# ALTERNATE-FUELED COMBUSTOR-SECTOR EMISSIONS

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## Abstract

In order to meet rapidly growing demand for fuel, as well as address environmental concerns, the aviation industry has been testing alternate fuels for performance and technical usability in commercial and military aircraft. Currently, alternate aviation fuels must satisfy MIL-DTL-83133F(2008) (military) or ASTM D 7566-Annex(2011) (commercial) standards and are termed "drop-in" fuel replacements. Fuel blends of up to 50% alternative fuel blended with petroleum (JP-8), which have become a practical alternative, are individually certified on the market. In order to make alternate fuels (and blends) a viable option for aviation, the fuel must be able to perform at a similar or higher level than traditional petroleum fuel. They also attempt to curb harmful emissions, and therefore a truly effective alternate fuel would emit at or under the level of currently used fuel. This paper analyzes data from gaseous and particulate emissions of an aircraft combustor sector. The data were evaluated at various inlet conditions, including variation in pressure and temperature, fuel-to-air ratios, and percent composition of alternate fuel. Traditional JP-8+100 data were taken as a baseline, and blends of JP-8+100 with synthetic-paraffinic-kerosene (SPK) fuel (Fischer-Tropsch (FT)) were used for comparison. Gaseous and particulate emissions, as well as flame luminosity, were assessed for differences between FT composition of 0%, 50%, and 100%. The data showed that SPK fuel (a FT-derived fuel) had slightly lower harmful gaseous emissions, and smoke number information corroborated the hypothesis that SPK-FT fuels are cleaner burning fuels.

## Introduction

In order for a fuel alternate to be truly effective, it must have a sustainable supply and cause little environmental harm. Combustor emissions are of great relevance in alternate fuel considerations for both combustor efficiency as well as environmental and human health. The life cycle analysis (LCA) of fuel feedstocks carries a great effect on the usability of the fuel in aviation and is directly related to the combustor emissions data. The LCA estimates the impact of the greenhouse gas emissions for the entire fuel process, from production to distribution to usage, and can determine the true efficacy of using alternate fuel blends [1]. The testing discussed in this study represents only the emissions created when the fuel is in use. Because alternative fuels from multiple feedstocks are still being explored, fuel-flexible engine combustors are the primary targets for these

tests, as they will be used for most of the fueling with alternate fuels in the near future.

The emissions trending described in this paper proves some expected trends while highlighting differences for further observation. Data were taken from "Combustor A," a proprietary-geometry three-cup combustor sector representative of current engine combustor technology (details withheld due to proprietary concerns). Both the gaseous and particulate sampling probes were placed at the nozzle exit plane. The probes were specially built for the cell facility at Wright-Patterson Air Force Base. The facility has two identical fueling systems in place: one for the JP-8+100 (herein referred to as "JP-8") fueling purposes and one for the FT fuel. The fuel is blended on line to achieve the desired blend. Further details regarding the facility, errors, post processing parameters, etc., are available in Shouse et. al [2]. This paper provides a full analysis of the data set introduced in that paper.

Generally, the FT fuel is expected to be a cleaner burning fuel than the JP-8 fuel, and the blend falls somewhere in between the two. The blend data appear to lean closer to the JP-8 emissions count rather than the FT emissions, allowing us to conclude that JP-8 is the dominating fuel in the blend, which is of potential importance when determining carbon credits or other emissions implications. This is corroborated by observations in performance data sets for these tests.

## Combustor Parameters and Collection of Data

Data from Combustor A emissions was assessed for the following variables:

1. Inlet pressure (P) and temperature (T): 75 psia (0.52 MPa) and 500 °F (533 K), 125 psia (0.86 MPa) and 625 °F (603 K), 175 psia (1.21 MPa) and 725 °F (658 K), and 225 psia (1.55 MPa) and 790 °F (694 K)
2. Combustor pressure drops ($\Delta P$): 3%, 4%, and 5%
3. Fuel blends: 100% JP-8, 50:50 JP-8:FT, and 100% FT (±5%) (4) Fuel-to-air ratios (*F/A*): 0.010, 0.015, 0.020, and 0.025
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Data were collected for the following emissions: NO (ppm), $NO_2$ (ppm), NOx (ppm), CO (ppm), $CO_2$ (%), $O_2$ (%), and THC (ppm). Photodiode output voltage was also taken, and both still and high-speed photography were used and can be correlated with this luminosity data.

