Partnership for AiR Transportation
Noise and Emissions Reduction
An FAA/NASA/Transport Canada-
sponsored Center of Excellence

SAE E31 Methodology Development and Associated PM Emissions Characteristics of Aircraft APUs burning Conventional and Alternative Aviation Fuels

PARTNER Project 34 Final Report

prepared by

Prem Lobo, Philip D. Whitefield, Donald E. Hagen, Lucas J. Rye, Simon Blakey, Christopher W. Wilson, Paul I. Williams, Simon Christie, David Raper, Ilona Uryga-Bugajska, Mohamed Pourkashanian

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U.S. Department of Transportation
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FINAL PROJECT REPORT

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PART I - PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. FAA Program	3. FAA Award Number
Missouri University of Science and Technology, G-7 Norwood Hall, 320 W. 12th Street, Rolla, MO 65409	PARTNER	07-C-NE-UMR, Amendment No. 9
	4. Award Period From To 07/01/2009 12/31/2009	5. Cumulative Award Amount $60,000.00

6. Project Title

SAE E31 Methodology Development and Associated PM Emissions Characteristics of Aircraft APUs burning Conventional and Alternative Aviation Fuels

SUMMARY OF COMPLETED PROJECT (For Public Use)

This report summarizes the findings of an international collaborative study to study the impact of alternative fuels on the emissions characteristics of an aircraft auxiliary power unit (APU) while at the same time acquiring information to resolve SAE E-31 related sampling methodology issues. The experimental campaign was conducted at the University of Sheffield's Low Carbon Combustion Centre during September 21 - October 01, 2009 using a recommissioned Artouste Mk113 APU as the emissions source. Emissions data was acquired when the APU was running in the idle and full power modes. The fuels used in this study included conventional Jet A1, a coal-based Fischer-Tropsch fuel – cTL, a natural gas derived Fischer-Tropsch fuel – gTL, a 50:50 blend of gTL and Jet A1, biodiesel and diesel. Reduction in PM number and PM mass concentration is observed for the gTL, 50:50 gTL:Jet A1 and Biodiesel fuels compared to Jet A1 at the two APU operating conditions. Difference in PM size distributions observed when dilution was introduced at the probe tip vs. downstream were due to agglomeration of PM (<20nm) prior to dilution in the downstream case. Statistically significant differences are observed in the number-based EI's measured in the high power sampling regime but no statistically significant differences are observed in the mass-based EI's or the number-based EI at idle.

PART III - TECHNICAL INFORMATION (For Program Management Uses)

1. **ITEM** (Check appropriate blocks)	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM	
				Check (X)	Approx. Date
a. Abstracts of Theses					
b. Publication Citations					
c. Data on Scientific Collaborators					
d. Information on Inventions					
e. Technical Description of Project and Results					
f. Other (specify)					

2. Principal Investigator/Project Director Name (Typed)	3. Principal Investigator / Project Director Signature	4. Date
Philip D. Whitefield		

Center of Excellence for Aerospace Particulate Emissions Reduction Research

PARTNER

FINAL REPORT

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Prepared by

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The research team would also like to acknowledge the sponsorship of the Shell Petroleum Company, the EU FP6 Network of Excellence on Environmentally Compatible Air Transport System (ECATS) and the Missouri University of Science and Technology Center of Excellence for Aerospace Particulate Emission Reduction Research.

Any opinions, findings, conclusions, or recommendations expressed in this report are those of the authors, and do not necessarily reflect the views of the sponsors.

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Abstract

This report summarizes the findings of an international collaborative study to study the impact of alternative fuels on the emissions characteristics of an aircraft auxiliary power unit (APU) while at the same time acquiring information to resolve SAE E-31 related sampling methodology issues. The experimental campaign was conducted at the University of Sheffield's Low Carbon Combustion Centre during September 21 - October 01, 2009 using a recommissioned Artouste Mk113 APU as the emissions source. Emissions data was acquired when the APU was running in the idle and full power modes. The fuels used in this study included conventional Jet A1, a coal-based Fischer-Tropsch fuel – cTL, a natural gas derived Fischer-Tropsch fuel – gTL, a 50:50 blend of gTL and Jet A1, biodiesel and diesel. Reduction in PM number and PM mass concentration is observed for the gTL, 50:50 gTL:Jet A1 and Biodiesel fuels compared to Jet A1 at the two APU operating conditions. Difference in PM size distributions observed when dilution was introduced at the probe tip vs. downstream were due to agglomeration of PM (<20nm) prior to dilution in the downstream case. Since this difference appears in total and non-volatile distributions, the agglomerating PM are not volatile PM. Statistically significant differences are observed in the number-based EI's measured in the high power sampling regime but no statistically significant differences are observed in the mass-based EI's or the number-based EI at idle.

Executive Summary

This report summarizes the findings of an international collaborative study entitled "**SAE E31 Methodology Development and Associated PM Emissions Characteristics of Aircraft APUs burning Conventional and Alternative Aviation Fuels.** The report describes the results of a 2-week measurement campaign focusing on SAE E31 extractive sampling methodology research needs and PM emissions from conventional and alternative fuels burned in an older technology APU. This work was performed in collaboration with an ECATS-Shell sponsored research project at the University of Sheffield in the UK. It is important to note that funding this proposal provided a cost effective solution to some key PARTNER objectives. As is always the case in such studies the lion's share of the cost comes from providing and operating the facilities to generate the PM emissions of interest. The ECATS Shell investment in this project was budgeted to exceed $750,000 whereas the PARTNER cost was $60,000.

The objectives of this study were:

- To address SAE E31 research needs in an engine laboratory setting. The laboratory environment provides a more hands-on approach to exploring research needs associated with probe design and sample tubing. Modifications to the sampling system can be made quickly. This is not the case in measurement campaigns where larger engines are used as the emissions source.
- To gather a data set on the physical characteristics of PM emissions for an older technology aircraft APU. These data will be used to populate the PARTNER sponsored PM database with first of a kind data on older technology APU PM emissions. Such measurements will provide a technology baseline from which to compare the emissions of more current APU combustors analogous to the JT8D data gathered early in the Delta Atlanta Hartsfield study. The APU burned both conventional and candidate alternative aviation fuels provided by Shell. The alternative fuels objective served to provide not only first of a kind data on non-US developed alt. fuel candidates but provides PARTNER and CAAFI with intimate access to European funded research in this area guided by ECATS - the EU FP6 Network of Excellence on 'Environmentally Compatible Air Transport System'

The experimental campaign to evaluate the gaseous and PM emissions characteristics of an aircraft APU burning several alternative fuels was conducted at the University of Sheffield's Low Carbon Combustion Centre during September 21 - October 01, 2009. The project team included members from teams from Missouri University of Science and Technology (Missouri S&T), Sheffield University, Manchester University, Manchester Metropolitan University and Leeds University.

A re-commissioned Artouste Mk113 APU, located at the University of Sheffield's Low Carbon Combustion Centre, was used as the test bed for the emissions measurements. The APU was instrumented to monitor and record key engine operating conditions, such as temperatures, pressures, engine RPM, fuel flow rates etc. Emissions data was acquired when the APU was running in the idle and full power modes. The fuels used in this study included conventional Jet A1, a coal-based Fischer-Tropsch fuel – cTL, a natural gas derived Fischer-Tropsch fuel – gTL, a 50:50 blend of gTL and Jet A1, biodiesel and diesel.

The following conclusions were drawn from this study:

SAE E31 Probe tip versus downstream dilution:

- Difference in PM size distributions observed when dilution is introduced at the probe tip vs. downstream were due to agglomeration of PM (<20nm) prior to dilution in the downstream case.

