complete sets of gas and particle emission measurements were made as a function of engine thrust. To delineate fuel-matrix related changes in emissions from those caused by variations in ambient conditions, samples were alternately drawn from the exhaust of the left inboard engine, which always burned JP-8, and the right inboard engine, which burned either standard JP-8 or one of the test fuels. To examine plume chemistry and particle evolution in time, samples were drawn from inlet probes positioned 1, 30, and 145 m downstream of the aircraft's engines. An instrumented vehicle also periodically profiled the exhaust plume from 30 to 300 m downstream to document temporal changes in exhaust composition. Engine runs were conducted in early morning and mid afternoon to examine the effects of ambient temperature on emission parameters. Results indicate that burning synthetic fuels substantially reduces particle emissions from both the aircraft engines and APU.

1 INTRODUCTION

The production of liquid fuel from coal and natural gas feedstocks dates back to the early twentieth century. However, only recently has the possibility for the use of these alternative fuels in aircraft been widely studied (Corporan *et al.*, 2007). The increased interest is the result of the possibility of these fuels to increase aviation fuel sources, increase fuel security and reduce particulate emissions. This contribution details preliminary results from the Alternative Aviation Fuel Experiment (AAFEX) which studied particulate and gaseous emissions from an aircraft fueled with fuels made via the Fischer-Tropsch (FT) process. Previous experiments have been performed on alternative fuels but this NASA sponsored experiment provides a large data set of measurements on an in-use aircraft that is completely publically accessible.

The primary goal of AAFEX was to determine the change in gaseous and particulate emissions when a FT fuel is burned in comparison to regular JP-8 fuel. Measurements were not only made of fresh emissions near the exhaust plane but also downwind plumes to determine the effects of aging on aerosol concentrations and composition. The composition of aerosols emitted by aircraft engines should change dramatically as they age. Because of high temperatures at the exhaust plane the aerosol is composed primarily of soot. As the plume ages it also cools allowing condensation of volatile

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species. This increase in volatile aerosols should be highly dependent on the ambient temperature with cooler temperatures promoting greater volatile aerosol formation.

In addition to the engine tests, the exhaust from auxiliary power units (APUs) was analyzed. These small engines provide the power needed for the start-up of the aircraft engines. However, despite their widespread use, they currently have very limited regulation. The aircraft studied had a Garrett AiResearch GTCP85-98CK power unit which is typical of those found on mid-size aircraft (such as the DC-8 studied).

2 EXPERIMENTAL DESIGN

The experiment was performed at the NASA Dryden Aircraft Operations Facility in Palmdale, California from January 20 – February 3, 2009 with participants from the Air Force Research Lab at Wright-Patterson, Arnold Engineering Development Center, Aerodyne Research Inc., Carnegie-Mellon, the EPA, Harvard, Missouri Science and Technology, Montana State University, NASA, the University of California, and United Technologies. The large collaboration allowed for a variety of measurements and comparison between similar measurements to determine optimal sampling methods. Many of the experimental techniques were similar to those used during the Aircraft Particle Emissions Experiment (APEX; Wey *et al.*, 2007).

The test aircraft was a DC-8 aircraft with four CFM-56 engines. The aircraft was parked on the tarmac and exhaust inlet probes were placed at 1, 30 and 144 meters behind the exhaust planes of the #2 and #3 engines (left and right inboard, respectively). Samples collected at 1 m were diluted with a concentric flow of dry nitrogen to prevent condensation of water and low-volatility exhaust components, whereas samples drawn into the downstream probes were typically diluted by a factor of 20 or more with background air and were thus processed without additional dilution. Stainless steel sample lines carried the exhaust stream to trailers located off the aircraft's right wing which housed instruments to measure CO₂, CO, NO, NO₂, HONO, SO₂ and CH₄ along with particle number densities, size distributions, mass loadings and composition.

During testing, the #2 and #3 engines were set at 8 different power settings over the range from 4% to 100% of maximum rated thrust (fuel flow rates of 1000-7600 lbs per hour), which corresponds to the range from ground idle to take-off. The standardized power for ground idle is 7%; however it is typical for aircraft to idle at powers closer to 4%. The right engine was fuelled with one of five test fuels: regular JP-8, an FT fuel made from natural gas (FT-1), a FT fuel made from coal (FT-2), and 50/50 blends of the FT fuels with JP-8 (Blend 1 and Blend 2). The JP-8 had an aromatic content of 19% and sulphur content of 2200 ppm while the pure FT fuels were essentially aromatic hydrocarbon and sulphur free; the Blends had concentrations of these components that were about halfway between the two extremes. The left engine was fueled with JP-8 throughout all experiments. The exhaust was alternatively sampled from the engines with the left engine acting as a reference.

Tests were performed between 5:00 and 16:00 local time. During the AAFEX timeframe the temperature ranged from about -5 at sunrise to 20°C in the mid-afternoon. Experiments were planned such that each fuel was analyzed twice with one of the tests early in the morning and the other in the afternoon. Emissions were characterized at all three sampling distances; the 1 and 30 m gas phase measurements are discussed by Miake-Lye *et al.* (this issue) whereas Herndon *et al.* (this issue) analyze the downwind gas-phase observations in greater detail.

3 RESULTS

At power settings above ground idle, the aircraft engines are extremely efficient, converting over 99% of the carbon in the fuel into carbon dioxide (CO₂). This species is easily measured and thus provides a convenient parameter against which to normalize trace species emissions. The fuels consumed during AAFEX contained about 86% carbon, which yielded CO₂ emission indices (EI) of around 3160g CO₂/kg fuel burned. The EI of species, X, is thus given by $EI_x = [dX/dCO_2] * [M_x/M_{CO_2}] * T * R * 3160/P$, where dX and dCO₂ are the enhancements of the species concentra-

tions above ambient levels, M_x and M_{CO_2} are their molecular weights, T is the sample temperature in Kelvin, R is the gas constant, and P is sample pressure.

