Center of Excellence for Aerospace Particulate Emissions Reduction Research

PARTNER

PM Emissions Characteristics of APUs burning Conventional and Alternative Fuels

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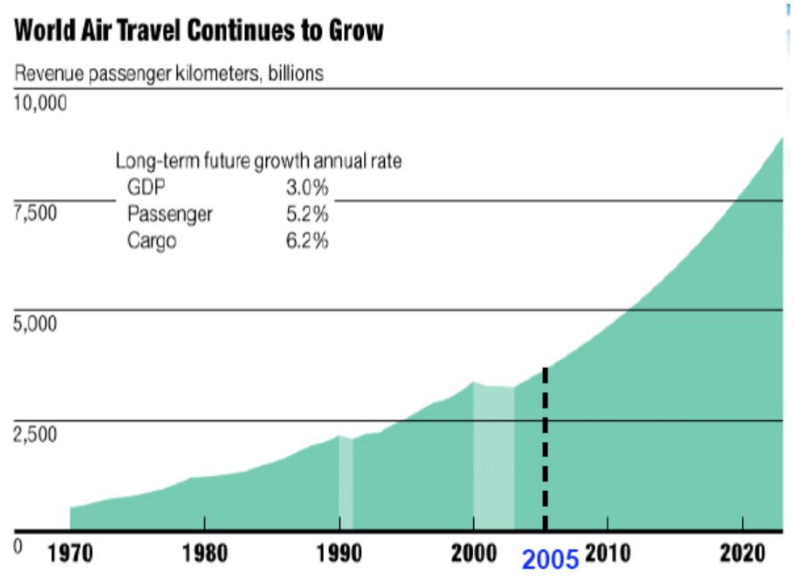
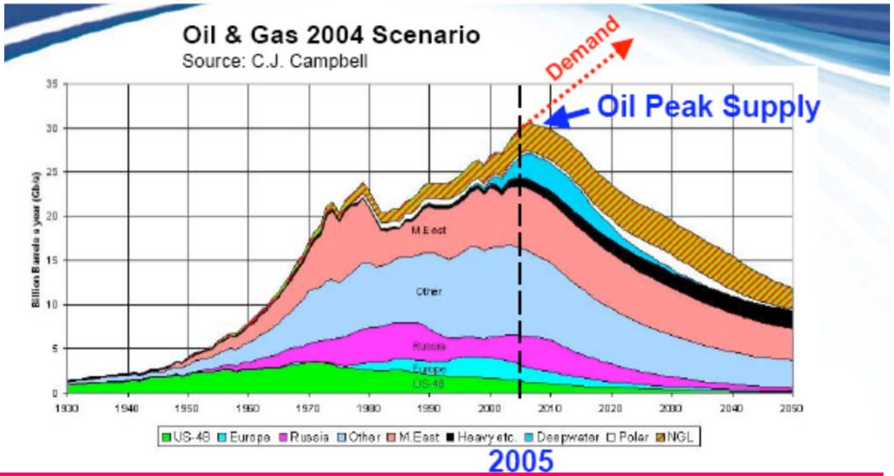
Cambridge Particle Meeting
Cambridge, UK
May 21, 2010

Motivation

- The rising cost of oil coupled with the need to reduce pollution and dependence on foreign suppliers has spurred great interest and activity in developing alternative aviation fuels.
- The objectives of the APU studies were to work with the aviation community to gather accurate data on emissions from candidate alternative fuels and to compare these emission characteristics with those of conventional aviation fuel types.
- These data will provide the essential information for the aviation community at large as it charts a course for environmental sustainability in an uncertain energy future.





Fuel costs are now the largest expense in civil aviation—increasing and fluctuating prices are causing an economic crisis in the industry

Objectives

- Long-term
  - Provide comprehensive data on the impact of candidate alternate fuels on PM emissions from engines currently operating in the commercial fleet. These are critical data for the Commercial Aviation Alternate Fuels Initiative (CAAFI) stakeholders.

- Near term
  - Characterize PM emissions from APUs
  - Examine and, where possible, quantify any changes in PM emissions from engines burning alternative fuels and blends compared to conventional JET A, JET A1, and JP-8 fuels
  - SAE E31 Aerospace Recommended Practice for Aircraft Non-Volatile PM
    - APUs as small scale gas turbine engines provide an ideal test bed for PM emissions measurement methods development

AAFEX

- Venue:
  - NASA Dryden Aircraft Operation Facility, Palmdale, CA
- Dates:
  - January 20 – February 03, 2009
- Participants:
  - NASA
  - AEDC
  - EPA
  - Aerodyne Research Inc
  - Air Force Research Lab at WPAFB
  - United Technologies Research Center
  - Missouri University of Science and Technology

AAFEX

- APU:
  - Honeywell (formerly Garrett) Model GTCP85-98CK
  - Single-stage radial inflow turbine
  - Mounted cross-wise in a forward baggage compartment of the DC-8
    - DC-8 was not supplied with an APU as original equipment

- Fuels:
  - JP-8 (Conventional Jet Fuel)
  - cTL (Fischer-Tropsch Fuel from Coal)

Fuel	Symbol	C Fraction	H/C Ratio	Sulfur	Aromatics	Naphthalenes	Olefins
		wt/wt	mol/mol	ppm	vol%	vol%	vol%
Base fuel	JP-8	0.8619	1.88	1204	18.55	1.55	1.6
Coal-derived Fischer-Tropsch fuel[a]	FT-2	0.8486	2.12	22	0.6	0	3.8

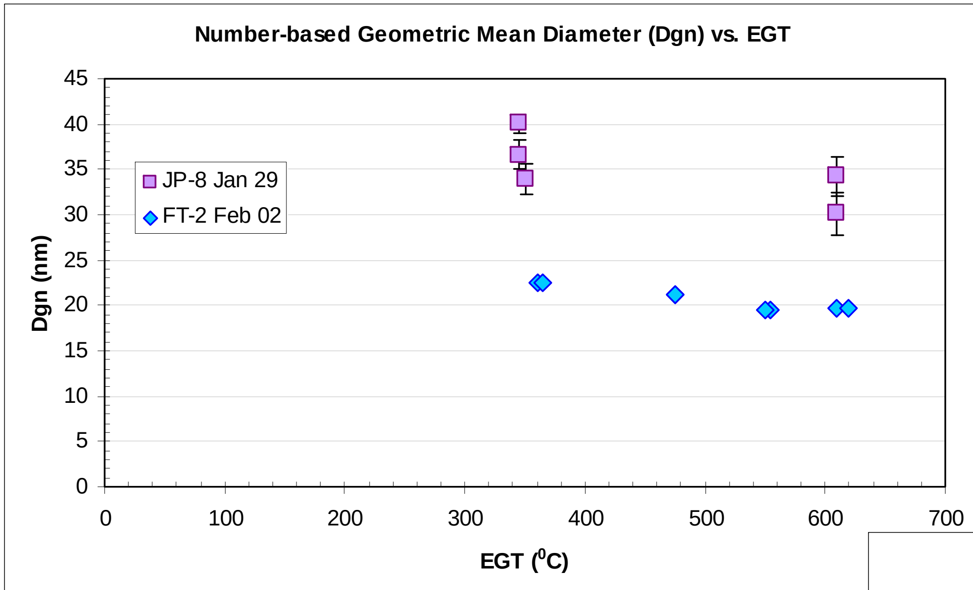
a. Product of SASOL, South Africa

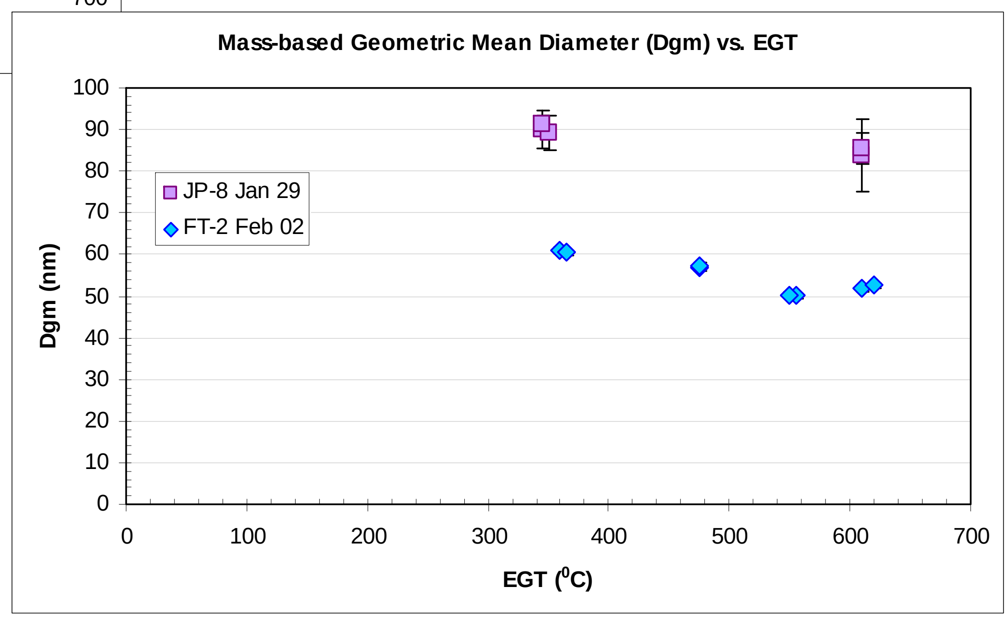
PM Emissions Measurements

- PM emissions were measured
  - Range of APU conditions from minimum load (cockpit power) to maximum load (full air conditioning and bleed air)

