Non-volatile PM Emissions Measurements

Project 002

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Alexandria VA

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Motivation

- Why is the work being done?
  - ❑ The FAA along with the EPA, NASA, Transport Canada, has committed to underwrite studies, that address research needs that related to corrections for ambient conditions, engine to engine variability and fuel composition in order to establish a regulatory standard to nvPM number and mass-based emissions.

- What distinguishes the efforts from prior work in the area?
  - ❑ This work is driven by the critical needs in the development of the ICAO aircraft engine nvPM standard.
  - ❑ This work is based and builds on field studies conducted under PARTNER projects 29 and 37.

Objectives and Outcomes

- **Long-term**

  Application of the standardized nvPM Measurement system to:

  - Understand and quantify the effect of fuel composition on non-volatile particulate matter (nvPM) formation in aircraft engines
  - Develop international standard atmosphere (ISA) corrections for NVPM measurements.
  - Acquire data to evaluate cruise nvPM models

- **Near term**

  – Close coordination with and feedback from SAE E-31 committee
  – Common agreement on way forward
  – Demonstrations and Inter-comparisons of ARP 6320/Annex 16 appendix 7 compliant systems
    - **Demonstrations and inter-comparisons of North American mobile reference system at OEM facilities**
    - **From all of these studies data is shared with E31 committee for systems evaluation purposes**
  – Contribute to the development of the system loss correction ARP – nvPM size measurement **(completed)**

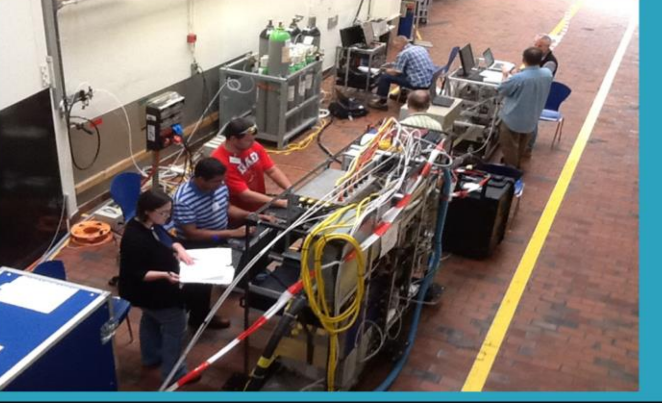
Approach

Validate

Validate

Deploy

Deploy



Schedule and Status

COMPLETED

- System Demonstrations and Inter-comp Thru 2014
- A-PRIDE 4 (Nov 2012)
- Pratt and Whitney Canada (Apr 2013)
- Williams International (May 2013)
- A-PRIDE 5 (Jul-Aug 2013)
- Pratt and Whitney (Mar 2014)
- Honeywell (Jul-Aug 2014)

- System Demonstrations and Inter-comp 2015 and on
- RR (Mar 2015)
- VARIANT 2 (Aug 2015)
- Honeywell (Dec 2015)
- NASA (Oct 2016)
- P&W (Q4 2016)
- GE (Q1 2017)

Completed

- Honeywell E to E var. 2017 - 2018

Underway

- ND MAX 2017 - 2018
- Honeywell Comb/rig/alt fuels 2018 - 2019

Progress on rig testing at Honeywell

- **Objectives**
- • Set up an RQL full annular combustor rig and standardized nvPM measurement system
- *An nvPM emissions measurement system and combustor rig adaptive hardware is to be assembled, tested and validated by Honeywell to enable nvPM and gaseous emissions data to be acquired from a Combustor Test Rig.*
- *Design and construct a sampling probe that minimizes nvPM losses, achieves isokinetic sampling conditions and samples representatively*
- • Perform rig testing using Jet-A fuel; and THREE alternative fuels supplied by FAA (TBD)
- • Analyze data to inform performance based nvPM emissions modeling for all altitudes