- Since this difference appears in total and non-volatile distributions, the agglomerating PM are not volatile PM.

- Statistically significant differences are observed in the number-based EI's measured in the high power sampling regime but no statistically significant differences are observed in the mass-based EI's or the number-based EI at idle.

Alternative fuels versus conventional fuels:

- The emissions of the Biodiesel fuel are higher than those for Jet A1 and the natural gas derived Fischer Tropsch fuel. The increase in PM emissions with Biodiesel can be attributed to the strong propensity of biodiesel to form volatile PM which is evidenced in the differences in the total and non-volatile size distributions. From compositional analysis performed using the AMS, the volatile PM was identified to be organic material.

- Reduction in PM number and PM mass concentration is observed for the gTL, 50:50 gTL:Jet A1 and Biodiesel fuels compared to Jet A1 at the two APU operating conditions – idle and full power.

- The smoke numbers for the alternative fuels (cTL, gTL, gTL blend and biodiesel) are all lower compared to that for Jet A1. The smoke number for diesel is higher than Jet A1 by a factor of 2.

1.0 Background

1.1 Introduction

Supply security and increasing environmental concerns are continually placing increasing pressure on the transport sector to diversify away from conventional petroleum products. In the European Union, Directives are in place to encourage this diversification towards product refined from renewable feedstock. The most recent Directive (2009/28/EC (European Union, 2009)) – which was introduced to amend concerns that previous targets specified in 2003/30/EC were damaging the environment and causing social issues (Harrabin, 2008) – specifies that by 2020, at least 10% of the energy used in each member state's transport sector must come from renewable resources.

The impact of the airport operations on the local air quality in and around airports is of prime importance as airports expand to accommodate increased demand. A growing number of airports around the United States and in Europe are studying measures to assess and reduce airport emissions. The major sources of emissions at airports include aircraft engines, auxiliary power units (APUs), ground support equipment (GSEs) and ground service vehicles (GSVs). Recently, the development of alternative fuels for use in gas turbine engines has been gaining momentum. Fuels derived from biomass via hydro-processing, or synthesis from coal or natural gas via the Fischer-Tropsch (FT) process are being considered for use in the aviation sector as "drop-in" alternative fuels (Rye et al., 2010).

Several flight demonstrations of commercial aircrafts burning various blends of conventional jet fuel and either biomass or FT fuels have been conducted recently (Blakey et al., 2011). Measurement campaigns focusing on the use of alternative fuels in military and commercial aircraft engines have shown that alternative fuels significantly reduce PM emissions (Corporan et al. 2007; Anderson et al., 2011, Lobo et al., 2011). Reduction in PM is of particular interest in terms of local air quality. Adverse health effects, including the development or exacerbation of respiratory tract diseases have been linked to the inhalation of small airborne exhaust particles (Donaldson et al., 2002). This is due to the higher probability of the small particles being deposited deep within the respiratory tract (Oberdörster et al., 2005).

The lack of availability of aircraft engines for emissions testing using alternative fuels and the costs associated with running such engines make them impractical to use for such evaluation applications. APUs however, are well suited to perform evaluations of alternative fuels for use in the aviation sector.

Data is urgently needed by the SAE E-31 committee to resolve outstanding sampling methodology issue before it can draft and ballot an aerospace recommended practice (ARP) for aircraft non-volatile PM. Sampling methodology issues such as comparing the effect of probe tip vs. downstream dilution can easily be accomplished in a laboratory setting.

1.2 Project Objectives

1.2.1 Focus on developing methods and acquiring additional data associated with extractive sampling under engine laboratory conditions.

The sampling methodology development focuses on several research needs identified by the SAE E31 committee under laboratory conditions using an APU as an emission source. The laboratory environment provides a more hands-on approach to exploring research needs associated with probe design and sample tubing. Modifications to the sampling system can be made quickly. This is not the case in measurement campaigns where larger engines are used as the emissions source. The SAE E31 research needs have been recognized not only by the FAA but also by the EPA and EASA as critical issues requiring resolution if an ARP for certification testing including PM characterization is to be approved and implemented.

1.2.2 Perform a high quality multidimensional study of PM emissions from APU engines burning conventional and alternative jet fuels.

The proposed study is to perform a high quality multidimensional study of PM emissions from an older technology aircraft APU burning conventional jet fuels (Jet A, Jet A1 etc.) and candidate alternative aviation fuels, coupling source emissions at the exhaust plane and in the near field to define specific source profiles that along with emissions inventories can produce reliable source apportionment estimation tools for airports. These high quality multidimensional studies will be modeled on the successful approach developed by the Missouri S&T team during the recent APEX and AAFEX measurement campaigns. They will include a thorough physical (size, number, mass, hydration properties etc.) analysis at the emissions source and in the near field (<20m downstream). Experience dictates that definitive jet engine emission studies should be performed in open test cell conditions where the emission source i.e. APU's are well instrumented for operational parameter control and acquisition.

Within these broad objectives, some of the specific questions addressed included:

1. Sampling methodology experiments
    a. Dilution study – dilution introduced at probe tip vs. downstream
2. Baseline fuel emissions as function of APU operating condition at 1m
    a. Particle size, number, mass, composition
3. Alternative fuels emissions as a function of APU operating condition at 1m
    a. Particle size, number, mass, composition
4. Downstream emissions characterization as a function of fuel and APU operating condition at exit of exhaust duct
    a. Particle size, number, mass, composition

2.0 University of Sheffield APU Study

An experimental campaign to evaluate the gaseous and PM emissions characteristics of an aircraft APU burning several alternative fuels was conducted at the University of Sheffield's Low Carbon Combustion Centre during September 21 - October 01, 2009. The project team included members from teams from Missouri University of Science and Technology (Missouri S&T), Sheffield University, Manchester University, Manchester Metropolitan University and Leeds University.

2.1 Auxiliary Power Unit (APU)

A re-commissioned Artouste Mk113 APU (Figure 1), located at the University of Sheffield's Low Carbon Combustion Centre, was used as the test bed for the emissions measurements. The APU was instrumented to monitor and record key engine operating conditions, such as temperatures, pressures, engine RPM, fuel flow rates etc. Table 1 lists the nominal values for Exhaust Gas Temperature (EGT), Air Fuel Ratio (AFR) and Fuel flow rate achieved when the APU was burning Jet A1 at two operating conditions - idle and full power.

Table 1: Nominal APU Operating Conditions

APU Operating Condition	Exhaust Gas Temperature (ºC)	Air Fuel Ratio	Fuel flow rate (lb/hr)
Idle	445	80	122
Full Power	460	76	240

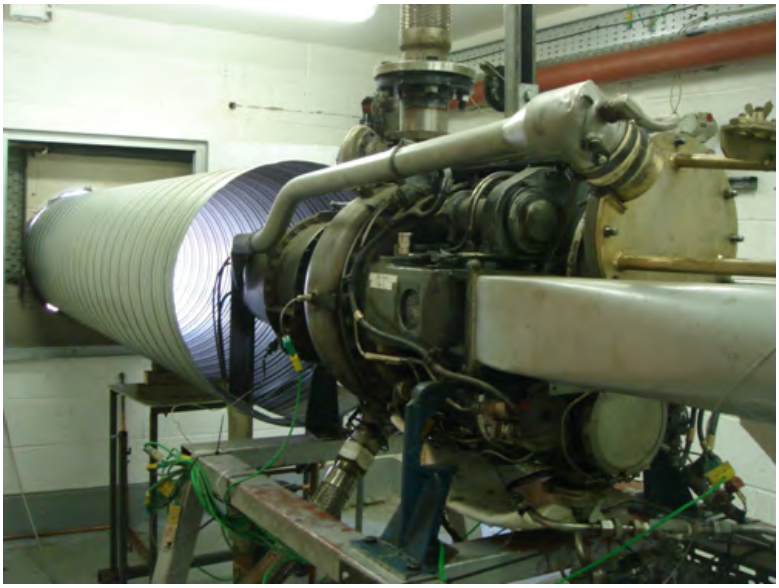

Figure 1: Recommissioned Artouste Mk113 APU

2.2 Fuels

The fuels used in the study along with their fuel properties are listed in Table 2.