Data such as smoke number information and particulate emissions are analyzed in part, due to an incomplete data set. Data from collaborative testing sites are summarized in relevance to the paper to illustrate uniformity of the results.

## Gaseous Emissions

<u>NO emissions:</u> Nitric oxide (NO) emissions (with molecular atomic dimension 0.115 nm), measured in ppm, show uniform results for all pressure levels. There is a monotone decrease as the change in percentage combustor pressure drop (%$\Delta P$) increases and a monotone increase as *F*/*A* increases.

<u>$NO_2$ emissions:</u> Nitrogen dioxide ($NO_2$) emissions, measured in ppm, (0.221 nm) follow a monotone increase with *F*/*A*. There is little change as %$\Delta P$ increases. The FT fuel trends show greater $NO_2$ emissions than the JP-8 fuel. Unlike other emissions data, the 50:50 blend trends towards the FT fuel data rather than the JP-8 data.

<u>NOx emissions:</u> NOx emissions (ppm) were taken as a combination of nitric oxide (ppm) and nitrogen dioxide (ppm) data. Because NO emissions were greater, the nitric oxide trends are dominant in the NOx emissions data. Therefore, the emissions show a monotone decrease as percent pressure drop $\Delta P$ increases, and a monotone increase with *F*/*A* ratio (Fig. 1), similar to the NO emissions. NOx emissions also increase with absolute pressure. Emissions from the 100% FT blend do tend to be lower than those of the JP-8 fuel, but the difference is too small to be conclusive.

<u>$CO_2$ emissions:</u> The percent of carbon dioxide ($CO_2$) emissions (0.116 nm) did not show a significant difference between fuels or %$\Delta P$, and maintained a monotone increase with *F*/*A*.

<u>CO emissions:</u> Carbon monoxide (CO) emissions (0.113 nm) (ppm) showed significant increases with *F*/*A*. In the 75-psia (0.52-MPa) pressure combustor, the only pressure for which the *F*/*A* data go up to 0.025, the CO concentration increased nearly an order of magnitude from *F*/*A* of 0.020 to 0.025 (Fig. 2). In the rest of the pressures, the concentration jump from *F*/*A* of 0.015 to 0.020

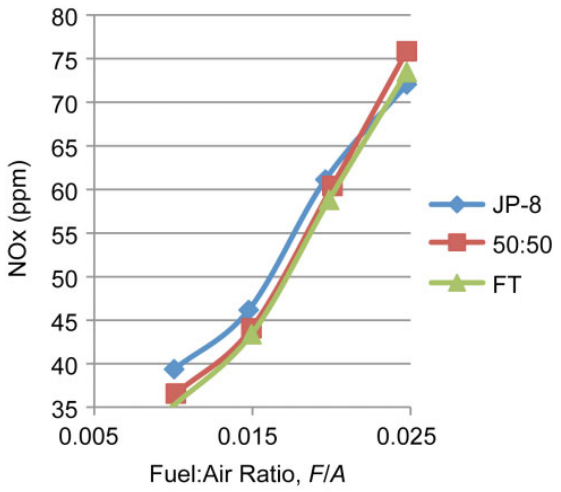


**Fig.1** NOx (ppm) emissions for combustor inlet pressure of 75 psia (0.52 MPa) at 5% $\Delta P$ at varied $F/A$. The FT fuel emissions are marginally smaller than both the JP-8 and 50:50 blend emissions.

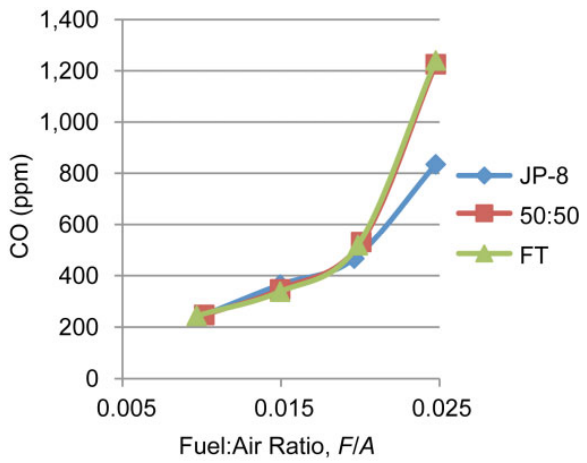


**Fig.2** CO (ppm) emissions for combustor inlet pressure of 75 psia (0.52 MPa) at 5% $\Delta P$ at varied $F/A$. The large jump from the lower $F/A$ values to $F/A$ = 0.025 is clearly demonstrated.