Recent Accomplishments and Contributions

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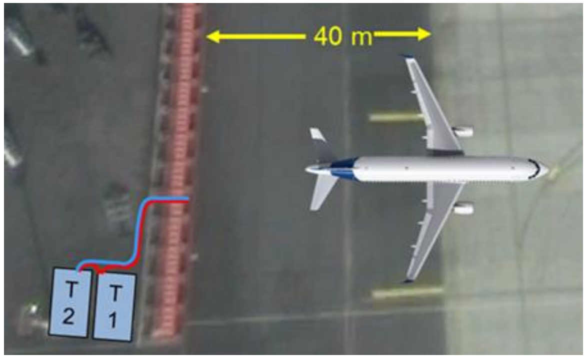
ND-MAX/ECLIF-II

NASA/DLR Multidisciplinary Airborne eXperiments /Emission and Climate Impact of Alternative Fuels Second Campaign

Ground Measurements



Emissions source: DLR ATRA A320/V2527-A5 (#2)

NASA
DLR
MISSOURI S&T
AERODYNE RESEARCH, Inc.
Transport Canada Transports Canada

Specific ground measurement research objectives include:

- obtain real-time on-line emissions measurements of non-volatile particulate matter (nvPM), total particulate matter (PM), and hydrocarbons as a function of both engine thrust and fuel composition
- link ground-based measurements to North American nvPM reference system and to in-flight measurements
- potential development of LTO-to-cruise correlation for nvPM
- evaluation of potential air quality effects due to emissions

additional support provided by: FEDERAL AVIATION ADMINISTRATION Transport Canada Transports Canada

ND-MAX/ECLIF-II Scientific Objectives

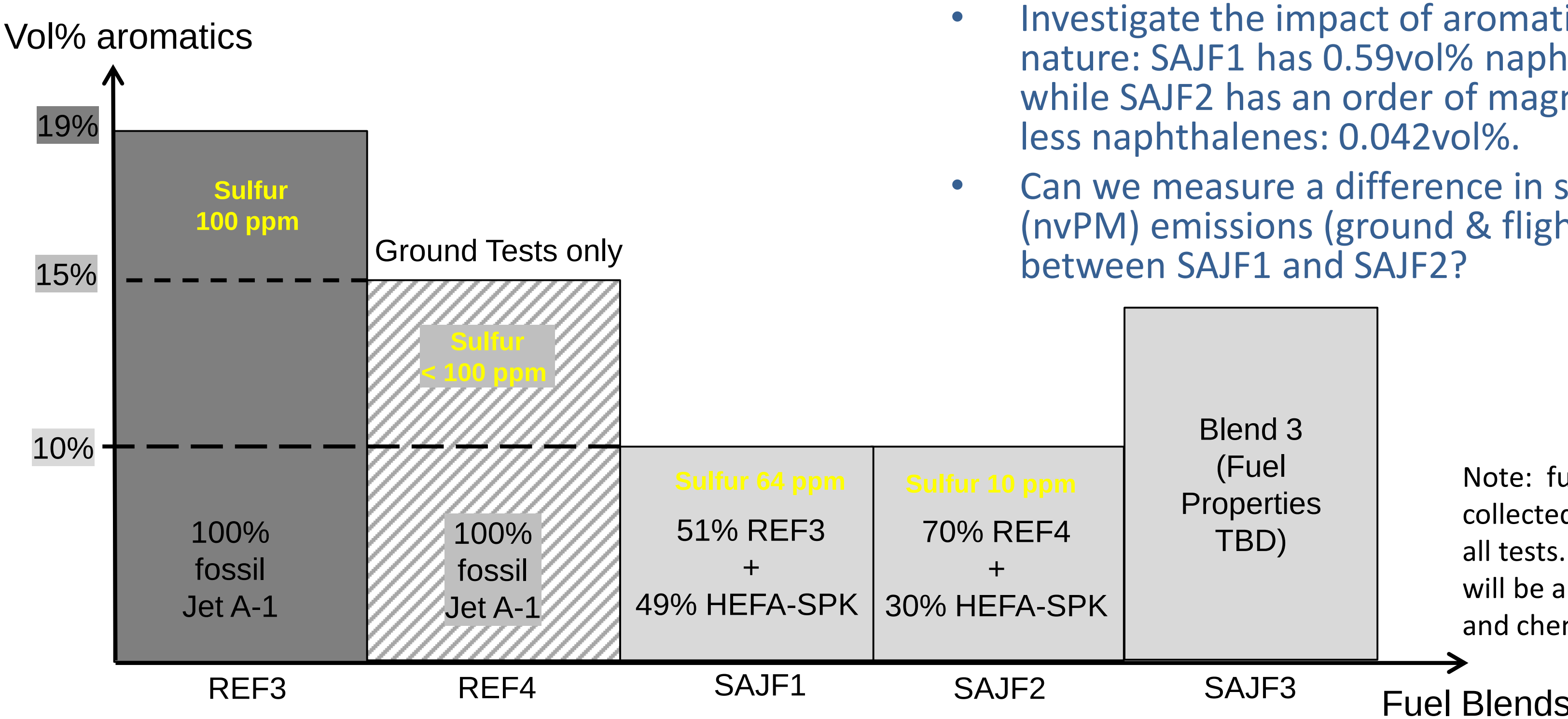
Design two sustainable alternative jet fuels (SAJFs), which yield substantial reductions in soot emissions & ice crystal concentrations with respect to conventional Jet A-1