As shown in Figure 1, the direct exhaust (1m) showed a marked decrease in both aerosol number and mass when burning the alternative fuels. At low power (4-45%), aerosol number and mass EIs decreased by over 90% when burning the FT fuels in comparison to the JP-8. Values for the blended fuels were intermediate between the FT and JP-8 fuels. At higher powers, there is less of a reduction for the alternative fuels. However, even at maximum rated thrust the reduction is over 60% for the FT fuels. Because of the high temperatures of the exhaust, the aerosol mass is composed almost entirely of black carbon (BC; Figure 2). A shift is also seen in the size of the particles with smaller sized particles seen for the alternative fuels.

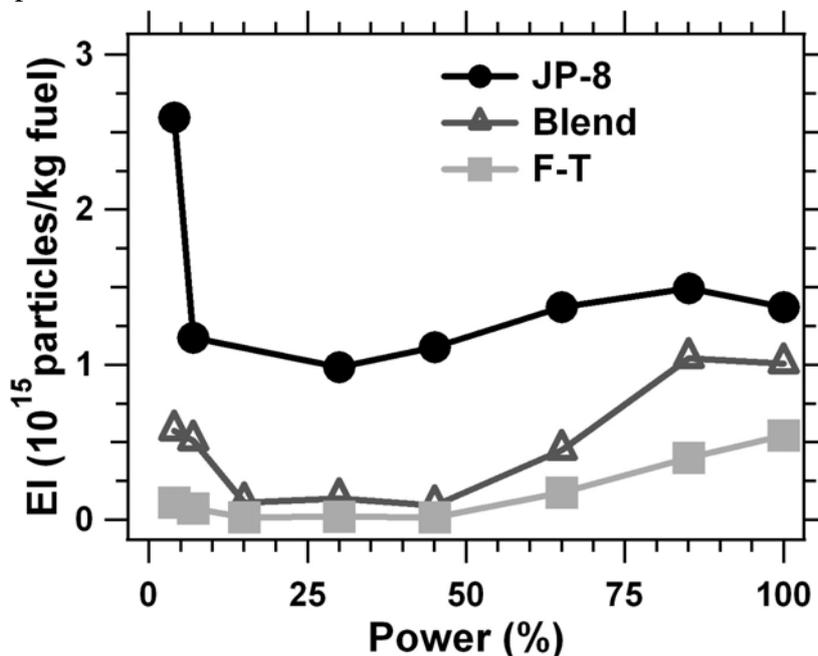


Figure 1. Aerosol emission indices 1m behind the #3 engine when fueled with JP-8, blended (average of both) and FT (average of both) fuels. Similar reductions are seen in the aerosol mass EIs.

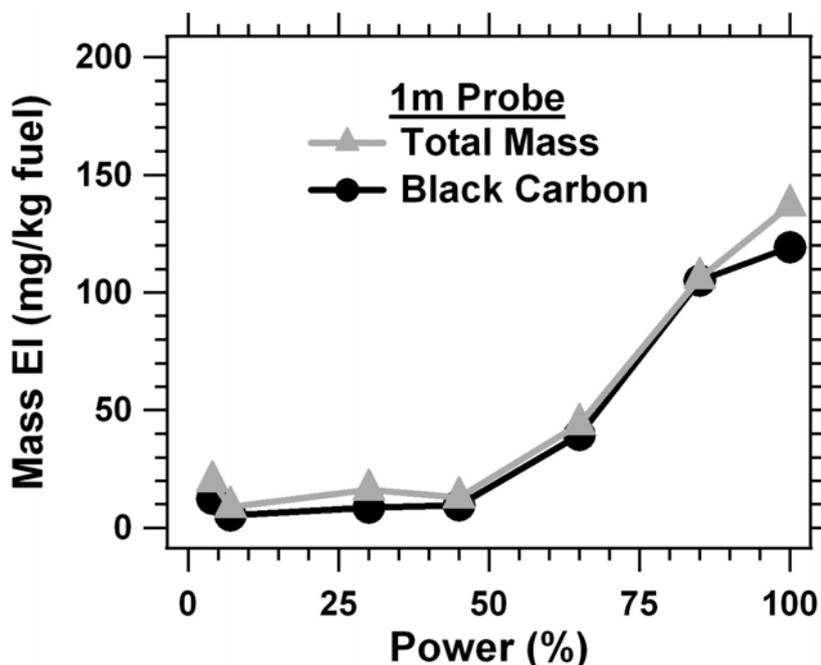


Figure 2. Black carbon and total aerosol mass emission indices measured 1m behind the engine when burning JP-8 fuel.

As the exhaust plume ages the temperature decreases and semi-volatile species begin to condense, either to form new particles or coatings on existing soot particles. As shown in Figure 3,

black carbon accounts for a majority of the total aerosol mass EI in the 1 m samples. However, at 30m the total aerosol mass is significantly greater than black carbon mass with the difference between the two measurements attributable to volatile aerosols (Figure 3). The volatile aerosols are most prevalent at low engine power, coincident with the peak in gas phase hydrocarbon emissions. As the power increases, the engines produce less hydrocarbons and the mass of volatile aerosols decreases. This volatile aerosol mass was determined to be highly temperature dependent (Figure 4) with a decrease in emission index of 10 mg/kg fuel per degree temperature at 4% power. As the power increases there is less of a dependence on ambient temperature and at 100% power volatile aerosol mass has no dependence on temperature.