Table 2: Properties of fuels being studied

Fuel	Density (g/l)	Energy Content (MJ/kg)	Fuel H/C ratio	Fuel Sulfur content (ppm)	Fuel Aromatic content (%v)
Jet A1	801.9	43.2	1.90	700	18.5
cTL	781.2	43.7	2.14	100	10.9
gTL	737.9	43.8	2.20	5	0
50 :50 gTL: Jet A1	769.9	43.5	2.05	352.5	9.2
Biodiesel	880	39.0	1.86	5	0
Diesel	N/A	N/A	1.80	46	N/A

2.3 Set Up and Instrumentation

A stainless steel plate was fixed behind the APU exhaust so that the installed sampling probes would sit no further than half an exhaust diameter behind the engine exhaust plane as required per the Aerospace Recommended Practice (ARP1256) (SAE, 2006). Exhaust blockage was no more than 5% of the exhaust exit plane. Three sample probes were mounted on the steel plate, two of which supplied PM samples to Missouri S&T and Manchester University. A third water cooled gaseous emissions probe was used to supply sample to Sheffield University. These probes have been used in previous measurement campaigns to extract PM and gas samples from a gas turbine engine (Wey et al., 2007). A schematic of the setup used for the study is presented in Figure 2. A probe sampling the APU exhaust after it had cooled and mixed with ambient air was positioned approximately 10m from the APU exit plane.

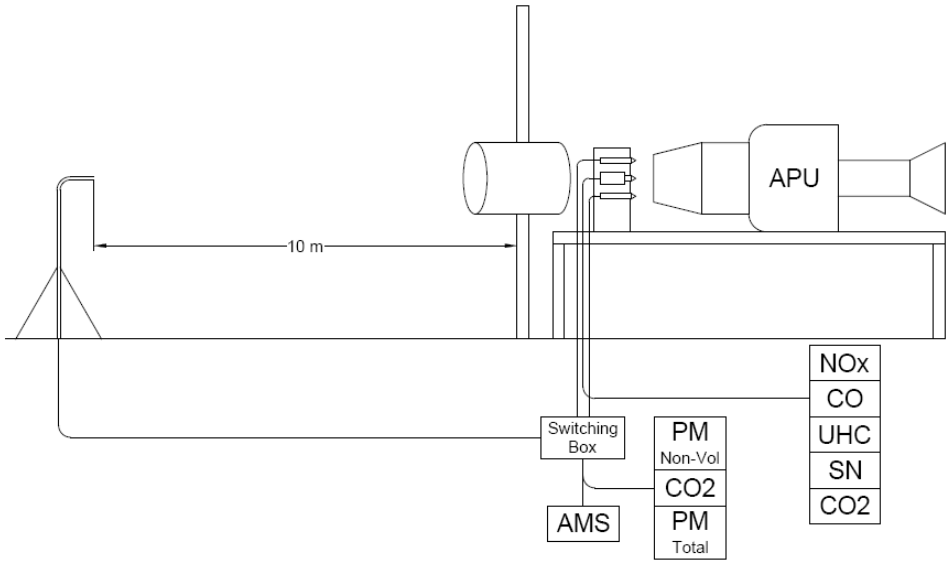

Figure 2: Schematic of the test set up with diagnostic instrumentation

Conditioned exhaust sample was drawn into the Sheffield University Mobile Emissions Laboratory through a 1/4 inch heated line before being split between the gaseous analysis suite and smoke meter using a y-connector. The sample lines were maintained at 150□C per ARP1256c (SAE, 2006), with a minimum bend radius of 10x the line diameter. Gaseous emissions (Unburned Hydrocarbon 'UHC' and Carbon Monoxide 'CO') were measured per ARP1256c (SAE, 2006), with instruments zeroed then spanned just prior to each experiment. UHC was monitored using a flame ionization detector (Signal 3000-M hydrocarbon analyser), with CO measured using a non-dispersive infrared analyser (Rosemount Binos 1000). Corrected emission indices (mass of pollutant measured (grams) per kilogram of fuel) were calculated per ARP1533a (SAE, 2004). Detail of the complete Sheffield University gaseous analysis equipment has been provided in earlier work (Leong et al., 2010). SAE smoke number was established using a Richard Oliver smoke meter, Whatman no. 4 filter paper and a reflectometer (BOSCH ETD 02050) per ARP1179c (SAE, 1997). The technique involves passing a set volume of sample through the conditioned filter paper, and measuring the change in the absolute reflectance of the filter paper due to the PM collected. The smoke number measurement procedure involved inserting a piece of filter paper (of known reflectance) into the pre-conditioned (per ARP1179c) sampling block of the Richard Oliver smoke meter. Once on condition, the user activated a solenoid which directed the exhaust sample through the conditioned sampling block. After sufficient volume had been sampled (9.2 l), the unit automatically returned to bypass mode and the filter was removed and its reflectance value measured. The procedure was repeated three times during both the idle and full power condition. It should be noted that sampling was not conducted at the hot idle condition as the inherent extra heat generated during the full power condition did not dissipate to a stable baseline prior to engine shutdown.

The primary PM probe permitted sample dilution at the probe tip with particle free dry N2 gas., thereby reducing and/or eliminating condensation, agglomeration and gas-to-particle conversion in the sampling system. PM-laden exhaust was extracted from the APU exhaust flow through the PM sampling probe and supplied to the Missouri S&T and Manchester University instrumentation suite located approximately ~20m away, using 3/8 inch stainless steel tubing. The PM sampling lines were not heated, with the sample temperature reaching ambient conditions prior to the instrumentation. Modification of the PM size spectrum due to inertial, thermophoretic, and diffusional effects is an artifact associated with extractive sampling. While it is harder to experimentally quantify losses due to thermophoretic effects, inertial and diffusional losses can be estimated by calibration (Lobo et al., 2007). In this study a size dependent line loss function from the probe tip to the PM instrumentation was determined and applied to the instrument data to yield an estimate of the PM size distributions at the point of entry into the sampling system.

The Missouri S&T suite included two Cambustion DMS500s to gather real–time size distribution information and concentration of exhaust PM over the full particle size spectrum from 5nm to 1000nm. One DMS500 measured the total PM, while the second DMS500 had a thermal denuder (operating at 300°C) upstream of it to remove any volatile PM and thus

measured the non-volatile PM. The DMS500 has a fast size distribution measurement rate (up to 10 Hz) (Biskos et al., 2005) and has been previously used to sample gas turbine engine exhaust (Lobo et al., 2007). A fast response CO2 detector (Sable Systems model CA-2A) was used to monitor exhaust sample dilution.

The University of Manchester provided a High Resolution, Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS), manufactured by Aerodyne Research Inc., for measuring the sub-micron, none-refractory PM composition. Briefly, the HR-TofToF-AMS samples PM into a vacuum chamber where they are impacted onto a heated surface held at ~approximately 600°C. Particles with a volatilization temperature of 600°C or less are vaporized to form a kinetic gas. The gas is then ionized by electron impaction at 70evV, and the ions are extracted into an ion time-of-flight mass spectrometer. The vaporization occurs in an oxygen free environment. The inlet of the instrument has 100% efficiency for particles in the size range ~60 – 600nm, and falls rapidly to zero either side of that window.