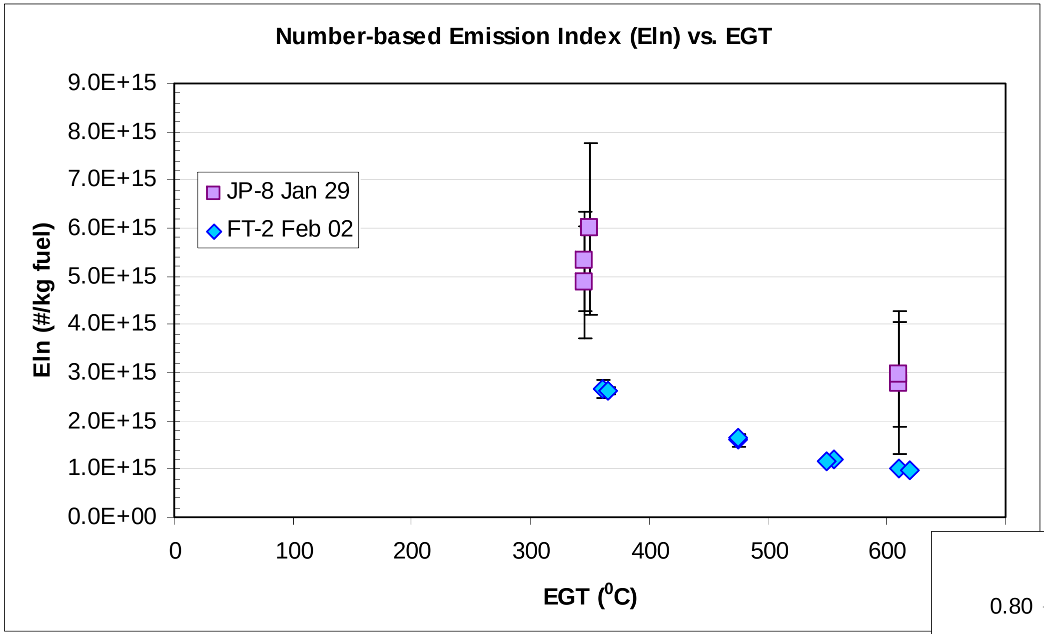
- The PM sampling instrumentation suite included a Cambustion DMS500 fast particle size spectrometer

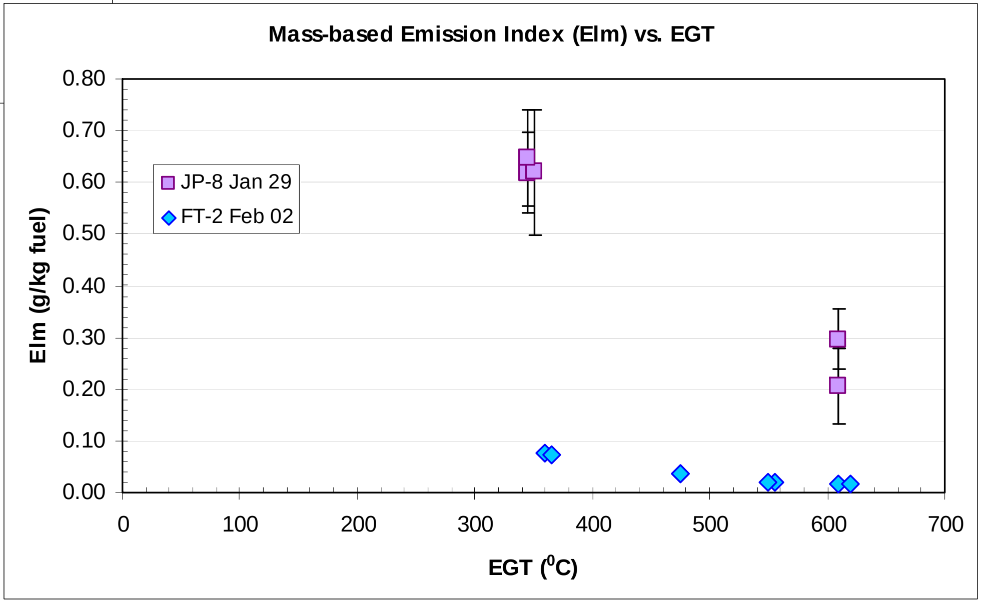
PM Size Dist. Shape Parameters (DMS500)



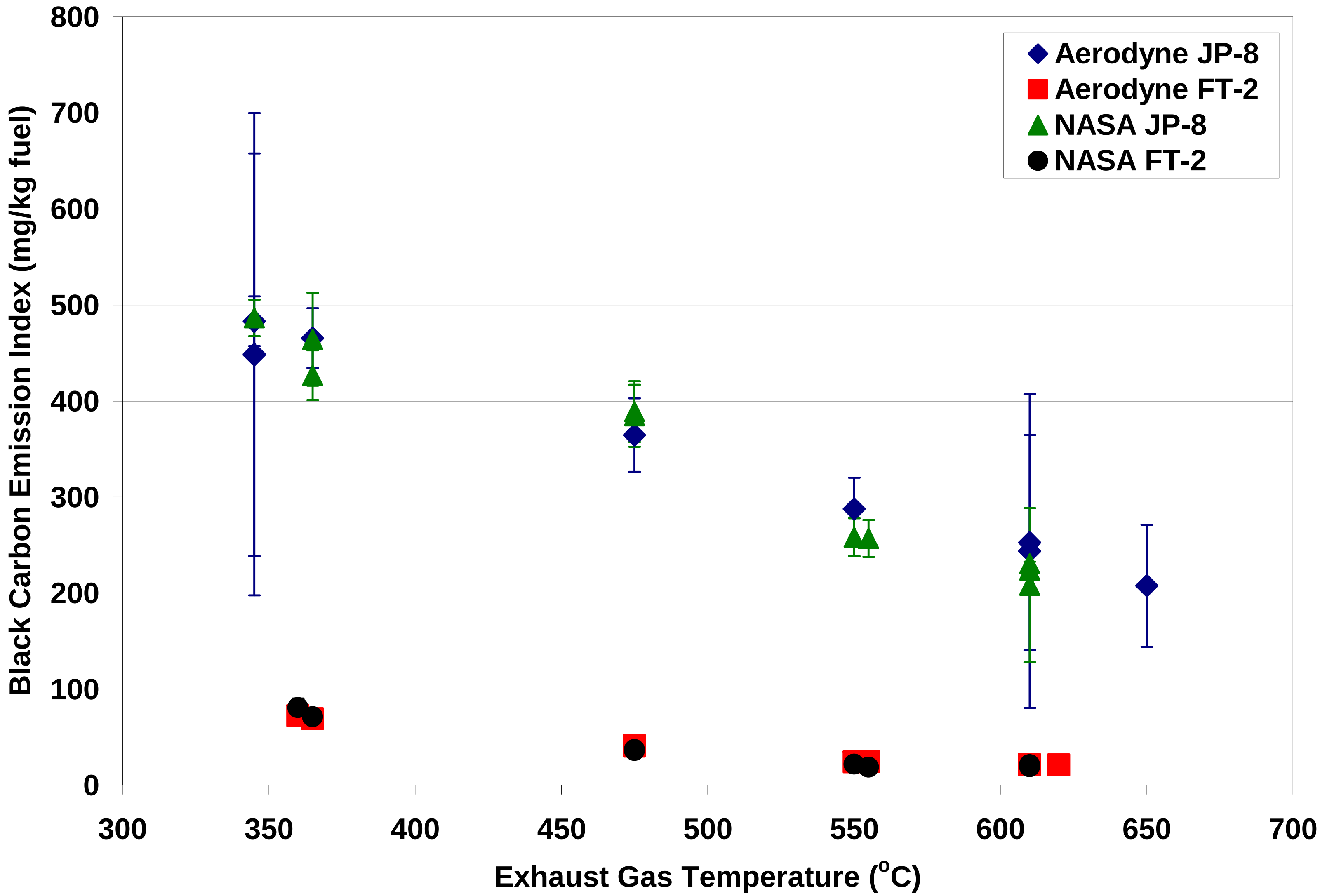


PM Emission Indices (DMS500)