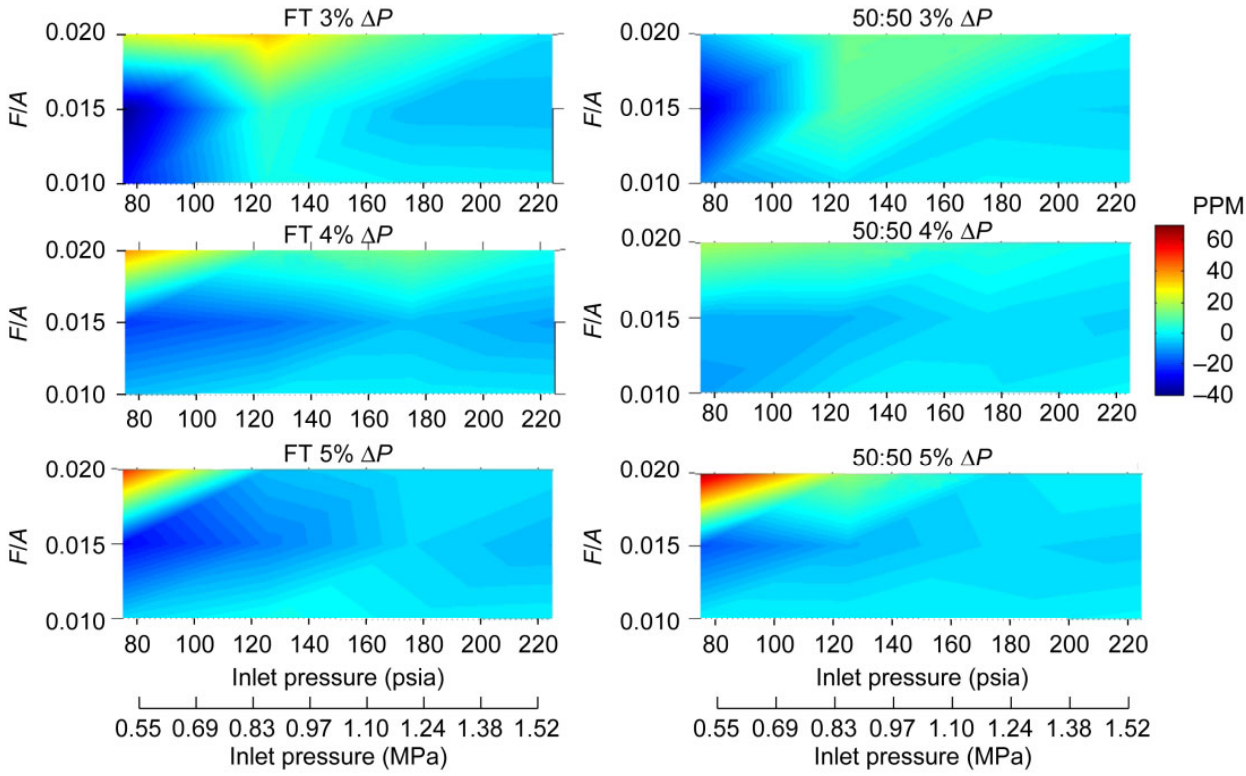


**Fig.3** CO (ppm) emissions differences versus inlet pressures and $F/A$ values at 3, 4, and 5% $\Delta P$. The differences the baseline JP-8 fuel emissions subtracted from the emissions of 100% and 50:50 FT fuel blends. The pressure and $F/A$ combinations that increase differences are shown by the warmer colors.

is significantly larger than the 0.010 to 0.015 jump. The FT and 50:50 fuels showed a more pronounced jump with the increasing $F/A$ ratio than the JP-8. CO emissions also showed a drastic decrease as absolute pressure increased.