The HR-ToF-AMS yielded three data types from two measurements modes. In Mass Spectrum (MS) mode, the HR-ToF-AMS provided compositional information from ~8 – 530 mass-to-charge (m/z) ratios with unit mass resolution. In Particle Time-of-Flight (PToF) mode, compositional information as a function of size at each m/z is produced. For the third data type, the MS data is analyzed in more detail, to give sub 1 m/z resolution information. The HR-ToF-AMS is an online, real-time instrument, where data was averaged over 30 seconds, with the instrument switching between MS and PToF during each save cycle. Details of the HR-ToF-AMS are provided elsewhere (DeCarlo et al., 2006).

3.0 Results and Discussion

3.1 Effect of Probe tip vs. Downstream Dilution

Gas turbine exhaust PM is very reactive on the fraction of a second time scale; they can interact with each other and with gas phase species in the exhaust, e.g. water vapor, to produce changes in concentration, composition, and size distribution. The sample train must be designed and operated with these processes in mind so as to minimize the artifacts that they can produce. Dilution with clean dry air or dry nitrogen is one technique that has been employed to suppress these reactions. The optimum point in the sample train to introduce the diluent is as early as possible, i.e. at the probe tip. In this campaign some measurements were performed to compare the impact of diluting 1-2m downstream, as compared to probe tip dilution. Several significant changes in the aerosol's characteristics can be observed in the results and be attributed to processes occurring in the sample before dilution.

Figures 3 and 4 explore the PM volatile components by comparing their size distributions with (non-volatile - NV) and without (total) passage through a thermal denuder. Figure 3 shows data taken from the sample train using probe tip dilution, has been corrected for dilution and line loss, and represents size distributions in the engine exhaust stream at probe tip. For both engine power conditions, idle and full power, the total and NV curves overlap, indicating that no volatile materials condensed onto the soot particles. The situation is different for the data taken with downstream dilution as reflected in Figure 4. The idle-NV curve shows the typical lognormal shape. The idle (total) size distribution shows evidence of gas-to-particle conversion; volatile material condensed onto the particles, the size distribution and its peak moved to the right. This is observed for both engine power conditions.

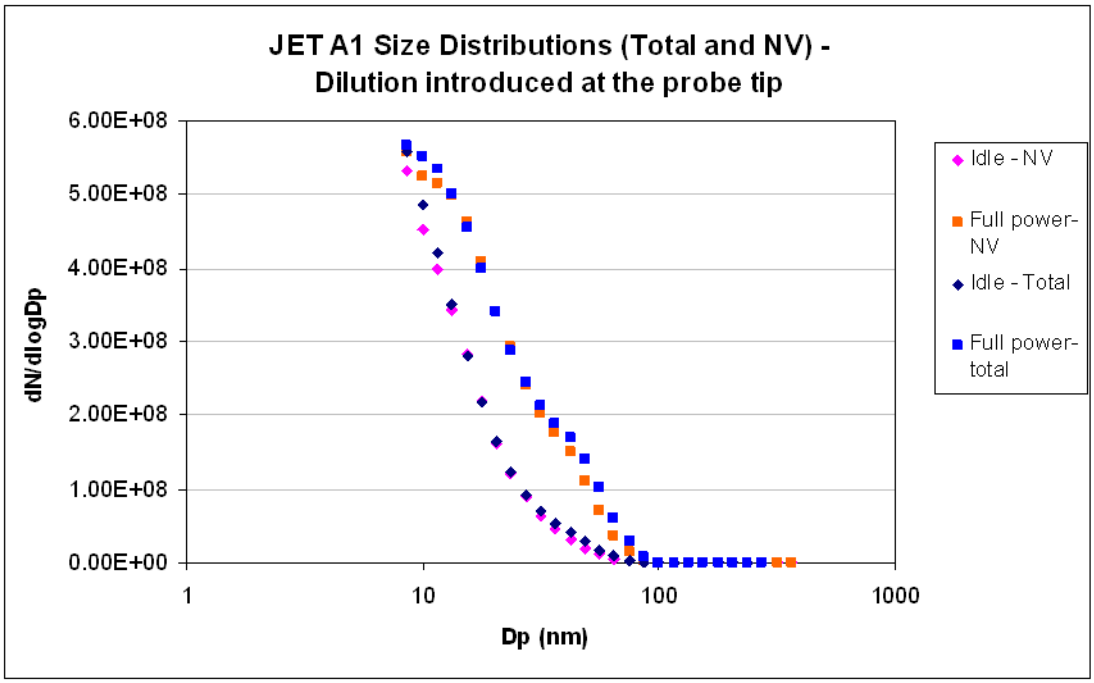

Figure 3: Total and Non-volatile PM size distributions when dilution was introduced at the probe tip

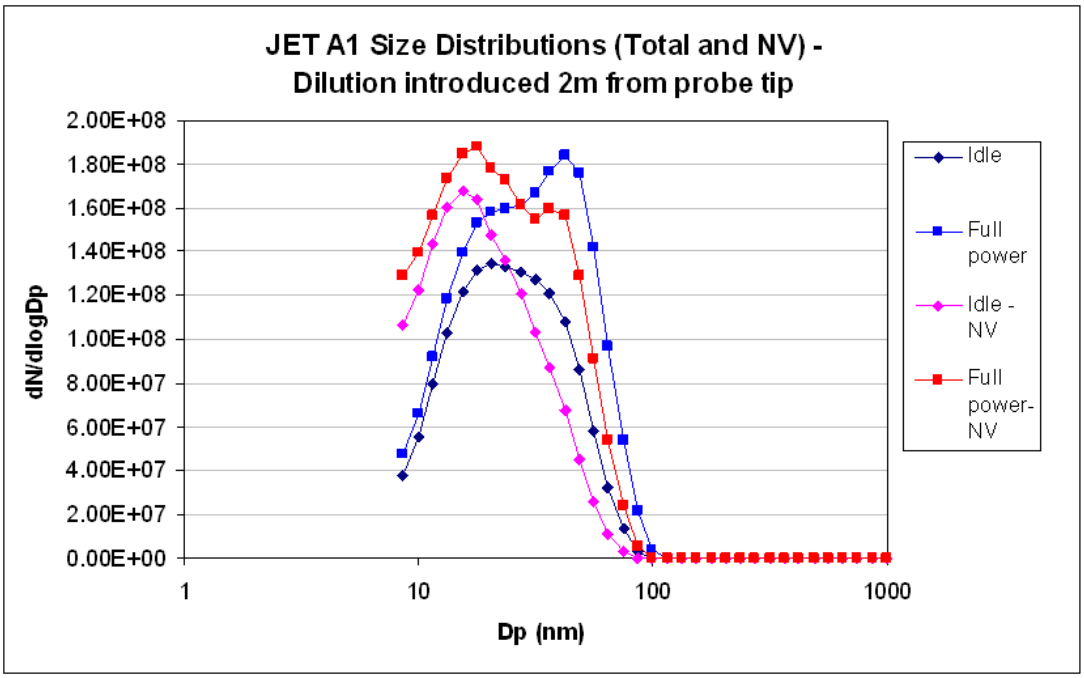

Figure 4: Total and Non-volatile PM size distributions when dilution was introduced 2m downstream of the probe tip

Figure 5 shows the effect of probe tip dilution separately for the cases of total and non-volatile PM. In the Total PM plot a comparison of the idle Probe 1 (tip dilution) and Probe 2 (downstream dilution) shows an agglomeration effect; small particles having high diffusion velocities collide, stick, and form larger aggregates. The small particle populations decrease and the larger ones increase. The same effect can also be seen in the full power case.