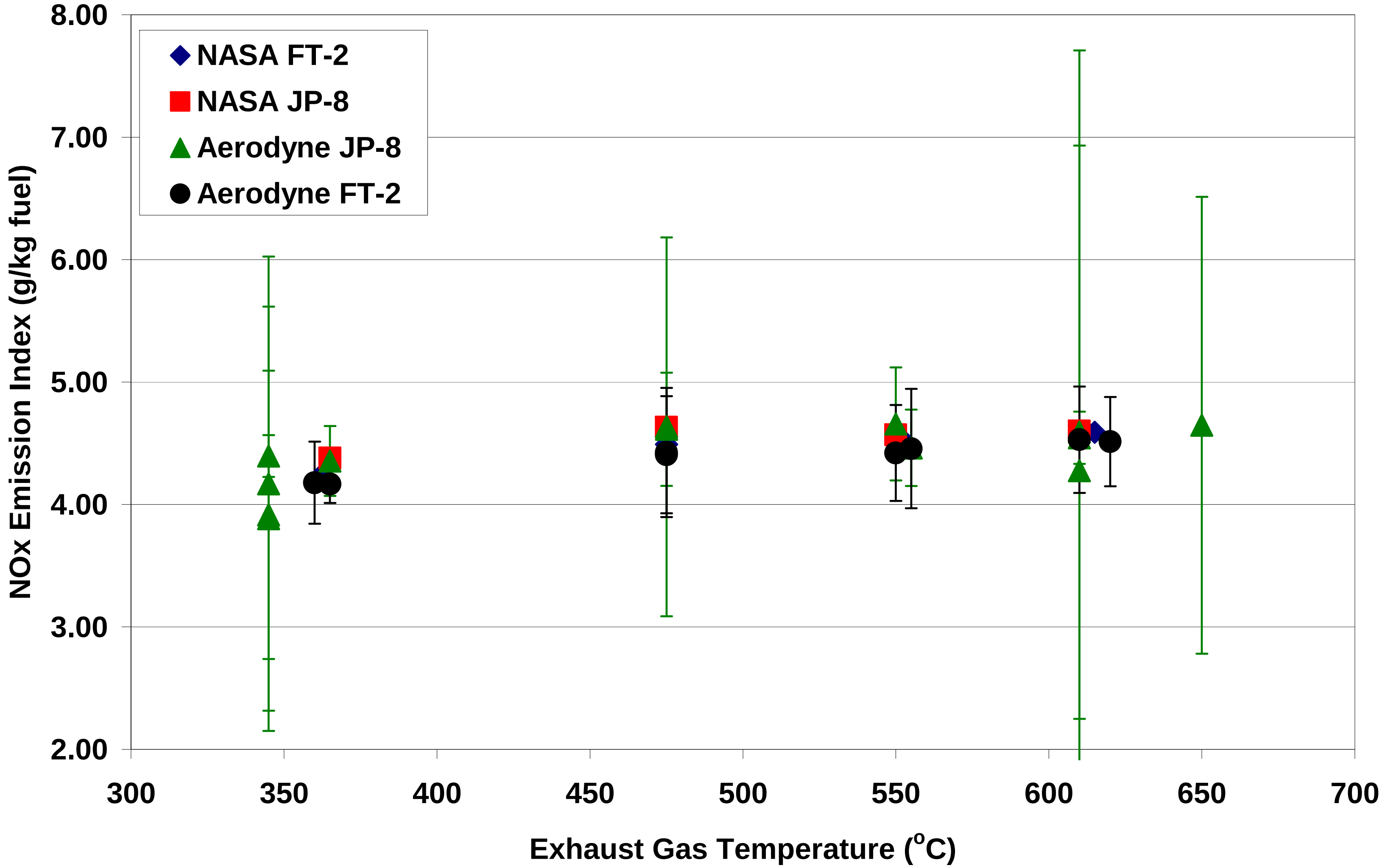




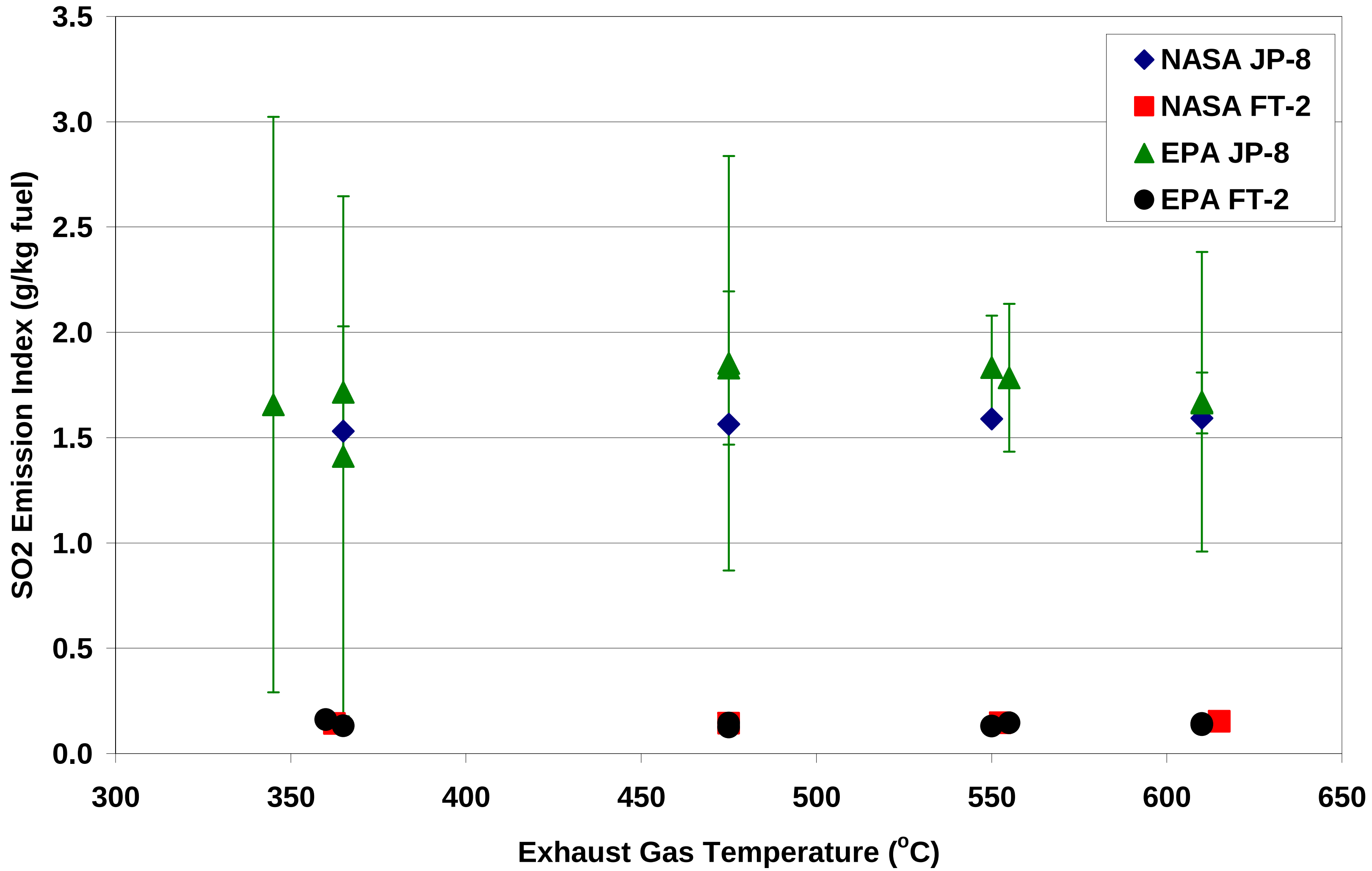
Black Carbon Emission Index (MAAP)