Figure 3 shows overall trends in CO emissions differences between JP-8 fuel and the 50% and 100% FT blends. A greater difference is apparent at higher $F/A$ values. The 100% FT fuel emits more than JP-8 at higher $F/A$, but dips lower at lower inlet pressures ($P$). The 50:50 blend shows similar trends to a lesser degree. CO for 100% and 50:50 FT is slightly—but consistently—higher compared with JP-8 emissions at $P$ = 75 psia (0.52 MPa)

conditions and higher *F/A*. The differences in CO become less significant at higher *P* and lower *F/A*.

$O_2$ emissions: The percent of oxygen ($O_2$) emissions (0.116 nm) did not show a significant difference between fuels or %Δ*P*, and maintained a monotone increase with *F/A*.

THC emissions: The total hydrocarbon emissions show no trends directly related to *F/A*, fuel type, or %Δ*P*. For the 75 psia (0.52 MPa) pressure data, there is again a significant increase in THC concentration from *F/A* of 0.020 to 0.025 (Fig. 4). The smoke number data are not available for this *F/A* of 0.025.

It is possible that a *F/A* of 0.025 represents the combustor efficiency drop-off ratio as the amount of uncombusted or poorly combusted fuel rises significantly, contributing to higher emissions as shown in CO and THC data (Figs. 2 and 4).

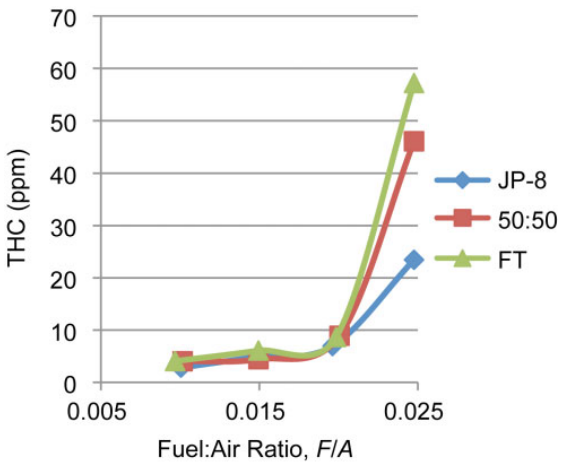


**Fig.4** Total hydrocarbon (THC) emission (ppm) variation with %FT fueling and *F/A* for combustor inlet pressure of 75 psia (0.52 MPa) at 5% Δ*P*. Trending for THC emissions is inconclusive, but the large emissions increase is again apparent as *F/A* approaches 0.025.

The data taken at the combustors shows that in the 75 psia (0.52 MPa) data, the combustor efficiency at *F/A* = 0.025 is slightly lower than the rest (Table 1). At a 3% Δ*P*, the efficiency of all fuel blends averages to 99.64% with a standard deviation of 0.024 for *F/A* of 0.010, 0.015, and 0.020. However, at 0.025, the average efficiency is 99.25% with a standard deviation of 0.058. Similar trends are shown at 4% Δ*P*, with averages and standard deviations of 99.56 and 0.011 as well as 99.05 and 0.080, respectively, along with 5% Δ*P* with averages and standard deviations of 99.47 and 0.013 as well as 98.99 and 0.181, respectively.

The efficiency difference between the first three *F/A* ratios and the fourth is much more significant than between the various types of fuel, as shown by the standard deviation. The data at 5% Δ*P* and *F/A* = 0.025 ratio is the one exception, as the difference between fuel blends is definite. The efficiency difference between fuel blends is more pronounced at higher %Δ*P* and *F/A*. The combustor efficiency for all three blends decreases as Δ*P* increases, but for all *F/A* values before 0.025 the efficiency differences between the blends are insignificant.

## Smoke and Photodiode Numbers

The smoke number measurements were taken by filtering an exhaust sample and comparing the change in reflectance. The smoke data and the total hydrocarbon emissions (THC, ppm) are expected to be somewhat correlated. The smoke number data from this testing run is partially incomplete, but the data obtained show some definite trends. Smoke number decreases as 100% FT fueling is approached, with more distinct decreases at higher *F/A* (Fig. 5). Figure 5 illustrates this with the available smoke number data.