The same agglomeration effect can be seen in the "Non V. PM" plot; the small diameter modes seen with probe tip dilution (probe 1) are greatly diminished by the downstream dilution sample train. This occurs for both power conditions, although the increase in the large size bins is down in the noise for the full power case.

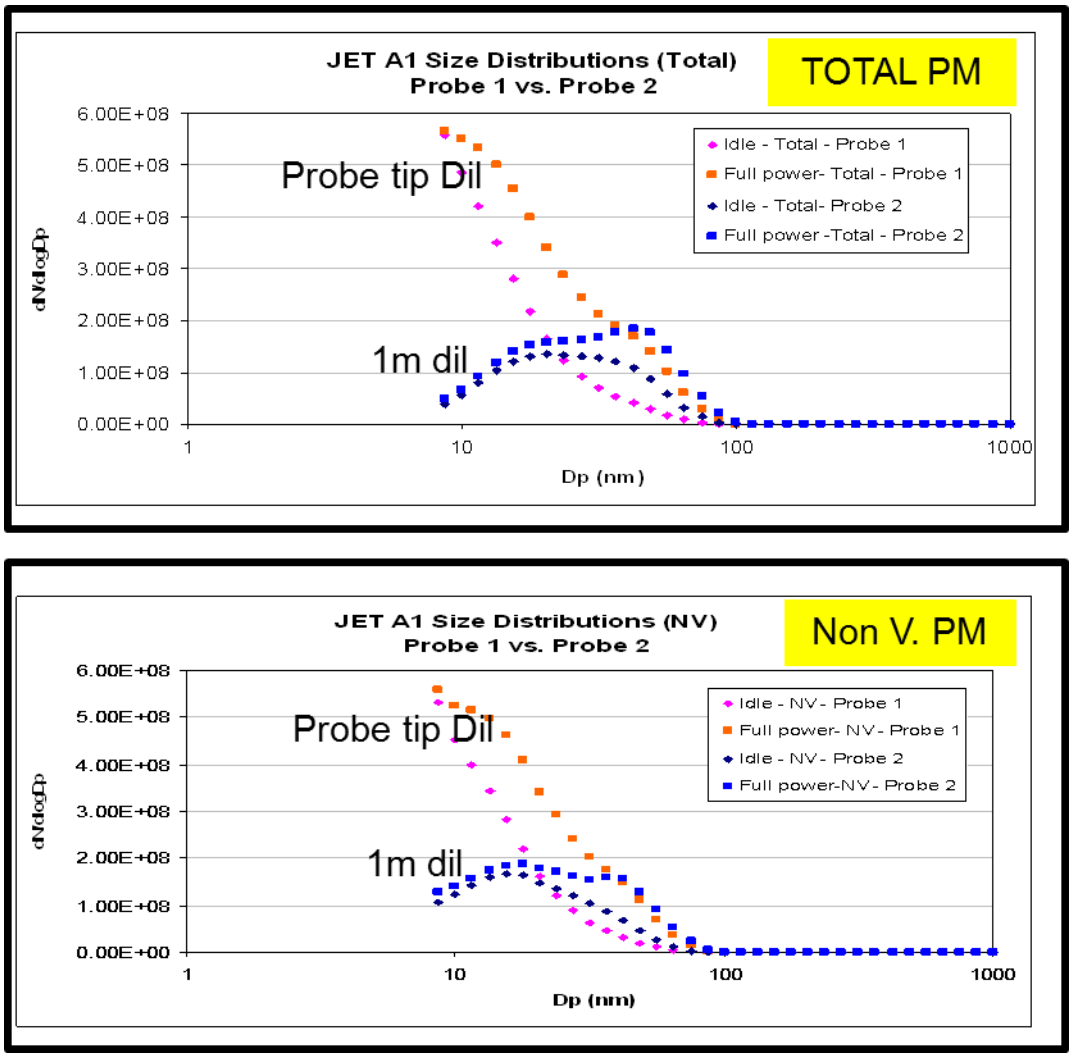

Figure 5: Effect of probe tip dilution vs. downstream dilution in terms of total and non-volatile PM size distributions.

Figure 6 gives a comparison between probe tip and downstream dilution in terms of the number based non-volatile emissions index, number of particles per kg of fuel burned. The gas-to-particle process, active in the first section of the sample train before dilution, increases the particle number count and hence the number based emissions index. For both engine power conditions the number based emissions index is higher for probe tip dilution as compared to downstream dilution. However for the idle condition the measurement error bars overlap, so this difference is not statistically significant. A statistically significance is seen for the full power case. Figure 7 shows a similar comparison for the mass based emissions index. For the mass based emissions index there is no statistically significant effect, since the gas-to-particle conversion process tends to produce small particles, which represent little mass.

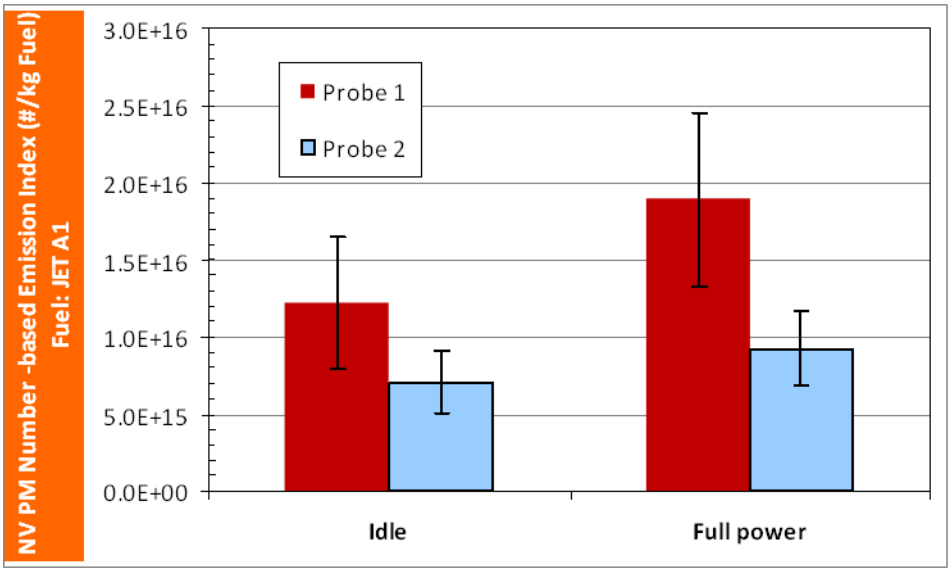

Figure 6: Comparison between probe tip and downstream dilution in terms of the non-volatile number based emissions index