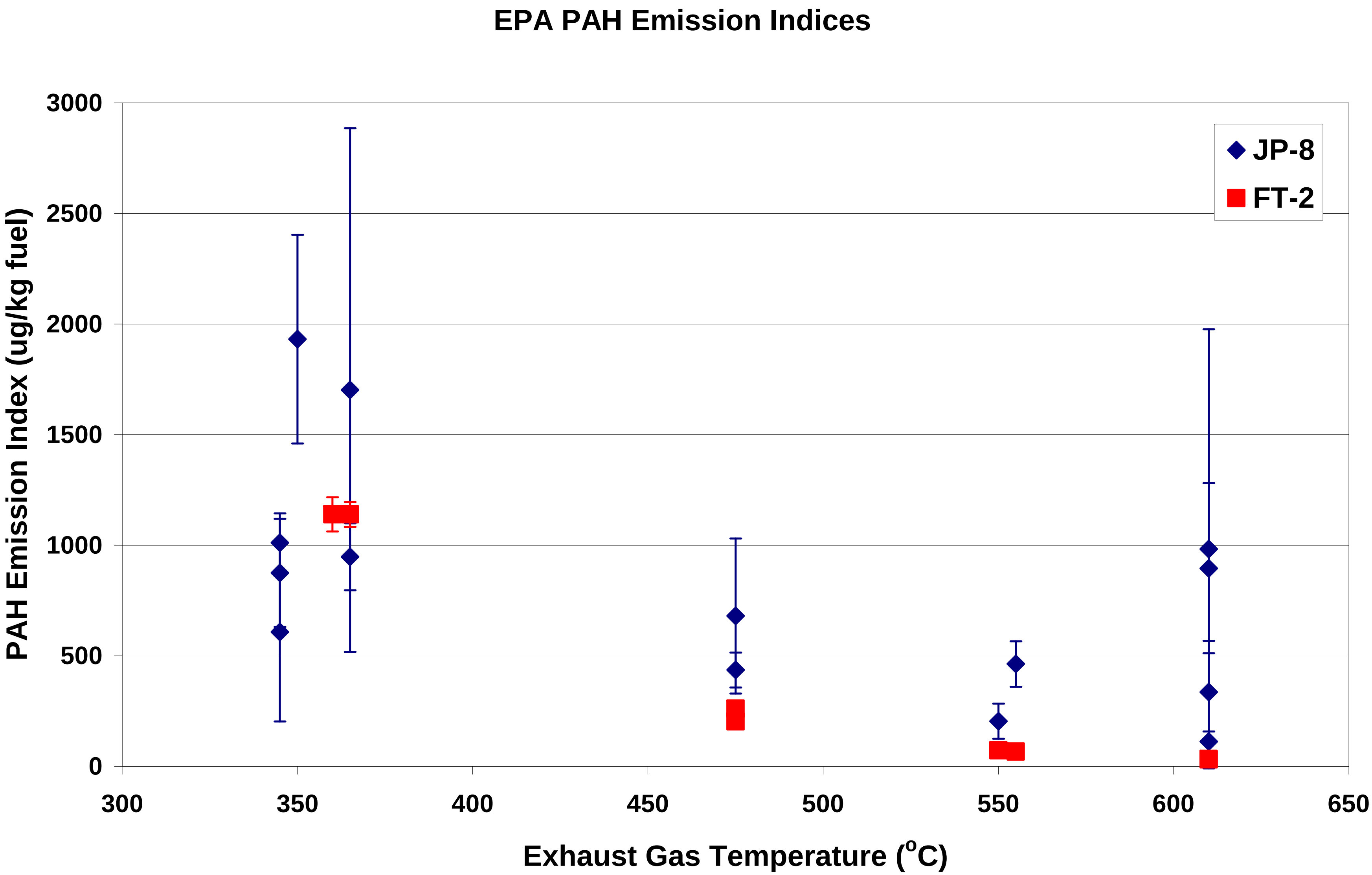
NOx Emission Index



SO_2 Emission Index



PAH Emission Index



AAFEX Summary

- APU gas and PM emissions decreased with increasing engine power as indicated by exhaust gas temperature.

- For JP-8, EIn and EIm respectively dropped from ~5 x 10^{15} kg^{-1} and ~500 mg kg^{-1} at minimum load (cockpit power) to 2.5 10^{15} kg^{-1} and 200 mg kg^{-1} at maximum load (full air conditioning and bleed air).

- Burning FT-2 fuel APU did not significantly effect APU NOx emissions

- Compared to JP-8, FT-2 fuel drastically reduced the APU's PM emissions.
    - Average EIn and EIm values were respectively factors of 6 and 13 lower when burning the alternative fuel.

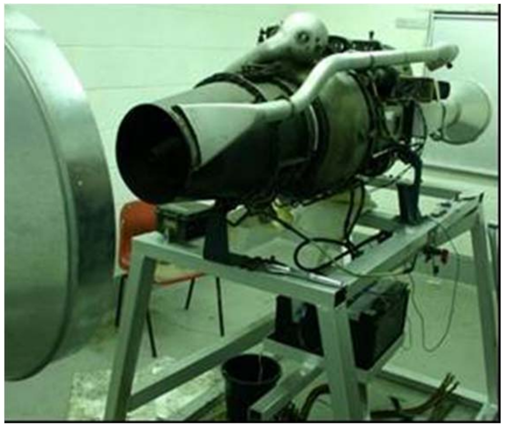
- APU FT-2 nonvolatile PM emissions were smaller compared JP-8 emissions.

Sheffield APU Study

- Venue:
  - University of Sheffield Low Carbon Combustion Centre, Beighton, S20 1AH, UK
- Dates:
  - September 21 - October 01, 2009
- Participants:
  - University of Sheffield
  - University of Leeds
  - University of Manchester/ Manchester Metropolitan University
  - Missouri University of Science and Technology

Sheffield APU Study

- APU:
  - Recommissioned Artouste Mk113 APU
  - Single spool gas turbine engine
  - Used on RAF Victor Bomber
    - Supplied air for engine starting and electrical power to the aircraft systems