Impact of Vol% aromatics on soot formation

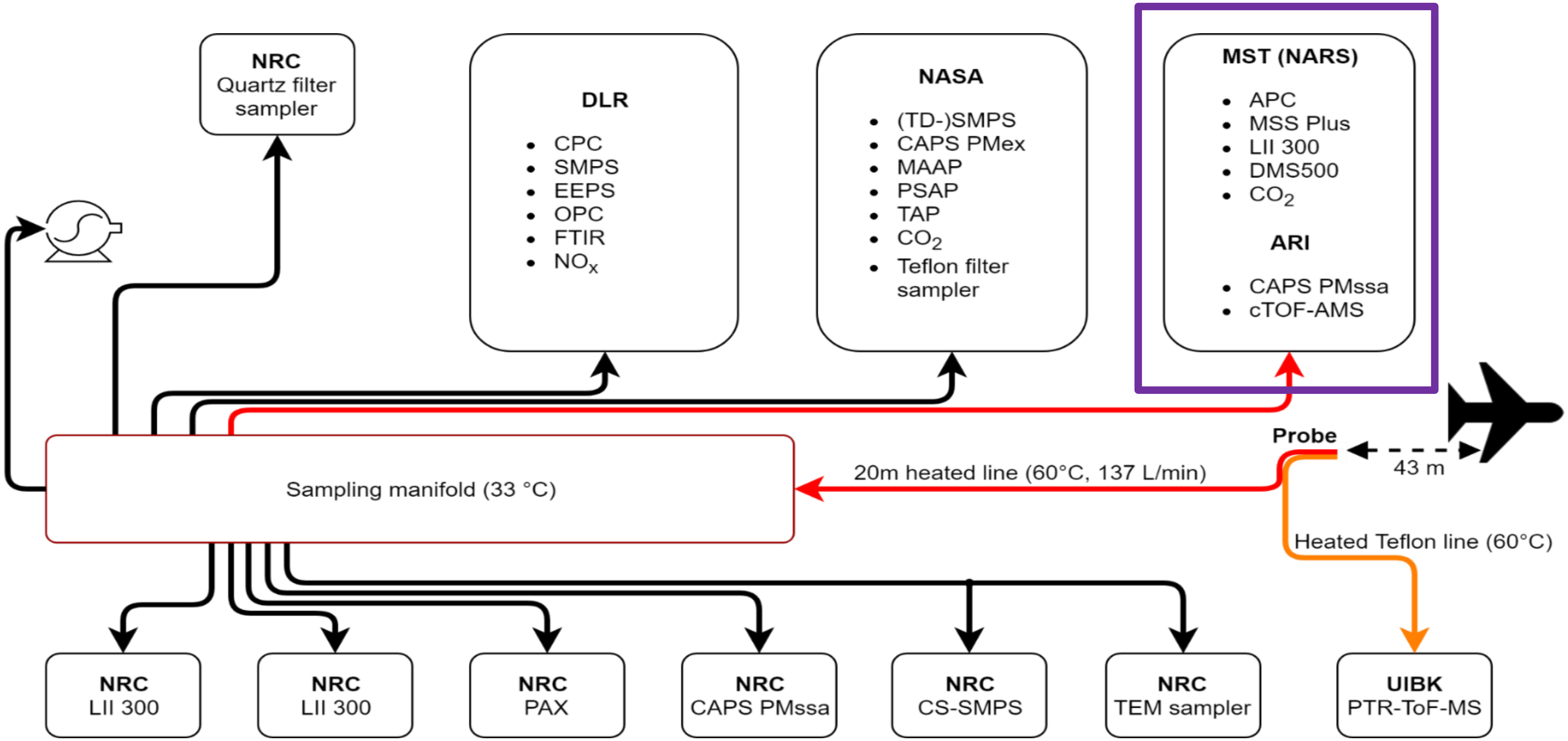
- Explore both extremes: close to 24% (REF3) and close to 8% (SAJF1&2)
- Collect sufficient data for statistics.