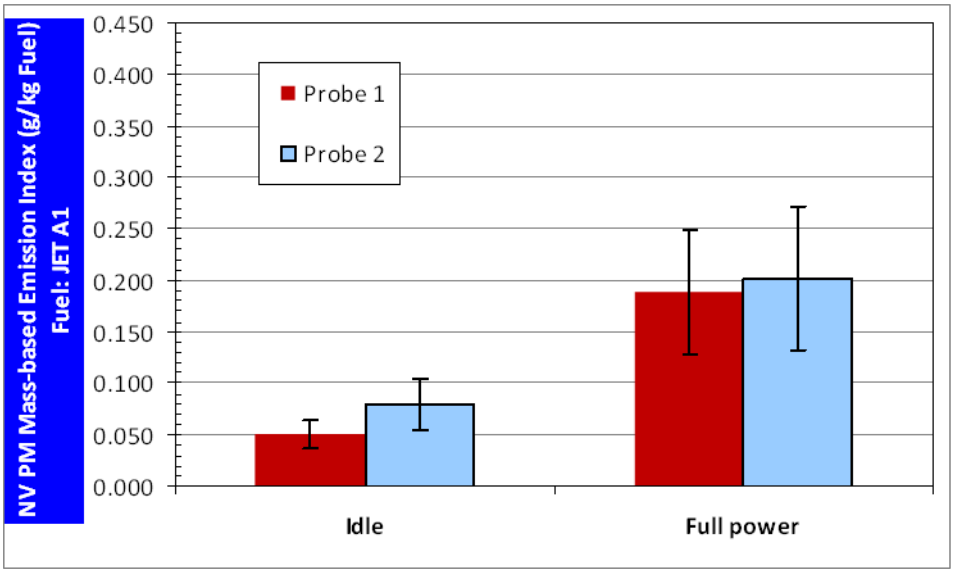

Figure 7: Comparison between probe tip and downstream dilution in terms of the non-volatile mass based emissions index

3.2 Emissions Characteristics of Alternative Aviation Fuels

3.2.1 Size Distributions

Total and non-volatile PM size distributions were measured by the DMS500s when the APU was burning Jet A1 and the alternative fuels for the idle and full power operating conditions. The size distributions for selected fuels are presented in figures below, using the same ordinate scale, when the APU was burning Jet A1 (Figure 8), gTL (Figure 9) and Bio-diesel (Figure 10). From the size distributions, it is apparent that the emissions of the Biodiesel fuel are higher than those for Jet A1 and gTL.

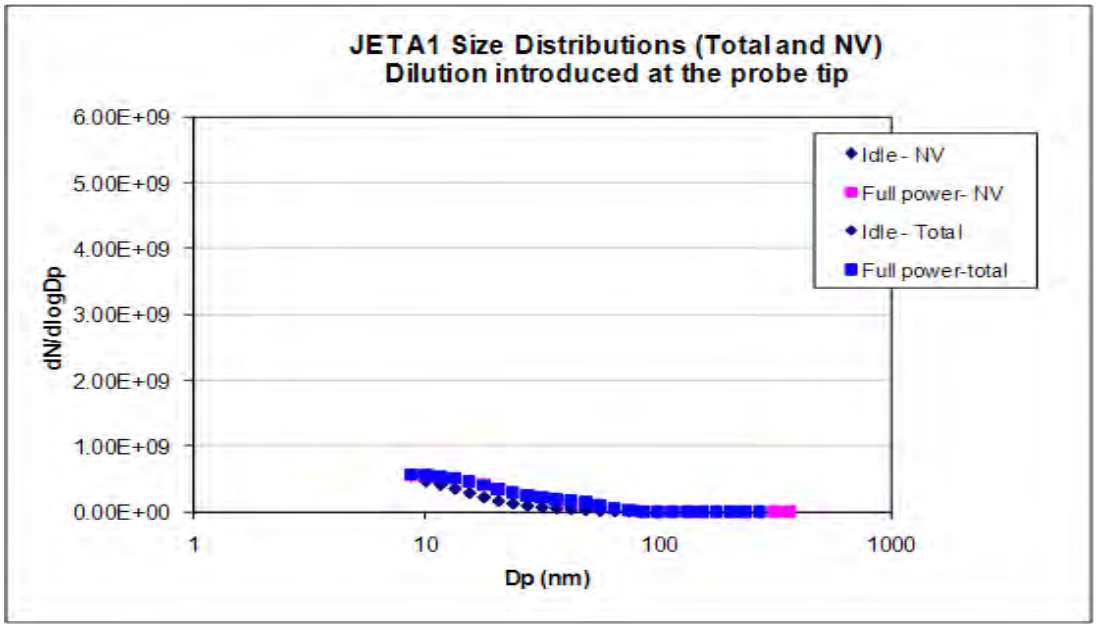

Figure 8: Total and non-volatile PM size distributions when the APU was burning Jet A1 at the idle and full power operating conditions

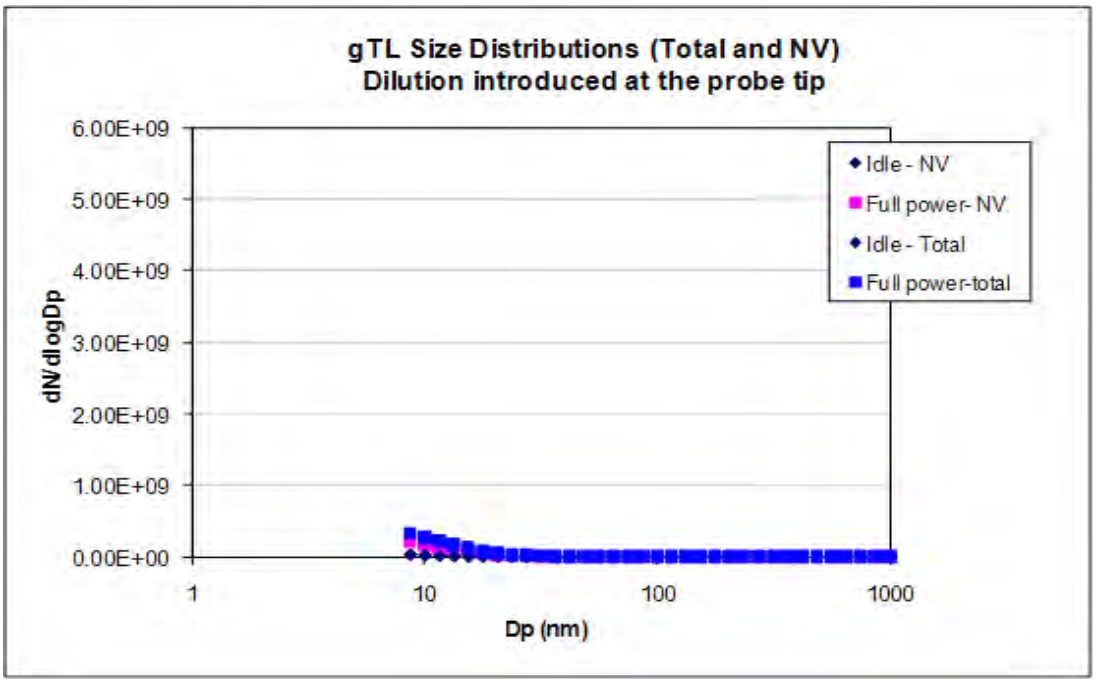

Figure 9: Total and non-volatile PM size distributions when the APU was burning gTL at the idle and full power operating conditions