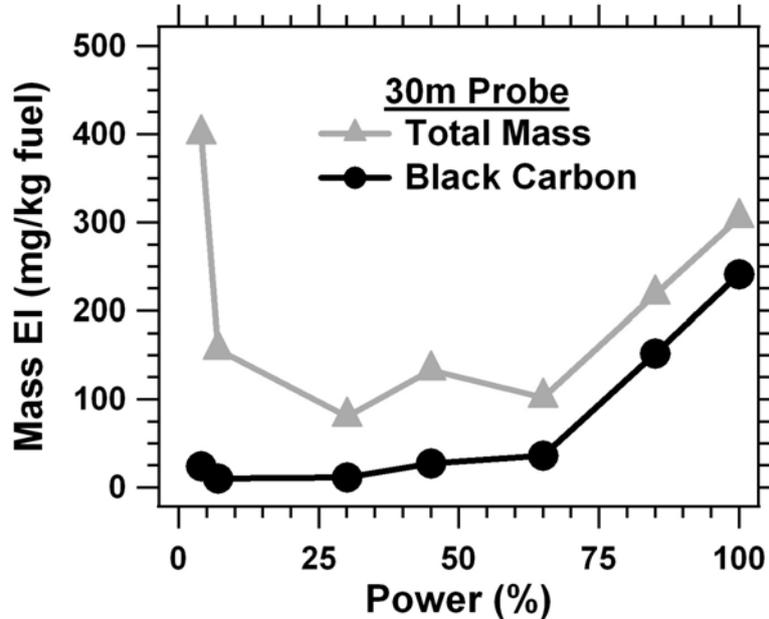


Figure 3. Black carbon and total aerosol mass emission indices measured 30m behind the engine when burning JP-8 fuel. Comparison to Figure 2 shows similar black carbon EIs but an increased total aerosol EI indicative of volatile aerosol formation.

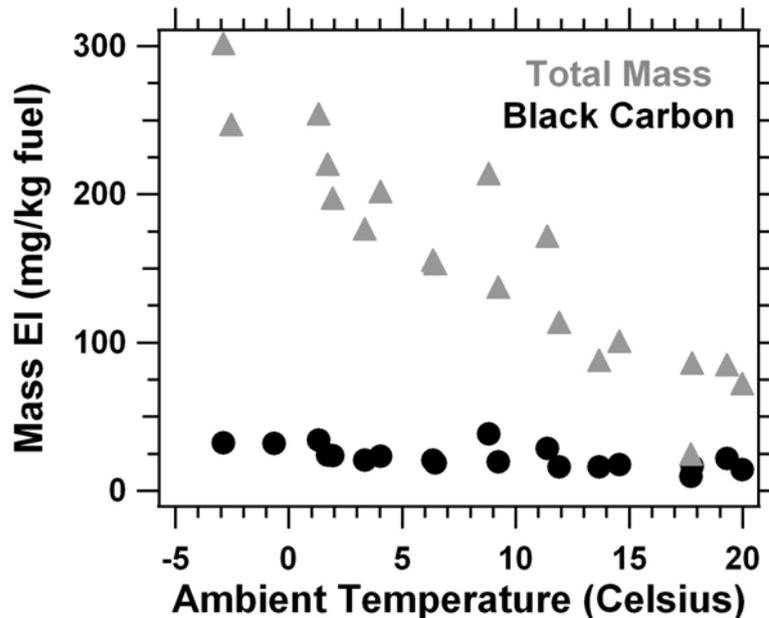


Figure 4. Black carbon and total aerosol mass emission indices measured 30m behind the engine when burning JP-8 fuel as a function of ambient temperature.

Emissions from the on-board APU were measured as it burned either JP-8 or FT-2 fuel. The APU running on JP-8 fuel had black carbon emission indices on the order of 200-500 mg/kg fuel burned. These values are 20 times greater than emitted by the aircraft engine running at idle. A significant reduction in both black carbon and organic mass was seen when burning the FT fuel (Figure 5).

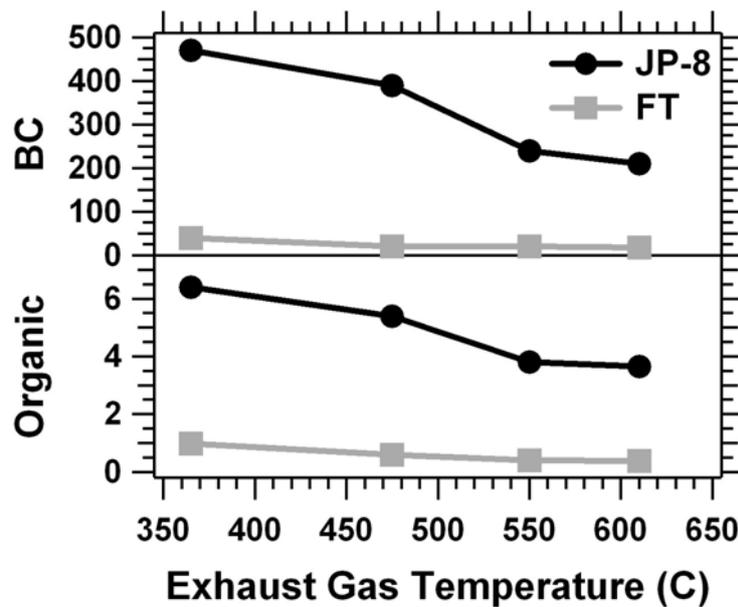


Figure 5. Aerosol mass emission ratios for black carbon (top) and organic compounds (bottom).