**Table 1** Combustor efficiency data summary at 75 psia (0.52 MPa).

| Δ*P* | 3% | | 4% | | 5% | |
|---|---|---|---|---|---|---|
| *F/A* | 0.010–0.020 | 0.025 | 0.010–0.020 | 0.025 | 0.010–0.020 | 0.025 |
| Average | 99.64 | 99.25 | 99.56 | 99.05 | 99.47 | 98.99 |
| JP-8 | 99.61 | 99.32 | 99.56 | 99.10 | 99.46 | 99.20 |
| 50:50 | 99.65 | 99.24 | 99.56 | 99.09 | 99.46 | 98.90 |
| FT | 99.66 | 99.20 | 99.58 | 98.96 | 99.48 | 98.87 |
| St. Dev. | 0.024 | 0.058 | 0.011 | 0.080 | 0.013 | 0.181 |

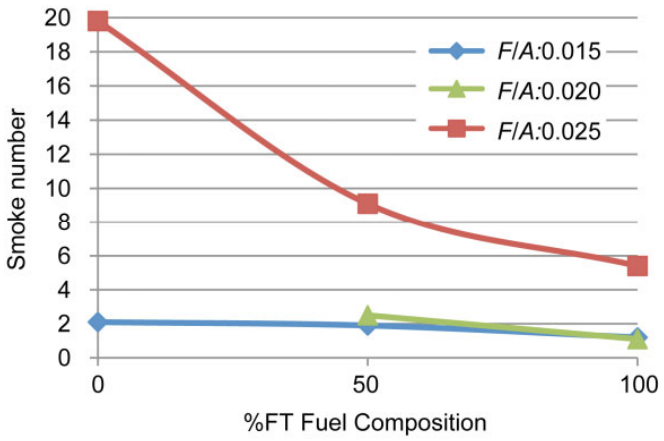


**Fig.5** Smoke number variation with %FT fueling for combustor inlet pressure of 175 psia (1.21 MPa) at 5% $\Delta P$ at varied *F/A*. The lower smoke number indicates that SPK-FT fuels are cleaner burning than JP-8 fuels, especially at higher *F/A*.

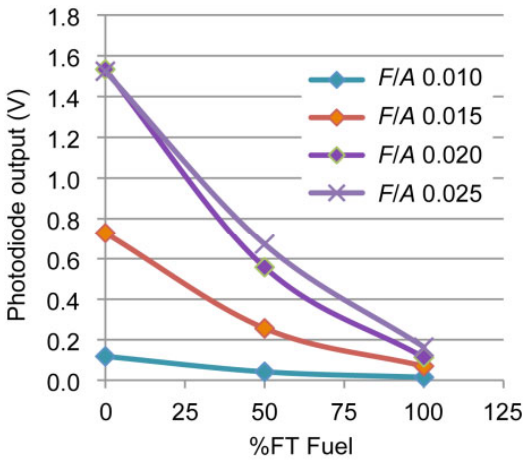


**Fig.6** Variation in photodiode voltage output with fuel blending at various *F/A* values, 75 psia (0.52MPa) at 5% $\Delta P$. The decrease in luminosity as the %FT fuel approaches 100% is demonstrated.

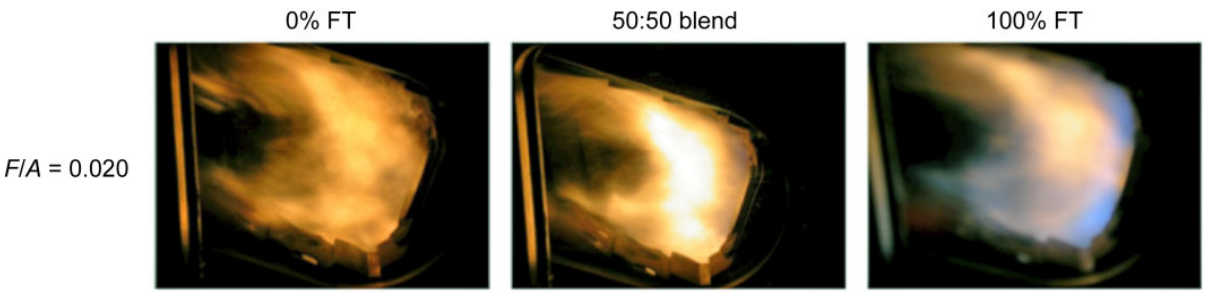


**Fig.7** Digital camera photographs showing flame changes with changes in fuel blend at *F/A* = 0.020. The JP-8 fuel is visibly more luminous.