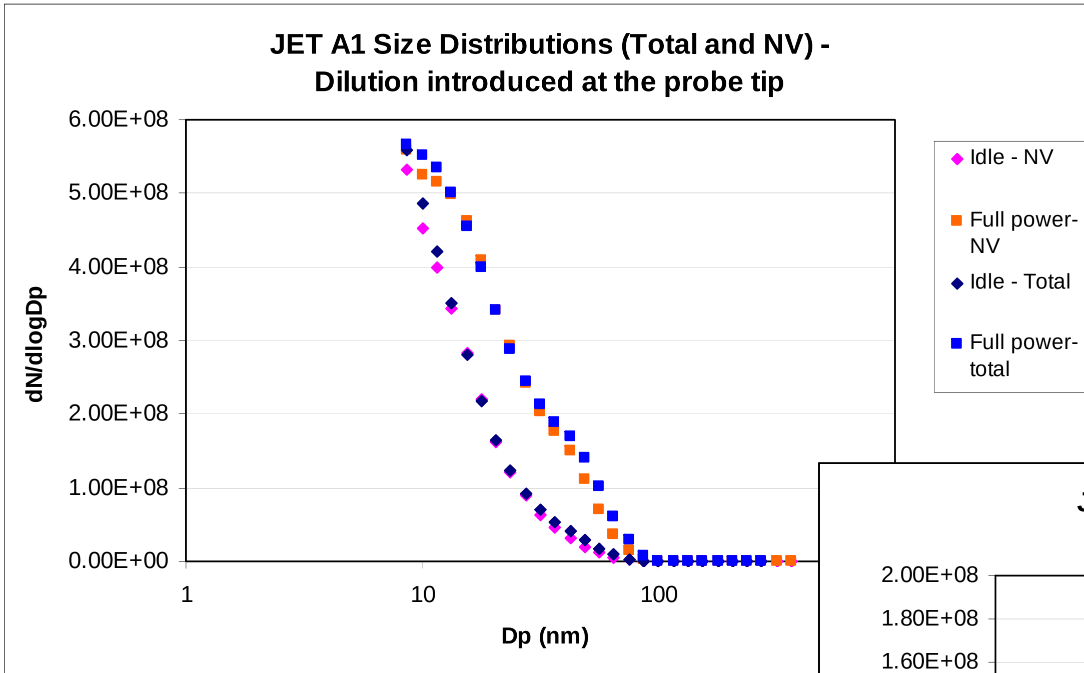


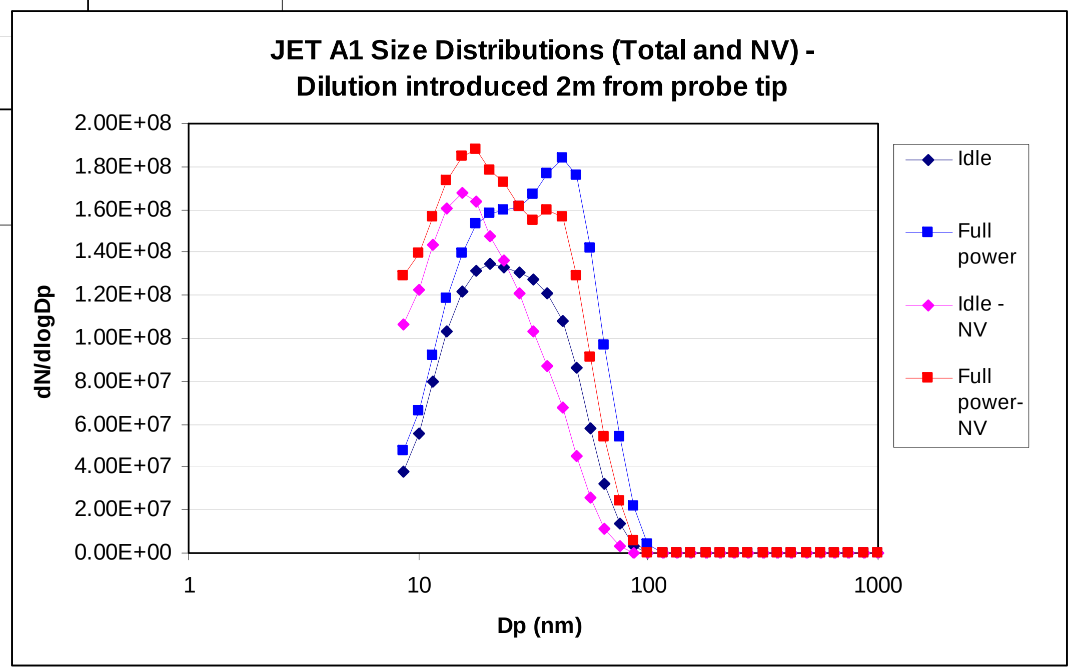
- Fuels:
  - JET A1 (Conventional Jet Fuel)
  - cTL (Fischer-Tropsch Fuel from Coal)
  - gTL (Fischer-Tropsch Fuel from Natural Gas)
  - 50:50 gTL-JET A1 blend
  - Biodiesel (FAME)
  - Diesel

PM Emissions Measurements

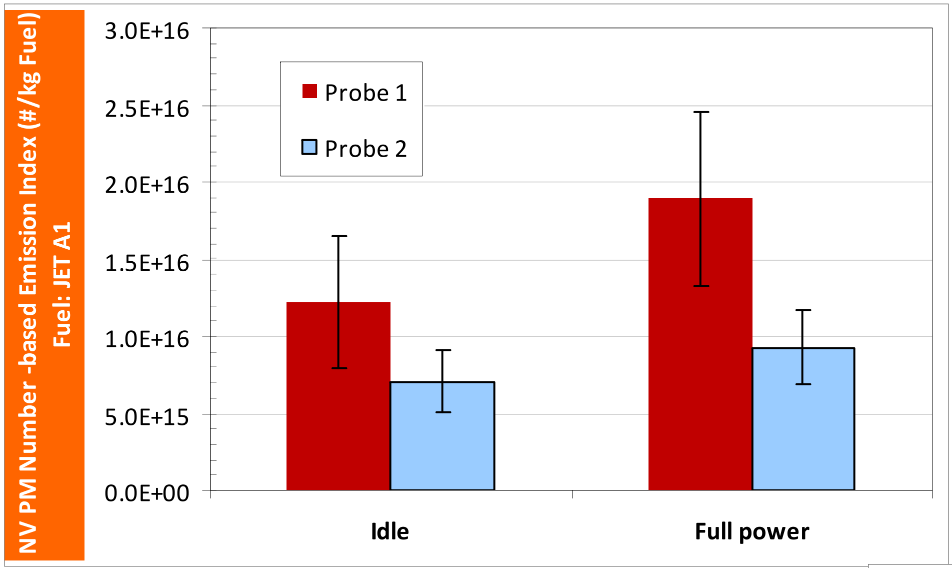
- PM emissions were measured
  - Two APU conditions: idle and full power
  - Three sampling locations:
    - Exit plane with dilution at probe tip
    - Exit plane with dilution 1m downstream of probe tip
    - 10m from the exit plane
- The PM sampling instrumentation suite included two Cambustion DMS500 fast particle size spectrometers
- A thermal discriminator operating at 300°C was used to remove volatiles from the exhaust samples to one of the DMS500s
- Three main measurement objectives:
  - Investigate effects of probe tip vs. downstream dilution
  - Investigate emissions characteristics of alternative fuels
  - Investigate plume evolution effects

Probe tip vs. Downstream dilution (SAE E31)

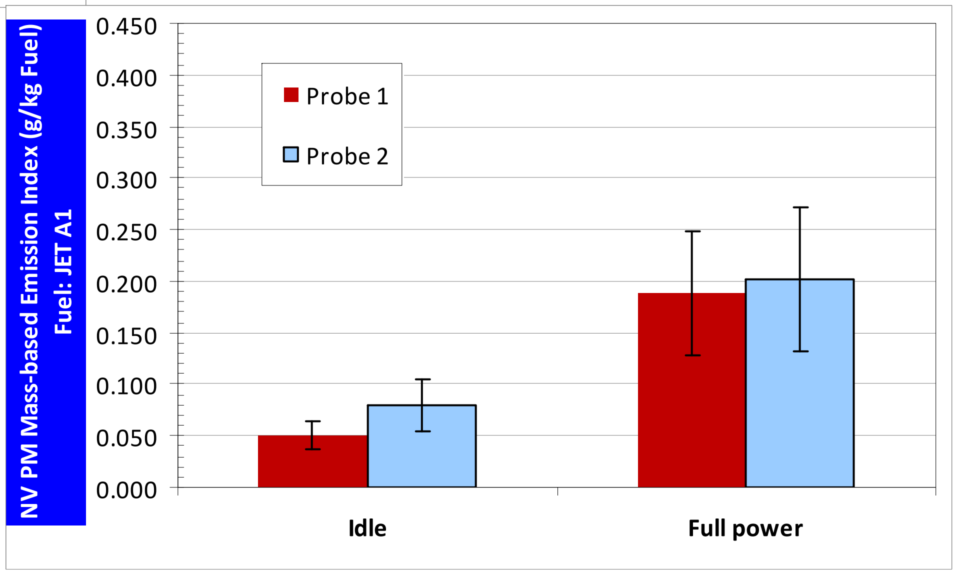




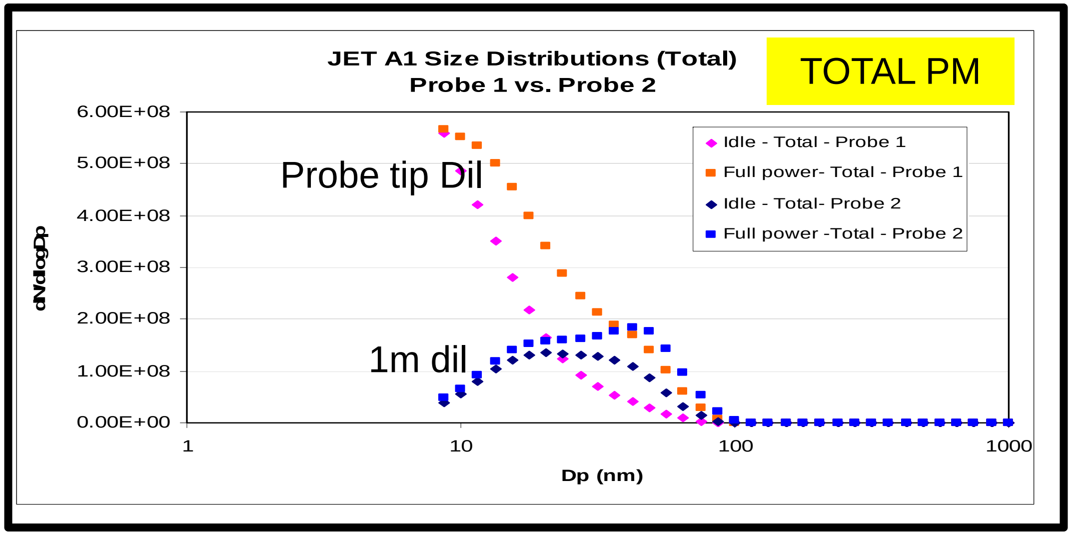
Probe tip vs. Downstream dilution (SAE E31)

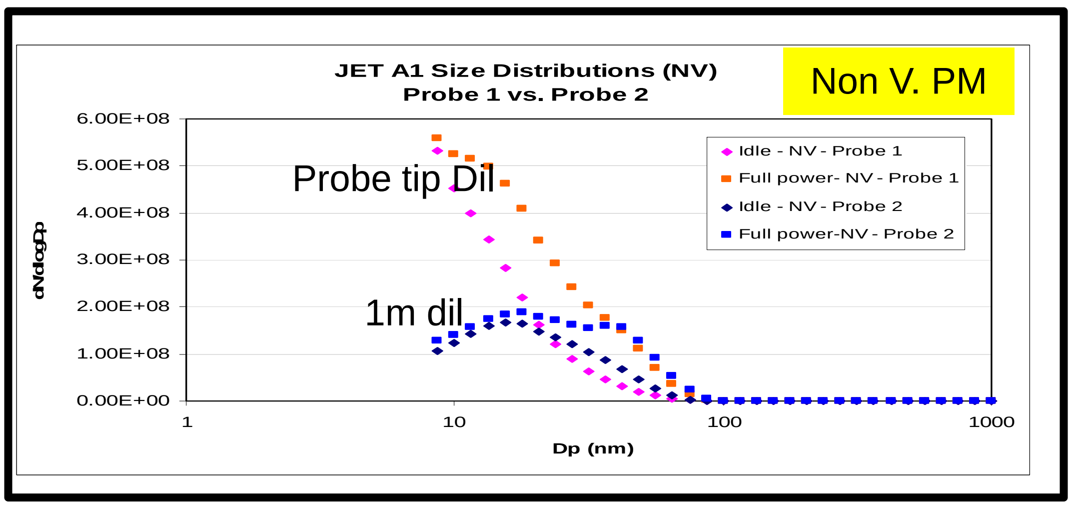


Probe 1: Dilution at probe tip
Probe 2: Dilution at 1m downstream of probe tip



Probe tip vs. Downstream dilution (SAE E31)