4 PRELIMINARY CONCLUSIONS

The driving force in the use of FT fuels as an aviation fuel is the goal of reducing dependence on foreign oil. However, a beneficial side effect of this is a potential decrease in particulate emissions. Significant decreases on the order of 90% were seen in aerosol emissions when using the pure Fischer-Tropsch fuels. During the test, no marked differences were seen in engine performance between the fuels. However, fuel leaks occurred in the aircraft fuel system and tanker trucks when the pure FT fuels were used due to the absence of aromatic compounds, which have been shown to increase seal swell (DeWitt *et al.*, 2009). No leaks were seen when the right engine was fuelled with the blended fuels. For this and other reasons, the initial alternative fuels used for aviation will likely be blends with normal jet fuel.

It should be noted that the Fischer-Tropsch process to make these alternative fuels typically produces a large amount of CO₂. Thus the use of FT fuels for aviation may reduce aerosol emissions but will not decrease CO₂ emissions. However, it is possible that carbon sequestration techniques will be able to eliminate the CO₂ emissions associated with FT fuel production (Jaramillo *et al.*, 2008). In addition, the reduction of aromatic and sulphur content in non-synthetic fuels are likely to produce similar particulate emission reductions.

5 ACKNOWLEDGEMENTS

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Effects of Alternative Fuels on Hydrocarbon and Particle Emissions from Aircraft Engines

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ABSTRACT: Alternatives to fossil, petroleum-based jet fuels are being considered for a variety of economic and environmental reasons. The possible alternatives usually result in a change in the detailed hydrocarbon make-up of the fuels, which might be anticipated to result in changes in the emissions released when burning these fuels. Several recent measurement campaigns have examined the gas-phase hydrocarbon emissions and the volatile contributions to particulate emissions from aircraft gas turbine engines. Preliminary results from the Alternative Aviation Fuel EXperiment (AAFEX) are presented that quantify the speciation of hydrocarbon emissions, especially at low power operation, and the organic and sulfate contributions to volatile particulate emission across the range of operating conditions. The measured differences suggest that alternative fuels can have significant impact on the emissions resulting from their use as aviation fuels.

1 INTRODUCTION

Alternatives to petroleum-based fuels may provide economic and environmental benefits relative to the continued use of fossil fuels. Using alternative fuels for aviation will require the fuel to satisfy all of the technical specifications needed for safety and operability across the range of conditions experienced during flight. While a major motivation for considering alternative fuels is the reduced emissions of carbon dioxide (CO₂) as a green house gas, the question naturally arises as to whether other emissions may also be affected by substituting alternative fuels for the traditional petroleum-based fuel sources. Other emissions, both gaseous and particulate, have been receiving increasing attention even in the context of aviation using petroleum fuels due to their potential impacts on both climate change and on local air quality. Especially since the fuel sulfur content and the detailed hydrocarbon speciation of alternative fuels are expected to be different from that of petroleum-based fuels, studies have been carried out to determine the emissions of aircraft engines when burning alternative fuels (e.g. Corporan et al., 2007).

In January 2009, a NASA-led field campaign called Alternative Aviation Fuel EXperiment (AAFEX) was carried out at NASA Dryden facilities in Palmdale, California using two Fischer-Tropsch fuels and comparing with a standard JP-8 fuel. This mission was reviewed by A. Beyersdorf and B. Anderson at the TAC-2 conference (see agenda in this proceedings), where the range of conditions, fuels, and measurements performed are described. The present extended abstract provides results from the measurements made by the Aerodyne team, which included members from Aerodyne, Montana State University, and Harvard University. These results are preliminary, given that the first AAFEX science team meeting was held one week prior to the TAC-2 conference at which these results were presented. On-going analysis is continuing and more complete reports and presentations at an AIAA meeting in January 2010 will be available in the near future.

The comparison of data for the different fuels requires careful consideration of comparable op-

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erational points. Clearly for very extreme changes in the emissions, like the observed decreases in black carbon particle emissions, effects of the fuel properties on emissions are unequivocal. However for more subtle changes and for accurate quantification of the effects on emissions, the determination of the equivalent engine power setting when using different fuels will require more detailed analysis. In specific, when the different fuels have differing energy content, on either a mass or volume basis, using standard mass flow rates for determining the power condition may be insufficient. Thus the power setting might be better interpreted on the basis of the amount of energy being provided per second by the fuel, for example, rather than the more usual mass per second. Similarly, when reporting the emissions numbers, the traditional practice of reporting the mass of emission per mass of fuel burned (as an “Emission Index” in g/kg-fuel) may need to be amended to account for the differing fuel energy contents as well. Due to the preliminary nature of the data reported here, such analysis has not yet been included, and thus further refinement of the quantification of these emissions will be required.

The range of measurements reported here are similar to what has been used in recent field missions such as the APEX1-3 campaigns (C.C. Wey *et al.*, 2007, Timko 2009a,b) with some important additions. For gaseous species, we again measured CO, speciated organics, NO, NO₂, NO_x, and HONO with significant refinements in some our measurement approaches, and methane (CH₄) was also measured. For particulate emissions, black carbon mass (Multi-Angle Absorption Photometer: MAAP), particle number (Condensation Particle Counter: CPC), particle size (Scanning Mobility Particle Sizer: SMPS), and particle volatile contribution composition (Aerosol Mass Spectrometer: AMS) were all measured. The AMS measures the size-dependent volatile contributions to the emitted particles, primarily based on the coatings on the black carbon soot particles due to the size sensitivity limits of the AMS of about 30 nm –800 nm in the mass based-size distribution. In essence, the AMS provides information mostly about the organic and sulfate coatings on the soot particles, since those are the primary volatile constituents seen in aircraft exhaust.