The change in flame photodiode luminosity is related to all variables tested. It increases with *F/A* and decreases steadily with increasing %$\Delta P$ and %FT composition (Fig. 6). The decreased luminosity of the 50:50 blend and the FT fuel show that they are cleaner burning fuels than JP-8 (Fig. 7). The luminosity indicates carbon presence in the flames, and therefore the potential for carbon deposits within or coming through the engine to be released into the environment. The decrease in luminosity as the fuel blend approaches full FT fuel implies that the radiative heat loss is also decreasing as would liner temperature. This decrease occurs across increasing %$\Delta P$ and decreased *F/A* as well, signifying lower heat losses, cleaner burning, and a higher exit temperature from the combustor engine.

## Particulate Emissions

The particulate emissions of any fuel are of utmost concern for both environmental and human health. Like the gaseous emissions, they relate to engine temperature and pressure, %$\Delta P$, *F/A*, and fuel composition. The data available from this study does demonstrate the clear reduction in particulate emissions from FT fuel at all pressures and *F/A* values (Fig. 8). Because the particulate emission size-distribution data available from this particular study was not enough to make definite conclusions, the effects of particulates will be left for another paper. A figure of particulate sample size distributions has been included (Fig. 9) to illustrate again the significant difference between pure FT fuel and the blend and JP-8. The total number of particulates is visibly smaller, as is the peak size of the particles. This indicates the need for further studies into the size-related particle health effects. There are many analyses underway to characterize and compare particulate emissions for alternate fuels (e.g., alternative fuels testing on a C-17 aircraft [3]).

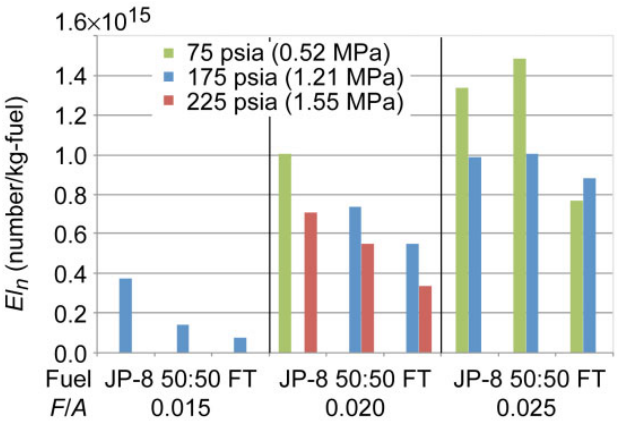


**Fig.8** Particulate emissions number index variations with test pressure and *F*/*A* for JP-8, 50:50 FT blend, and FT fueling. (Note: Test data set incomplete at 75 and 225 psia (0.52 and 1.55 MPa) for *F*/*A* = 0.015 and at 225 psia for *F*/*A* = 0.025) [1].

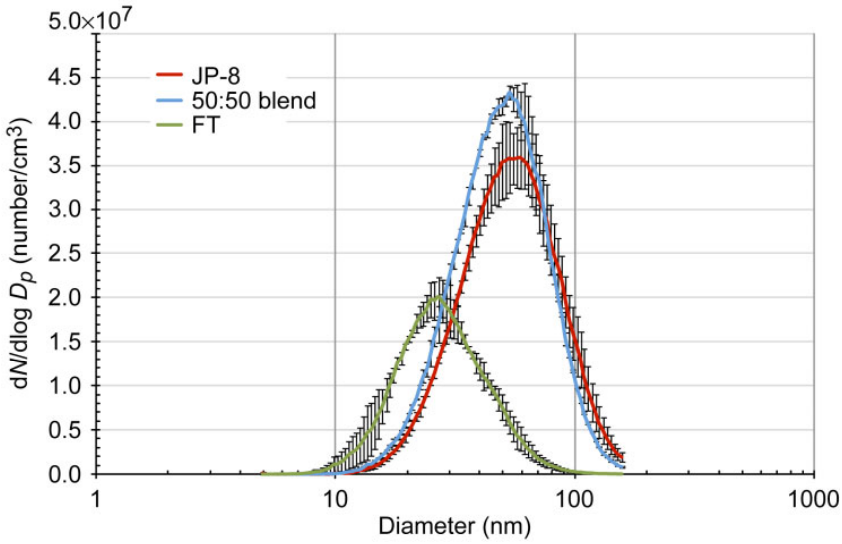


**Fig.9** Alternate fueling particle size distribution with JP-8, 50:50 FT blend, and FT for combustor pressure at 75 psia (0.52 MPa) and *F*/*A* = 0.025 [2].