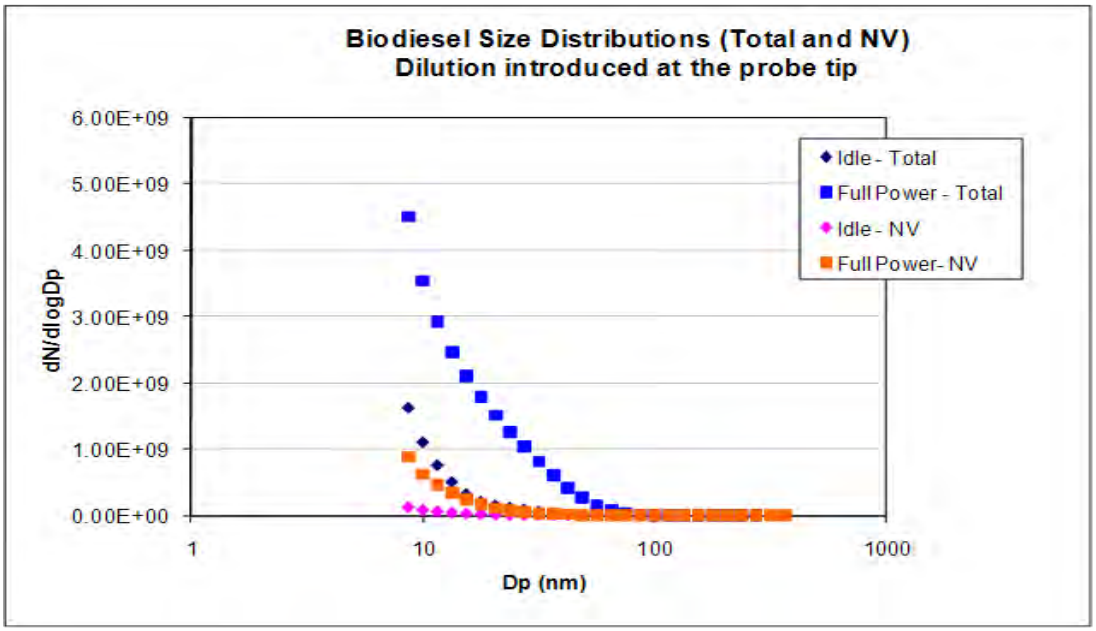

Figure 10: Total and non-volatile PM size distributions when the APU was burning Biodiesel at the idle and full power operating conditions

The increase in PM emissions with Biodiesel can be attributed to the strong propensity of biodiesel to form volatile PM which is evidenced in the differences in the total and non-volatile size distributions. From compositional analysis performed using the AMS, the volatile PM was identified to be organic material.

Figure 11a – d shows the average mass spectra for Jet A-1 and biodiesel, with probe tip dilution for idle and full power test conditions. The mass spectra are shown between m/z 10 – 150, where the majority of the mass is located. For the idle conditions, the HR-ToF-AMS was able to measure some volatile/semi-volatile material from biodiesel, whereas for Jet A-1 the mass spectrums are effectively showing noise. At full power, the difference between Jet A-1 and biodiesel is markedly different, with significantly more organic material produced or condensed from the biodiesel. Furthermore, the relative peak heights of the two fuels are different, indicating the type of the organics measured are different.

Data presented in figure 11a – d are for unit mass resolution; however the signal at a given m/z can contain material from several components. For example, m/z 48 will have contributions from SO and C_4. Determining how much signal at m/z 48 belongs to each component is achieved by either pre-defining a ratio based on previous data or by examining the high resolution information which can separate out the components. Analysis of the high resolution data showed that there were small amounts of sulphate present, but that the levels were close to the limit of detection of the instrument and the limit of the tools used to extract the information. Therefore, no quantifiable information or differences between the two fuels and the PM sulphate is given.

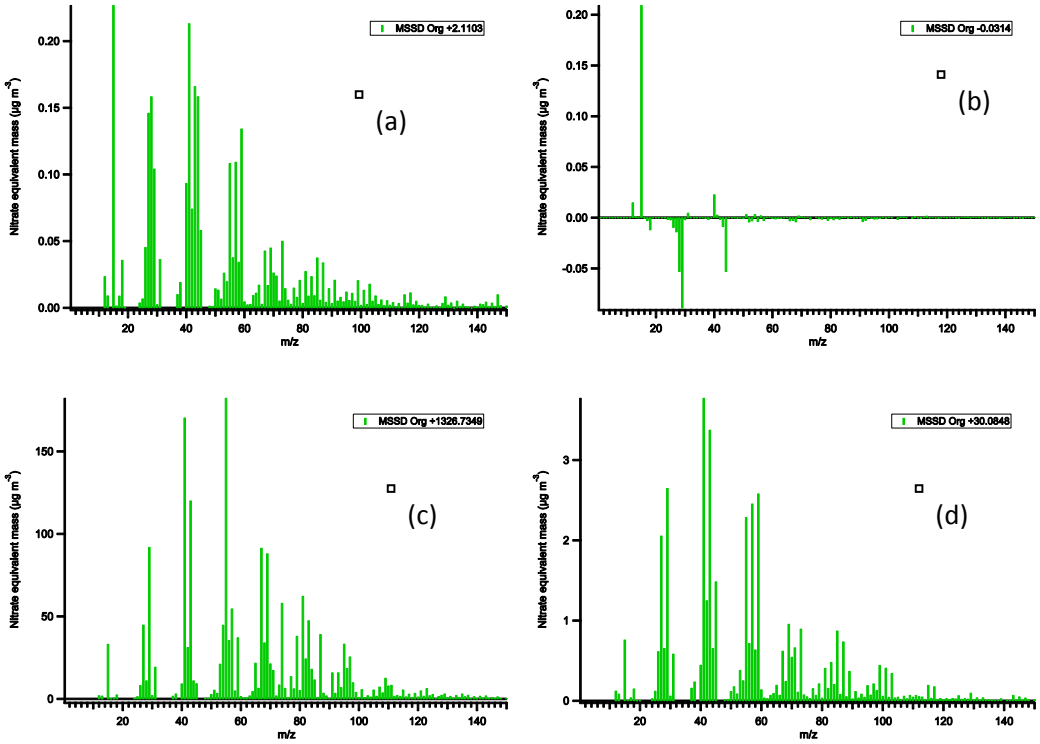

Figure 11: Mass spectra of the volatile and semi volatile organic species from the HR-ToF-AMS: (a). biodiesel (idle), (b). Jet A-1 (idle), (c). biodiesel (full), (d). Jet A-1 (full).

3.2.2 Number and Mass concentrations

Figures 12 and 13 present a comparison between Jet A1 and the alternative fuels in non-volatile PM number and PM concentration, respectively, for the two APU operating conditions – idle and full power. Reduction in PM number and PM mass concentration is observed for all fuels compared to Jet A1 at both operating conditions. The greatest reductions are observed with the gTL fuel, which can be attributed to the low fuel aromatic content.