2 GASEOUS EMISSIONS

The speciation of the emitted organics of petroleum fuels (Spicer *et al.*, 1992, 1994, Anderson *et al.*, 2006, Yelvington *et al.*, 2007, Knighton *et al.*, 2007) has been measured to be a largely invariant profile of a range of species which is highest at the lowest idle conditions and that is mostly been reduced to immeasurably small values at power greater than about 30% power. Carbon monoxide (CO) as another product of incomplete combustion also demonstrates this rapid drop off with increasing power, and both CO and the emitted organics have a significant temperature dependence, decreasing with increasing ambient temperature. These features are also seen with the two alternative fuels, and the differences between the FT fuels and JP-8 suggests a small decrease in these products of incomplete combustion near idle for the FTs, but this may be confounded by temperature effects and effects of the varying fuel energy content and will require further analysis.

A more marked difference is noticed in comparing the speciation of the organic emissions. Both of the FT fuels had very low fuel aromatic content. This has impact on the emitted species as shown in Figure 1. The value of benzene emission index (EI in g/kg fuel) is plotted versus formaldehyde in the left panel and against ethene in the right. For petroleum fuels, the ratio of benzene to HCHO (or C₂H₄) is largely invariant, and the plot gives a single slope near 0.16 for HCHO (or 0.13 for C₂H₄). For the two FT fuels, the slope is markedly lower in both panels, which is due to the lower aromatic content of the FT fuels resulting in lower benzene emissions relative to HCHO or C₂H₄. Interestingly, while the benzene is lower for both FT fuels relative to that of JP-8, the slope changes are somewhat different for HCHO vs C₂H₄ (c.f. left and right panels) indicating that even the relative amounts of HCHO and C₂H₄ depend on which fuel is considered.

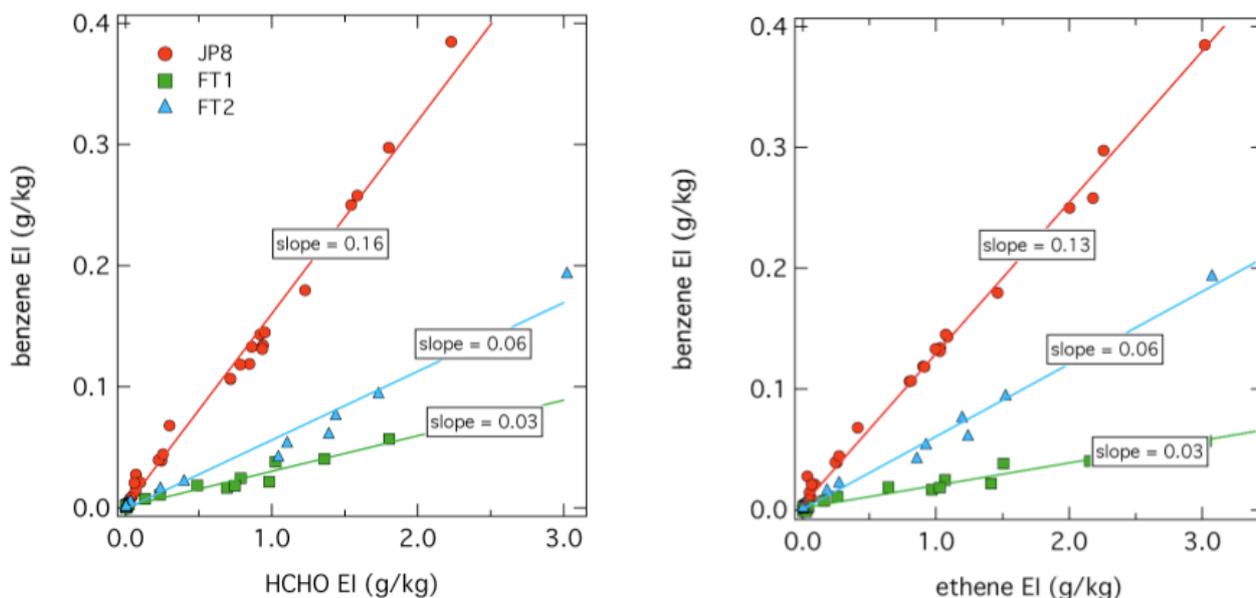


Figure 1. Benzene Emissions Index (EI) plotted versus formaldehyde (HCHO) EI, left panel, and versus ethene (C_2H_4), right panel, indicating that the relative amount of benzene compared to HCHO or C_2H_4 is less for the FT fuels. In addition, the relative amounts of HCHO vs C_2H_4 is also affected since the two FT fuels have different behaviors in the right and left panels.

While benzene is a smaller contributor to the organic profile for the FT fuels, the contribution does not scale simply with the aromatic content, suggesting benzene may be produced in the combustion process even in when very low aromatics are present in the fuel itself, as shown in Figure 2. Here benzene is ratioed to HCHO for a number of recent emissions studies, and the two AAFEX FT fuels represent the left most points in the fuel analysis range.