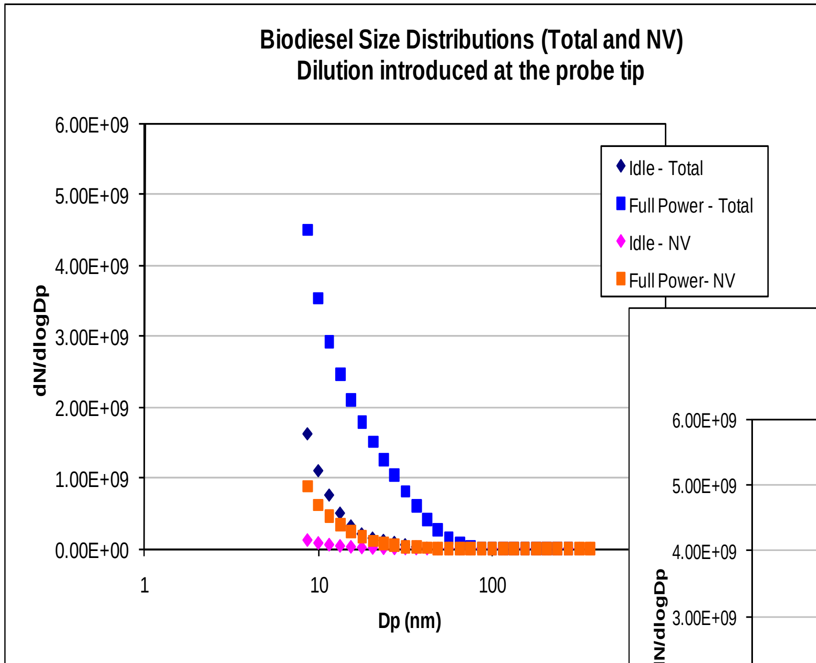




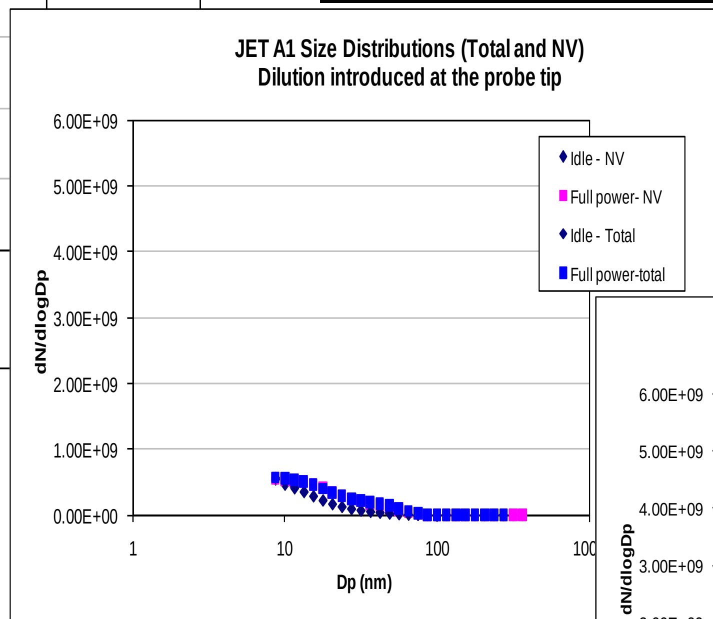
SAE E31 Sampling methods Issues:

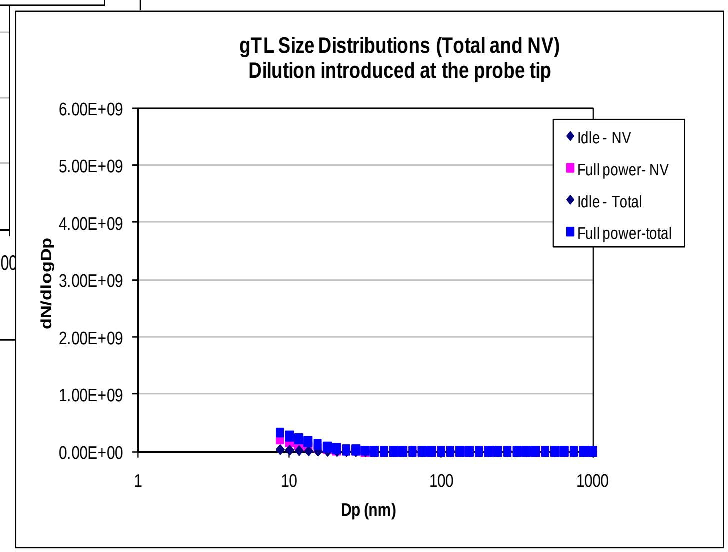
- Probe tip vs downstream dilution (1m)
- Difference in distributions due to agglomeration of PM (<20nm) prior to dilution in the downstream case.
- Since it appears in total and non-volatile distributions the agglomerating PM are not volatile PM.
- Statistically significant differences are observed in the number-based EI's measured in the two sampling regimes but no statistically significant differences are observed in the mass-based EI's

Fuel Comparison (Probe tip dil)



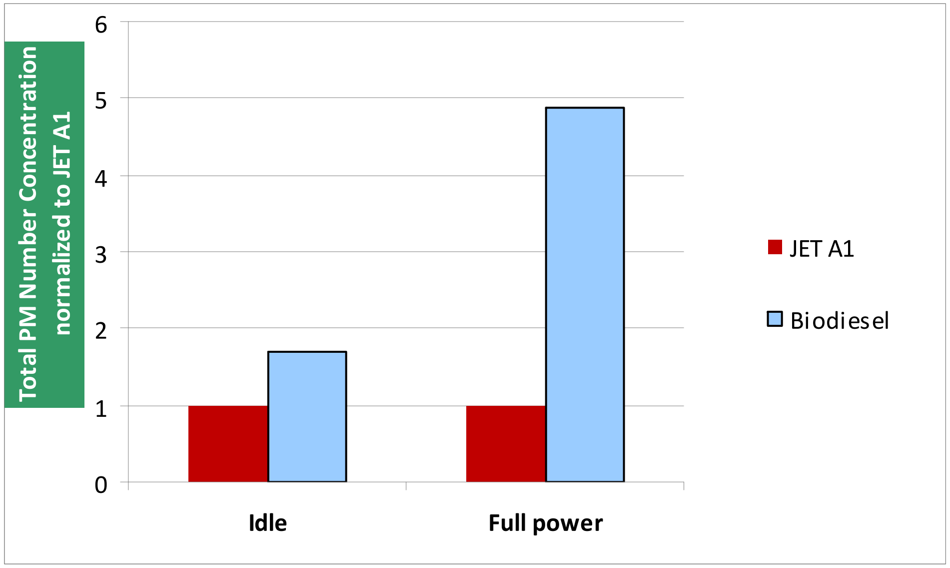
Fuel	Total PM		Non-volatile PM	
	Mass Conc	Num. Conc	Mass Conc	Num. Conc
	mg/m3	#/cm3	mg/m3	#/cm3
Bio diesel	9.20E+00	1.46E+09	6.00E-01	1.89E+08
Jet A1	3.00E+00	3.00E+08	2.70E+00	3.81E+07
gTL	2.50E-01	8.00E+07	2.50E-01	4.65E+07