The effect of these particulate emissions on human health has been concluded by a number of researchers, and the U.S. Environmental Protection Agency has launched a program involving multiple research centers to further investigate the hazards. The hazards include distress in respiratory and cardiovascular function—contributing to the development or worsening of common distresses such as asthma, chronic obstructive pulmonary disorder, angina pectoris, myocardial infarction (heart attack), and more. The possibility and problems associated with particles moving into the blood stream and being transported to other vital organs is also being considered [4].

## Engine Emissions Testing

Further testing that provides other insight into particulate emissions for both small and large engines has been done in collaboration with a large group of organizations, including government agencies, private industries, and educational institutions.

Testing run by General Electric showed that for alternate fuels, the emissions level of the regulated emissions (NOx, CO, hydrocarbons, and smoke number) were within the limits set for traditional fuels. The GE study observed power levels starting from idle through to take-off, capturing a full performance that the data in this paper does not span. This study corroborates our results, presenting alternative fuel emissions and indicating that similar trends occur all through the flying process, offering further insight for true life cycle analysis [5].

A small-engine test with similar fuel parameters to ours was conducted with a Pratt & Whitney small turbine engine, including 100% FT fuel and JP-8 as well as a 50% blend. The trends observed in this test were similar, with small reductions in NOx emissions as the SPK-FT fuel percentage increased, especially at higher power. The smoke number data was more conclusive, with the FT fuels having significantly lower smoke measurements than the JP-8 fuel [6].

Larger engine tests, such as those conducted in the Alternate Aviation Fuel Experiment (AAFEX) study [7], point in the same direction with regards to emissions trends. The C-17 test also tested both gaseous and particulate emissions data with similar results [3].

## Emissions Implications

The European Union has recently moved to implement a carbon emissions tax on airlines flying in and out of its airspace, an act that has enraged officials in foreign countries such as the United States and China. America's aviation industry contributes approximately 2% of greenhouse gas emissions, and a law requiring payment per metric ton of carbon emission would strike a huge blow to an already troubled industry [8]. In order to maintain current flight profit and availability as well as market competitiveness, it is necessary for countries to move towards alternate fuels such as those proposed in this paper.

## Discussion and Conclusions

Gathering preliminary data is essential for establishing baseline information to compare performance and emissions data for alternate-fuel-flexible combustor-sector systems. Observing pure SPK (FT) and blended fuel with respect to JP-8+100 fuels can lead to the future development of new, efficient, and effective combustor systems for these up-and-coming types of fuel. Fuel-flexible systems are the near-term goal for the industry, and analysis of combustor performance is necessary to continue down the alternative fuel path. The data from Combustor A summarized in this paper provide analysis and comparison based on a variety of engine variables.

Inlet temperature and pressure, fuel-to-air ratio, combustor pressure drops, and fuel blends were the parameters varied for this study.

Generally, the gaseous emissions varied more based on fuel-to-air ratio (*F/A*) than the fuel blend used. This indicates that both 100% FT and the 50:50 blend emit at or under currently acceptable rates. While the differences were not enormous, FT fuel did have generally lower NOx emissions, one of the primary regulated emissions species today. However, at higher *F/A*, the combustor efficiency drops and emissions increase more with FT fuel blends than JP-8.

The smoke number differences were very distinct and point to the fact that, as hoped, SPK fuels are cleaner burning than JP-8 fuels, and the 50:50 blend is an intermediate step towards environmentally friendly fuel. It is important to note that a 50:50 blend does not directly correlate to a 50% reduction in smoke or emissions, which has implications towards the effectiveness of using a blend as an economic substitute.

Multiple studies and data sets show that SPK fuel and fuel blends do not have a significant negative impact on the performance of combustor sector systems, and that emissions produced certainly do not exceed the current limitations on traditional fuel. Taking into account the life cycle analysis and emissions reduction for alternate fueling, these SPK fuels are a promising near-term alternative for jet fuels.

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