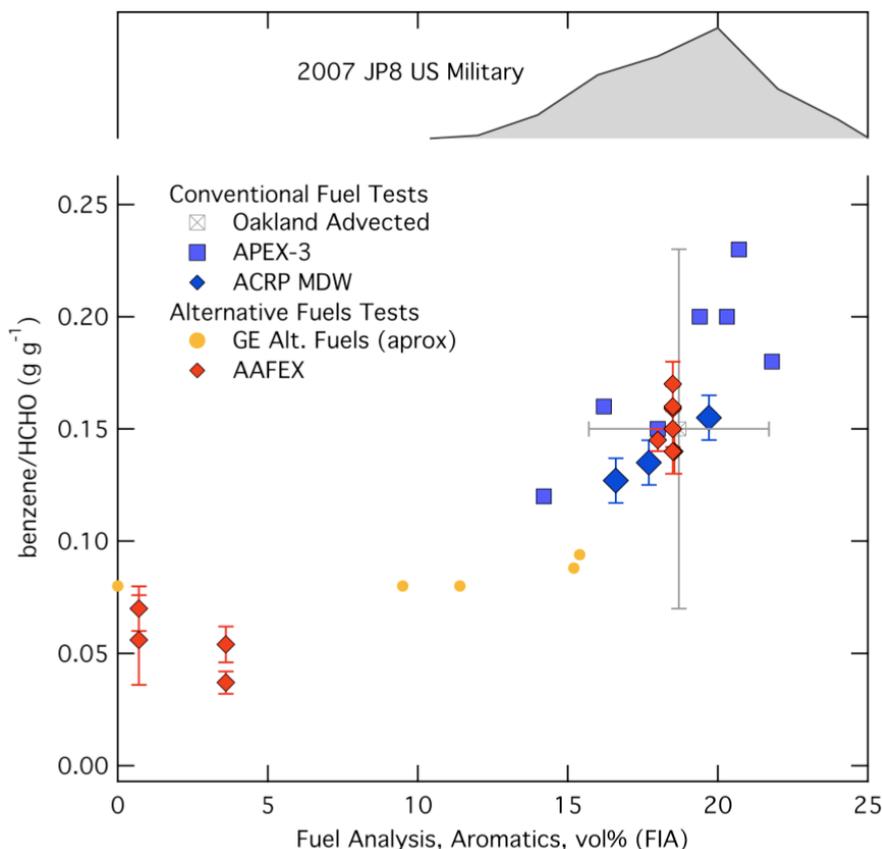


Figure 2. Benzene to HCHO ratio versus fuel aromatic content, indicating that benzene drops as aromatic content is reduced, but the benzene does not approach zero even as fuel aromatics go to zero.

Emissions of oxides of nitrogen (NO_x , NO_y) are important both for climate impact and for local air quality. NO , NO_2 , and HONO were all measured in AAFEX. While one might expect that NO_x emissions would be primarily dependent on the power condition properly accounting for fuel energy content, it is possible that difference in chemical kinetics in the flame zone could depend on the fuel HC mixture by affecting flame peak temperature and structure in the combustor. Since NO_x production is non-linear in combustor temperature, this could affect the NO_x produced. Proper quantification will require careful analysis accounting for the fuel energy content as discussed in the introduction, but Figure 3a shows that the NO_x EI at 85% power is lower for the two FT fuels compared the JP-8 fuel. It will be important to assess whether the FT fuels produce less NO_x for operation at these higher power settings.

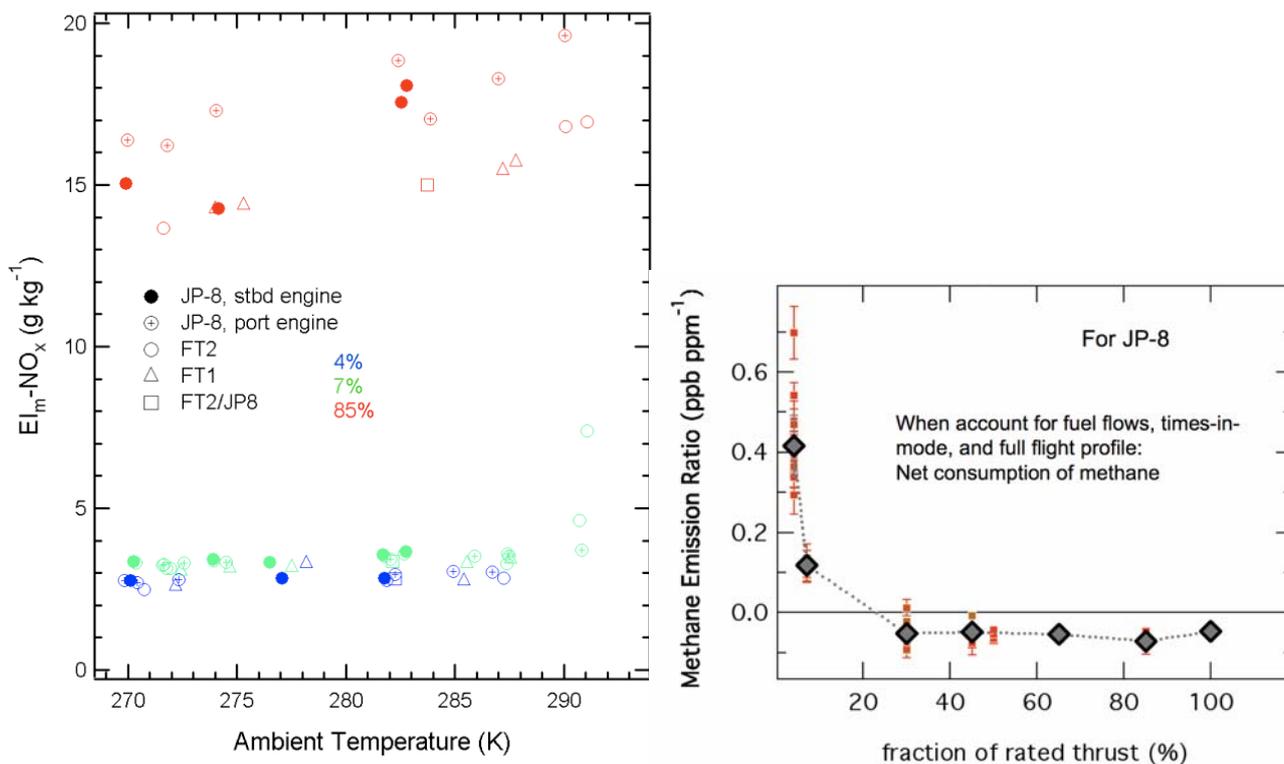


Figure 3a (left) NO_x EI vs ambient Temperature for idle and 85% power. FT fuels (triangles and squares) are lower than the JP-8 fuel.