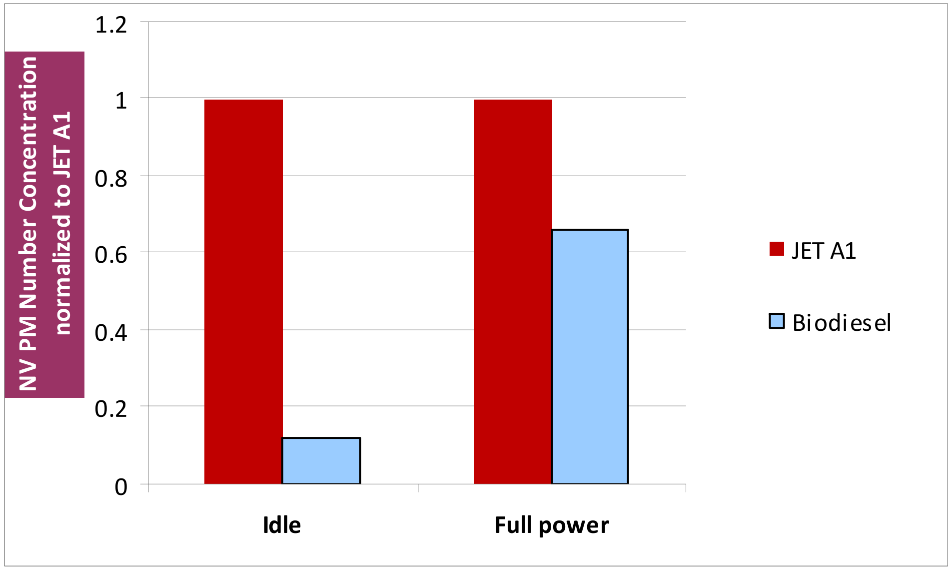




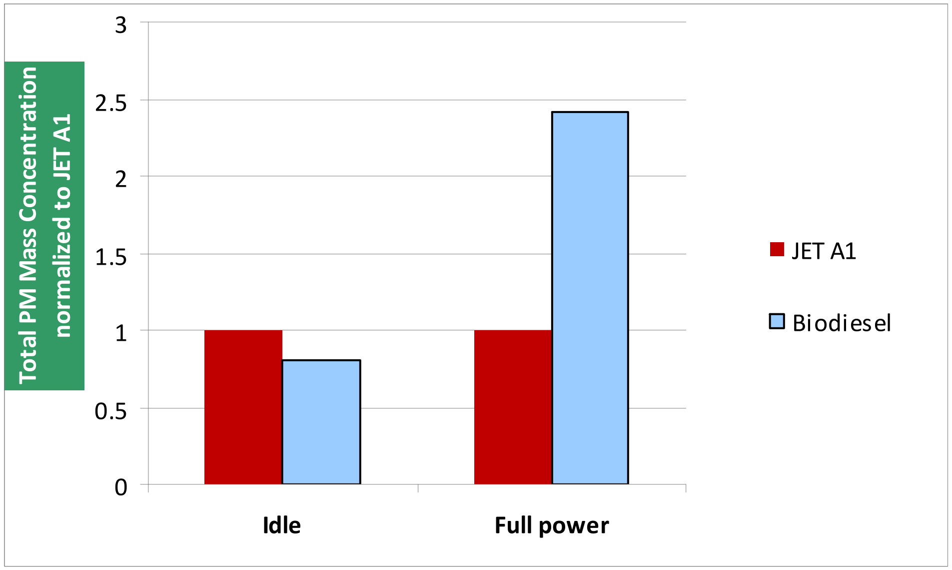
PM emissions studies on a series of alternative fuel candidates: gTL and bio-diesel with Jet A1 as the baseline fuel for emissions comparison