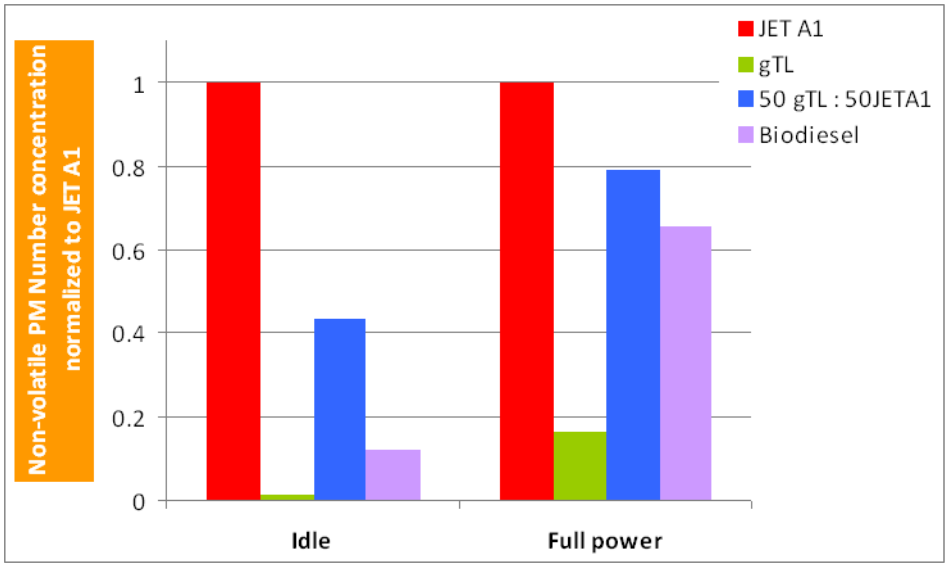

Figure 12: Non-volatile PM number concentrations normalized to Jet A1

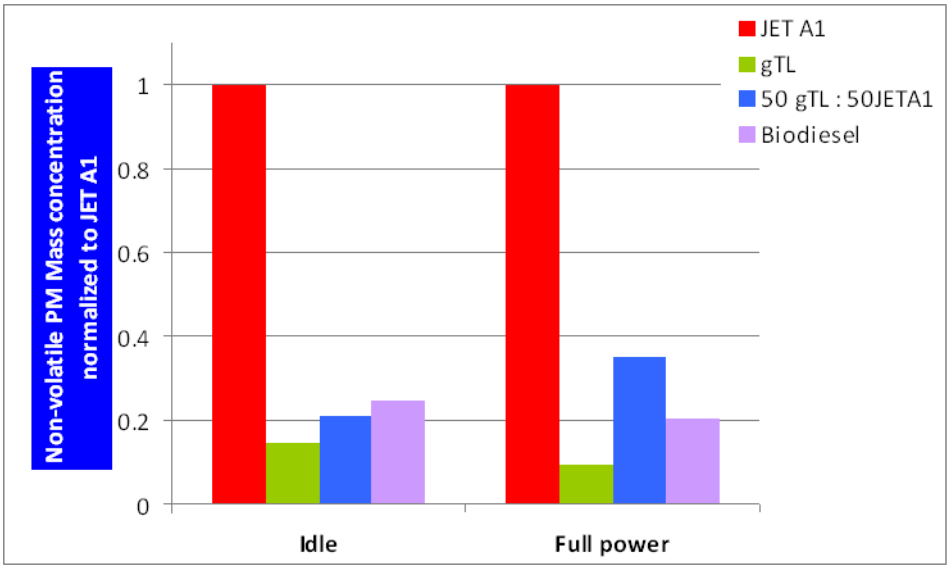

Figure 13: Non-volatile PM mass concentrations normalized to Jet A1

3.2.3 Smoke Number

Smoke number measurements were made using the Richard Oliver Smoke Meter. A total of three material samples were collected at each experimental window. The change in filter reflectance was immediately analyzed at the conclusion of each test. The resulting smoke numbers of the material collected on each filter at the idle and full power operating conditions for various fuels are presented in Figure 14.

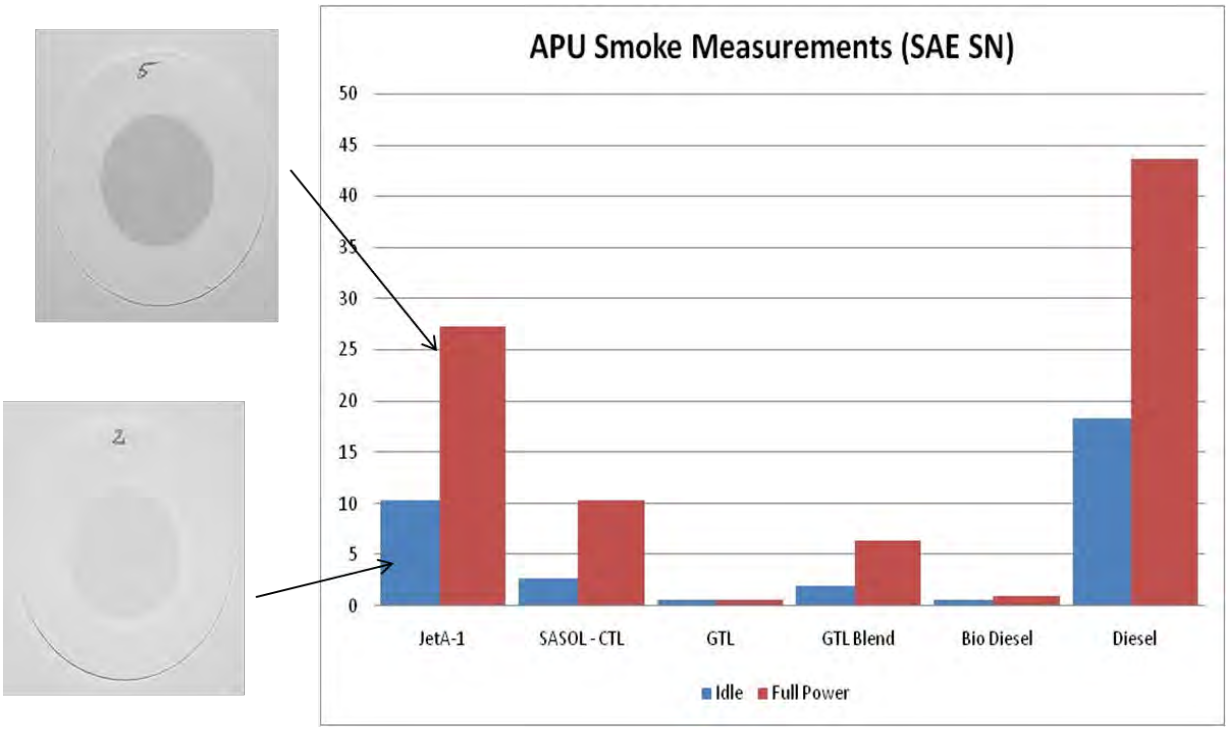

Figure 14: Smoke number measurements for various fuels at the idle and full power operating conditions

The smoke numbers for the alternative fuels (cTL, gTL, gTL blend and biodiesel) are all lower compared to that for Jet A1. The smoke number for diesel is higher than Jet A1 by a factor of 2. Note that the smoke number results do not show the emissions increase for biodiesel reflected in the particle size distributions discussed in section 3.2.1 and Figure 10. This could be due to the fact that the smoke number sample is kept at high temperature throughout the sampling and measurement, and hence the sample never sees the colder ambient temperatures which the exhaust would of course experience when injected into the atmosphere.

4.0 Conclusions

The following conclusions were drawn from this study:

SAE E31 Probe tip versus downstream dilution:

- Difference in PM size distributions observed when dilution is introduced at the probe tip vs. downstream were due to agglomeration of PM (<20nm) prior to dilution in the downstream case.

- Since this difference appears in total and non-volatile distributions, the agglomerating PM are not volatile PM.

- Statistically significant differences are observed in the number-based EI's measured in the high power sampling regime but no statistically significant differences are observed in the mass-based EI's or the number-based EI at idle.

Alternative fuels versus conventional fuels:

- The emissions of the Biodiesel fuel are higher than those for Jet A1 and the natural gas derived Fischer Tropsch fuel. The increase in PM emissions with Biodiesel can be attributed to the strong propensity of biodiesel to form volatile PM which is evidenced in the differences in the total and non-volatile size distributions. From compositional analysis performed using the AMS, the volatile PM was identified to be organic material.

- Reduction in PM number and PM mass concentration is observed for the gTL, 50:50 gTL:Jet A1 and Biodiesel fuels compared to Jet A1 at the two APU operating conditions – idle and full power.

- The smoke numbers for the alternative fuels (cTL, gTL, gTL blend and biodiesel) are all lower compared to that for Jet A1. The smoke number for diesel is higher than Jet A1 by a factor of 2.

5.0 References

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