Fig 3b (right) Methane emission ratio (ppb methane per ppm CO_2) as a function of engine power.

Improvements in measuring HONO allowed a more accurate speciation of the emitted NO_y family of species. This resulted in an upward refinement of the fraction of HONO in the NO_y speciation. NO_2 continues to be measured as the dominant NO_y emission at idle, which will take on increasing significance as NO_2 regulations become tighter and/or more widespread.

Methane was also measured as part of the suite of gaseous measurements, and largely corroborated the methane measurements made by Spicer *et al.* (1992). More detailed power dependence has been mapped out in the AAFEX study (Figure 3b), and measurements at both downwind locations and the engine exit plane were performed. The important point to note is that while CH_4 is emitted at idle conditions, the exhaust concentrations are lower than ambient for engine powers of 30% and above, which indicates that ambient methane is being consumed for most power conditions. When one considers the fuel flow and time in mode for a typical aircraft operation, it is clear that methane is being consumed in net by this engine.

3 PARTICLE EMISSIONS

The most notable effect of the FT fuels on particle emissions is the pronounced decreases in black carbon particles, with the fractional decrease largest at the lowest engine powers. This was reported at length by Whitefield *et al.* at TAC-2 (see elsewhere in these proceedings) and these results were

confirmed in the MAAP, CPC, and SMPS data taken by the Aerodyne team. These results were presented at TAC-2 and will be documented in forthcoming reports.

The particle mass EI measured at 1 and 30 m downstream of the engine exit is shown in Figure 4 for JP-8 and cold ambient temperatures (near 0 C). When comparing MAAP black carbon data to total mass data taken from an integrating particle size distribution (EEPS data courtesy of Bruce Anderson, NASA and David Liscinsky, UTRC, where a density of unity is assumed to convert to mass), it is noted that the black carbon mass does not change from 1 to 30 m and represents most of the total mass for engine powers greater than about 30% power. However at idle, the total mass is much greater than the black carbon mass, indicating a substantial volatile component. Interestingly, the total mass at idle is not much different than that at take-off, yet at idle most of the mass is due to volatile contributions, while at take-off most of the mass is black carbon/non-volatile PM.

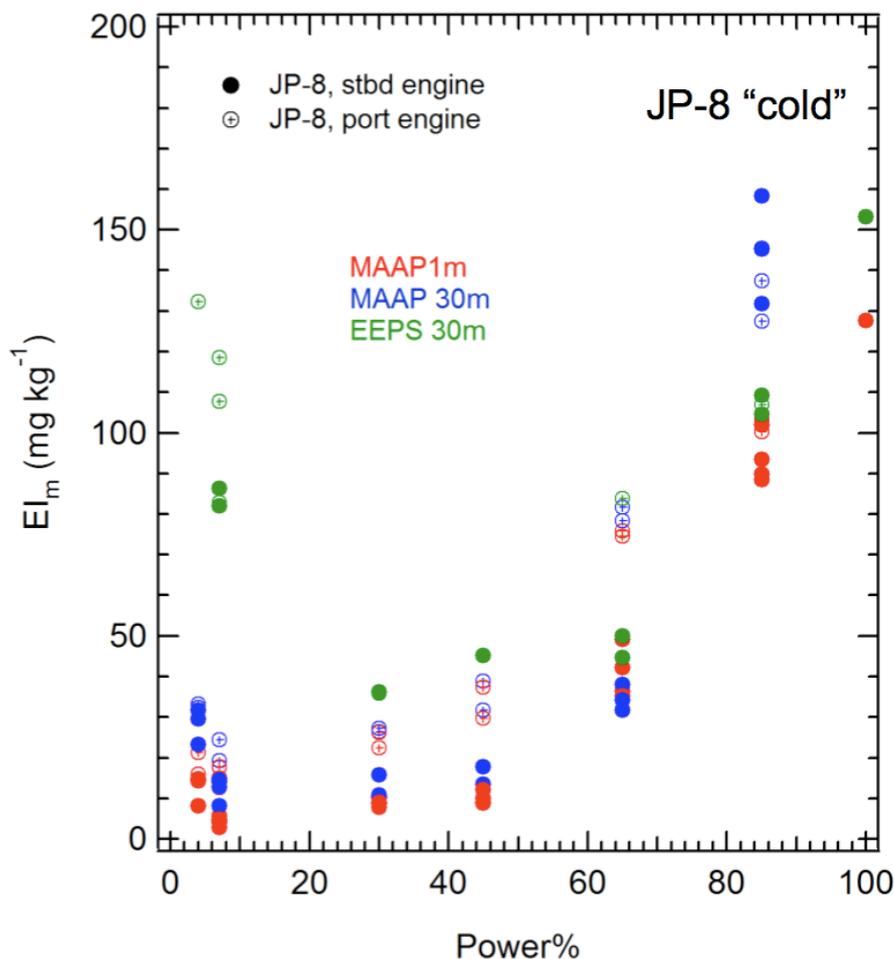


Figure 4. Particle Mass EI versus engine power for measurements at 1 and 30 m downstream of the engine exit. Both black carbon mass (red: 1 m and blue: 30 m) and total mass (green: 30 m, EEPS data courtesy Bruce Anderson, NASA and Dave Liscinsky, UTRC) show the changing volatile/non-volatile particle composition versus power.