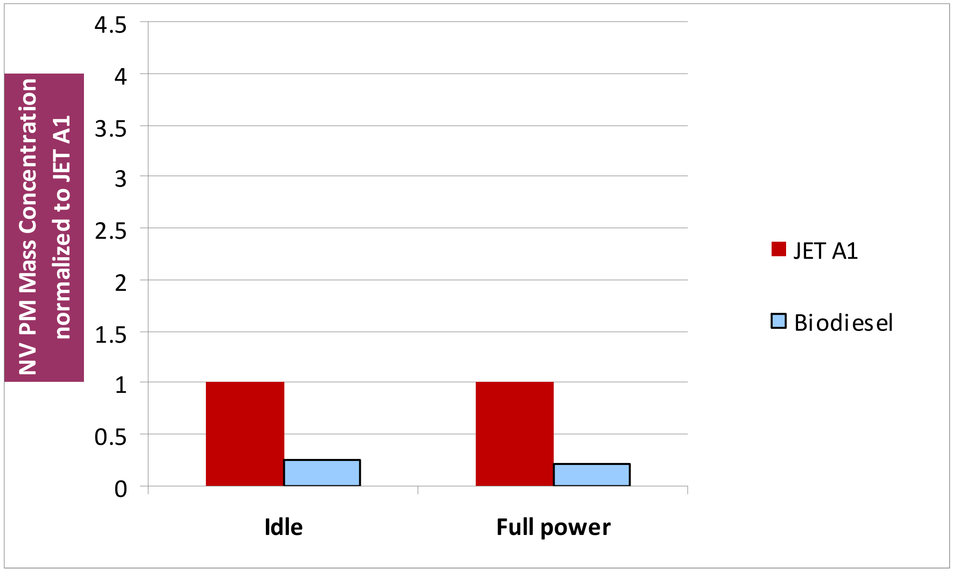
Probe tip Dilution - Number





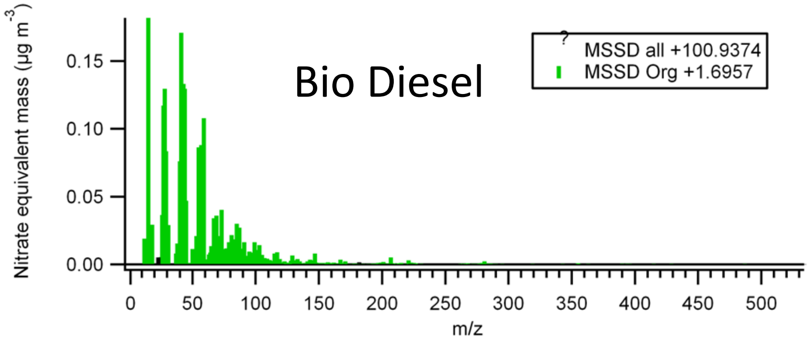
Probe tip Dilution - Mass

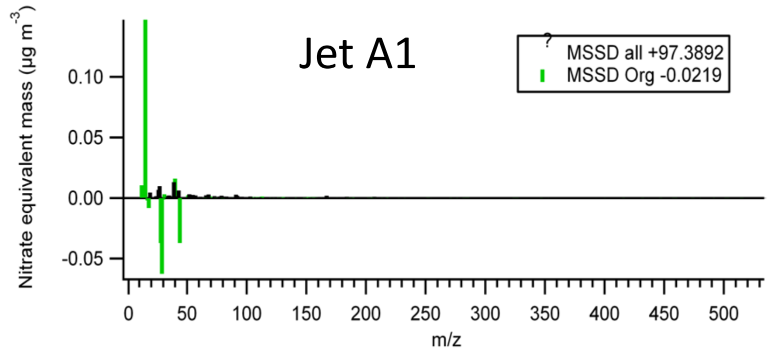




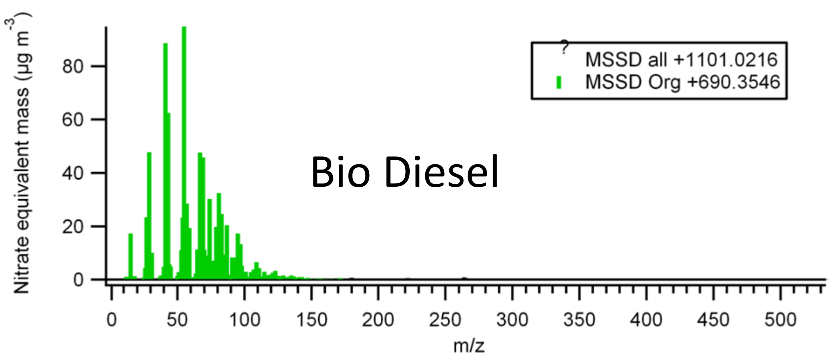
AMS Data

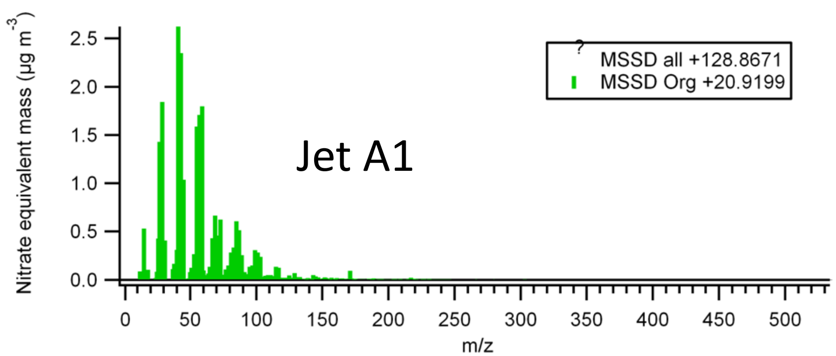
Idle





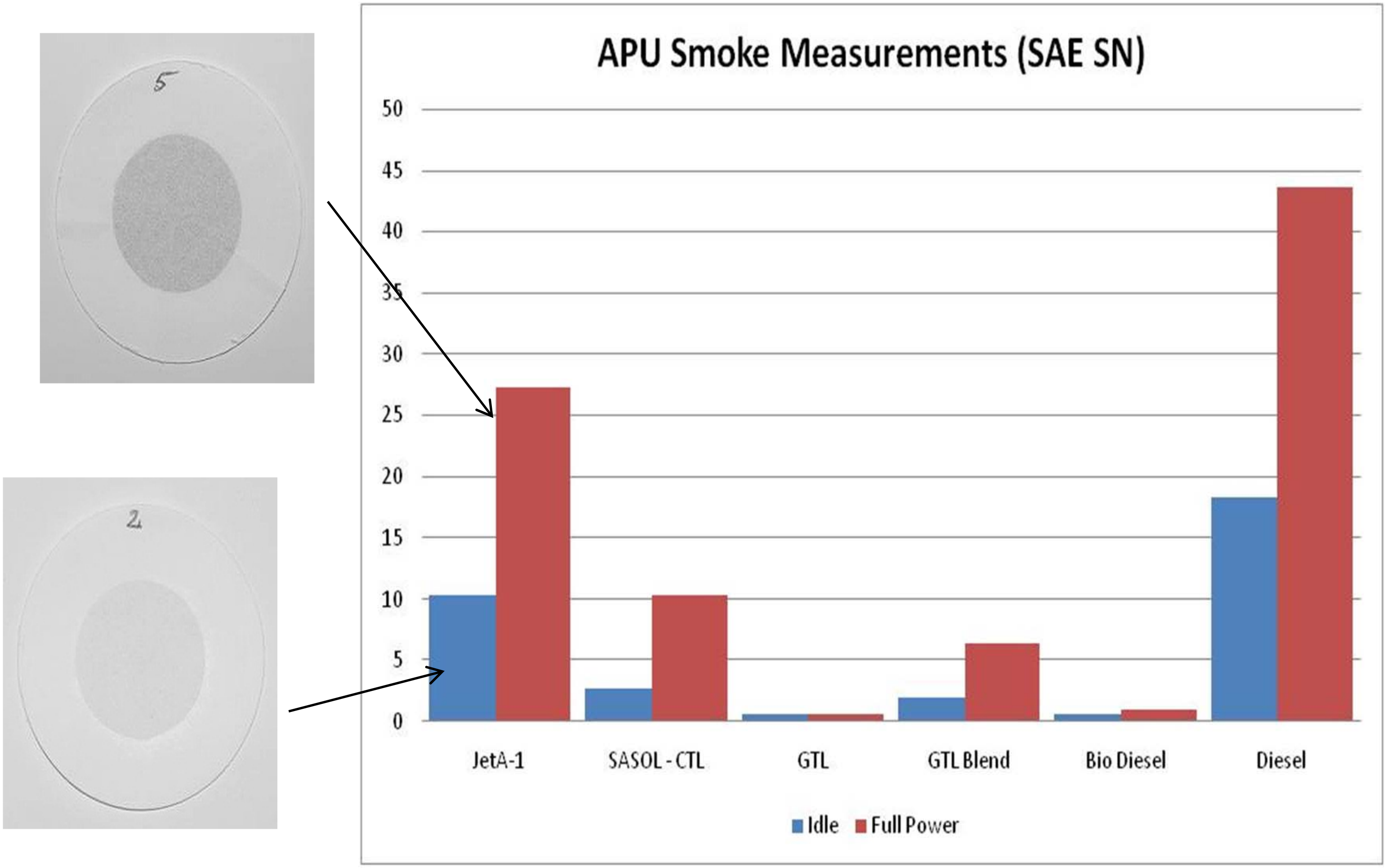
Full power





AMS Data provided by Paul Williams (The University of Manchester)

Smoke Number Data



Smoke Number Data provided by Chris Wilson (The University of Sheffield)

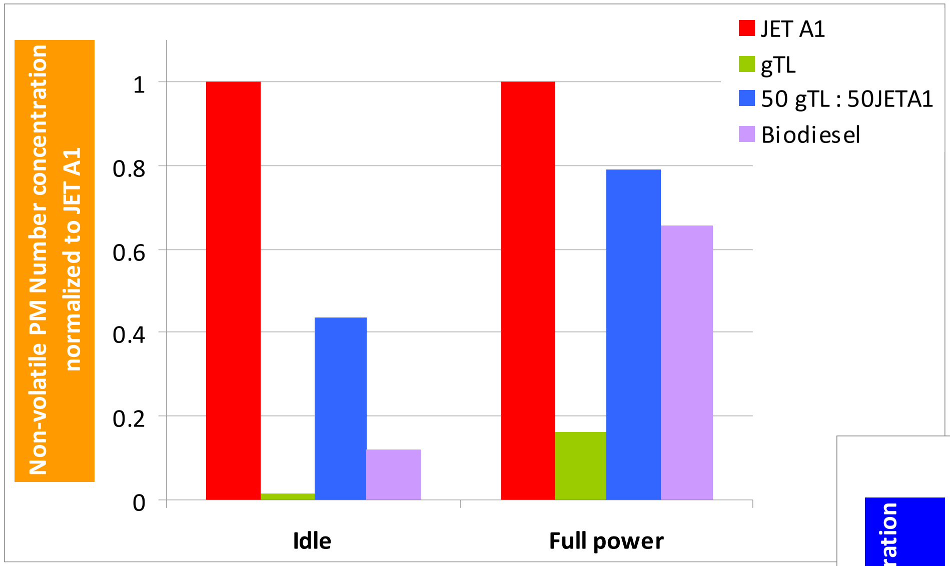
JET A1 – Biodiesel Comparison

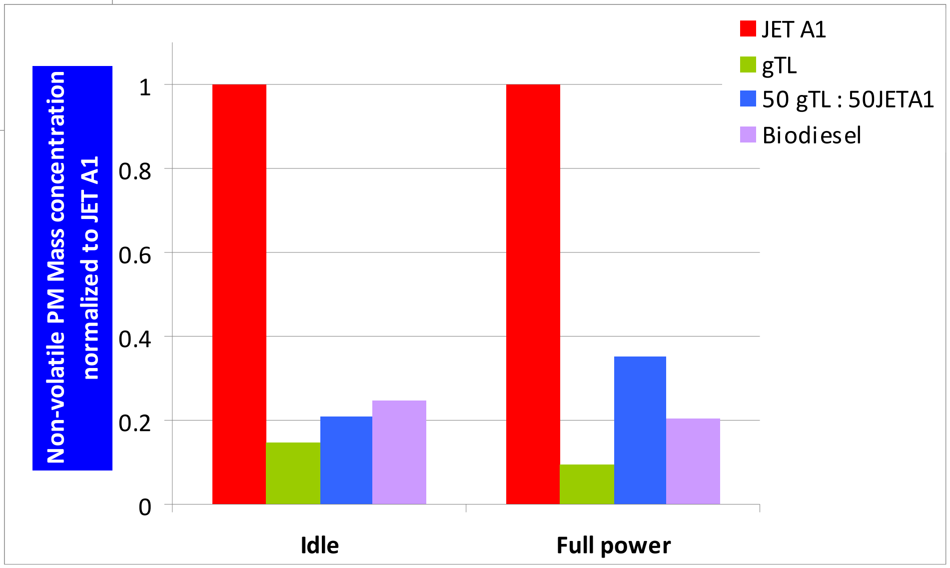
- Increases in total PM at idle and full power for bio-diesel are observed when compared to jet A1
  - This is due to gas-to-particle conversion in the unheated sample line as evidenced by the differences in the total and non-volatile size distributions.

- The AMS data indicates that the condensable material is organic in composition. This condensable material is volatile at 300^{o}C (the discriminator set point)
  - This organic material has a strong propensity to condense as evidenced by its condensation despite probe tip dilutions typically >20:1
  - It is reasonable to assume that such condensation would occur with natural dilution and cooling in the atmosphere.

- The reduction in PM observed in the non-volatile samples is consistent with the results from filter sample analysis for exhaust ducted through heated sample lines (150^{o}C) to the filters (smoke meter measurements).

Non-volatile PM Emissions data





Next Steps

- APU Emissions
  - Emissions Characterization of modern commercial APUs
- Alternative Fuels
  - Emissions Characteristics of gas turbine engines burning Biofuels (AAFFEX II)
- SAE E31
  - Resolve sampling, mass and number issues to complete ARP by Dec 2011

Acknowledgements

- AAFEX team, and NASA DC-8 personnel
  - NASA, ARI and EPA for use of their data
- Sheffield APU study team
  - The Universities of Manchester and Sheffield

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