Figure 5 uses the AMS to quantify the volatile contributions at 30 m downstream. The left panel (Fig. 5a) shows the particle bound sulfate versus engine power for the several fuels. Sulfate is absent for the FT fuels, which is consistent with the lack of sulfur in those fuels. The JP-8 shows a rising trend with engine power, which is indicative of the increasing soot surface area as the soot increases with engine power. As discussed elsewhere (Timko et al., 2009b, Onasch et al., 2009), the total particulate sulfate likely has less of a power dependence, since the AMS is not measuring sulfate in small volatile particles that are important at low engine powers.

Figure 5b shows the equivalent data for organic contributions to volatile PM at 30 m downstream. The organics decrease dramatically with power, which is even more noticeable when one includes the AMS's lack of sensitivity to small particle mass. The FT fuels and the FT mixture lie below the JP-8, indicating that organic contributions to the PM mass are less for these fuels. This may be explained, similarly to the gas-phase benzene effects, as being a result of the lower aromatic

content of the FT fuels, however one must also account for the fact that the available soot surface area is also significantly lower for the FT fuels. While the particle phase organics are significantly lower, both fuel aromatic content and available soot surface area for condensation may play a role in that reduction.

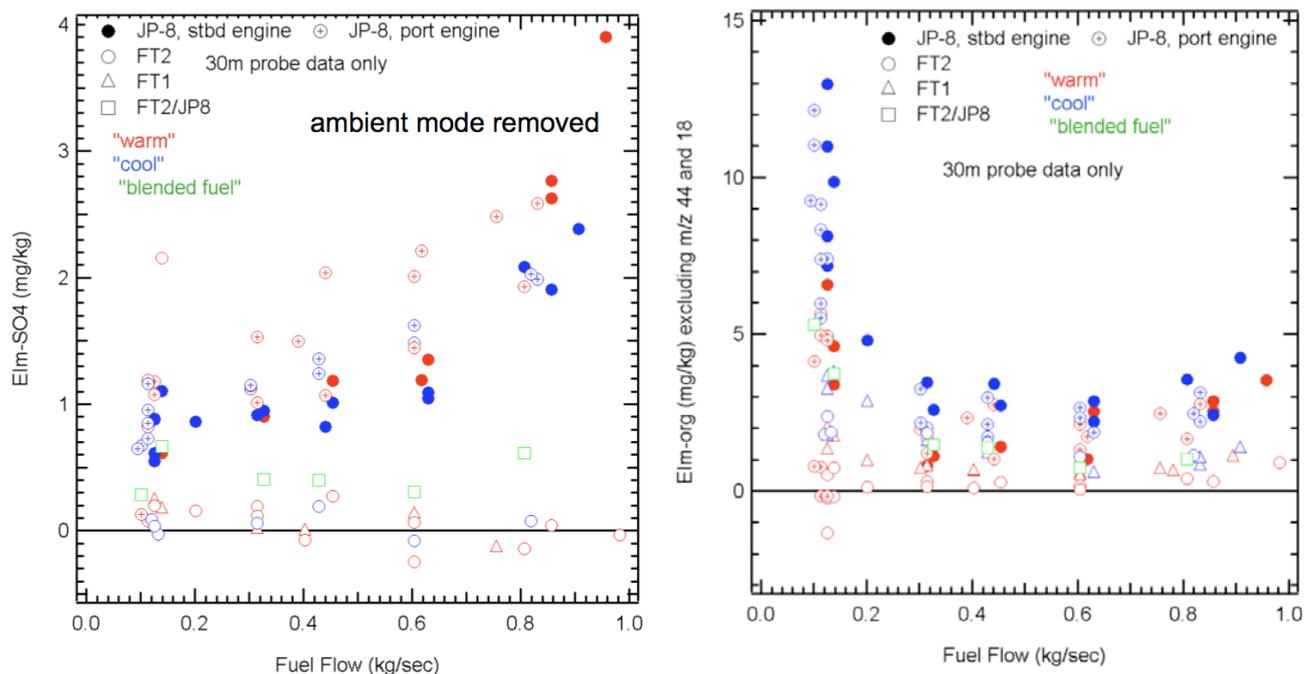


Figure 5. Volatile PM mass contributions measured at 30 m downstream of the engine exit. Fig 5a (left panel) shows sulfate contributions, which are essentially absent for FT fuels. Fig 5b (right panel) shows organic contributions, which are lower for FT fuels relative to JP-8.

4 CONCLUSIONS

The alternative FT fuels explored in AAFEX indicate that the low fuel sulfur content and low aromatic content of these fuels have impact on the gaseous and particulate emission from an aircraft gas turbine engine. The hydrocarbon speciation profile depends on fuel type, and notably aromatic species emissions (e.g. benzene) are lower relative to major emissions like formaldehyde and ethene (which also change somewhat relative to one another). At AAFEX, the NO_y speciation was measured more accurately for all fuels, and further analysis is required to determine if the use of alternative fuels could affect the total NO_x emissions, after properly accounting for fuel energy content. Methane emissions were measured and the data confirm that modern gas turbine engines have CH_4 emissions at idle, but consume CH_4 at higher power, resulting in a net CH_4 consumption for a full flight profile. This methane result applies to all fuels.

FT fuel resulted in significant reductions of non-volatile (soot) and volatile (sulfate, organic) emissions with FT fuel. The volatile contributions, and especially what is measured by the AMS, are coupled to the non-volatile (soot) particle emissions through the soot particle providing surface area for the volatile species to condense. Thus, at higher power where there is more soot, more of the volatile PM appears as coatings on the soot. At lower powers, more of the volatile PM is contained in particles smaller than the AMS can measure. Organic contributions decrease with increasing engine power, and the FT fuels have lower organic PM contributions than the JP-8. Sulfate is not detected for the FT fuels as a direct consequence of their very low fuel sulfur content.

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