Impact of aromatics structure on soot emissions

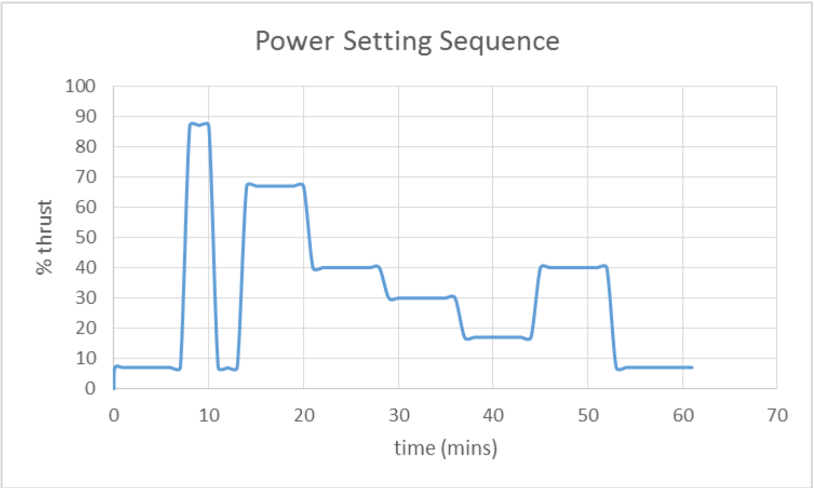
- SAJF1 and SAJF2 have the same Vol% aromatics, very close ppm concentration of sulfur, and same H-content, 14.46%m/m and 14.45%m/m respectively.
- Investigate the impact of aromatics nature: SAJF1 has 0.59vol% naphthalenes while SAJF2 has an order of magnitude less naphthalenes: 0.042vol%.
- Can we measure a difference in soot (nvPM) emissions (ground & flight) between SAJF1 and SAJF2?



Note: fuel samples were collected from the wing for all tests. These fuel samples will be analyzed for physical and chemical properties.


NRC
Quartz filter sampler
DLR
CPC
SMPS
EEPS
OPC
FTIR
NOx
NASA
(TD-)SMPS
CAPS PMex
MAAP
PSAP
TAP
CO2
Teflon filter sampler
MST (NARS)
APC
MSS Plus
LII 300
DMS500
CO2
ARI
CAPS PMssa
cTOF-AMS
Probe
43 m
20m heated line (60°C, 137 L/min)
Sampling manifold (33 °C)
Heated Teflon line (60°C)
NRC
LII 300
NRC
LII 300
NRC
PAX
NRC
CAPS PMssa
NRC
CS-SMPS
NRC
TEM sampler
UIBK
PTR-ToF-MS


DLR


Power Setting Sequence
% thrust
time (mins)
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70

Experiment Plan MS&T team Contributions

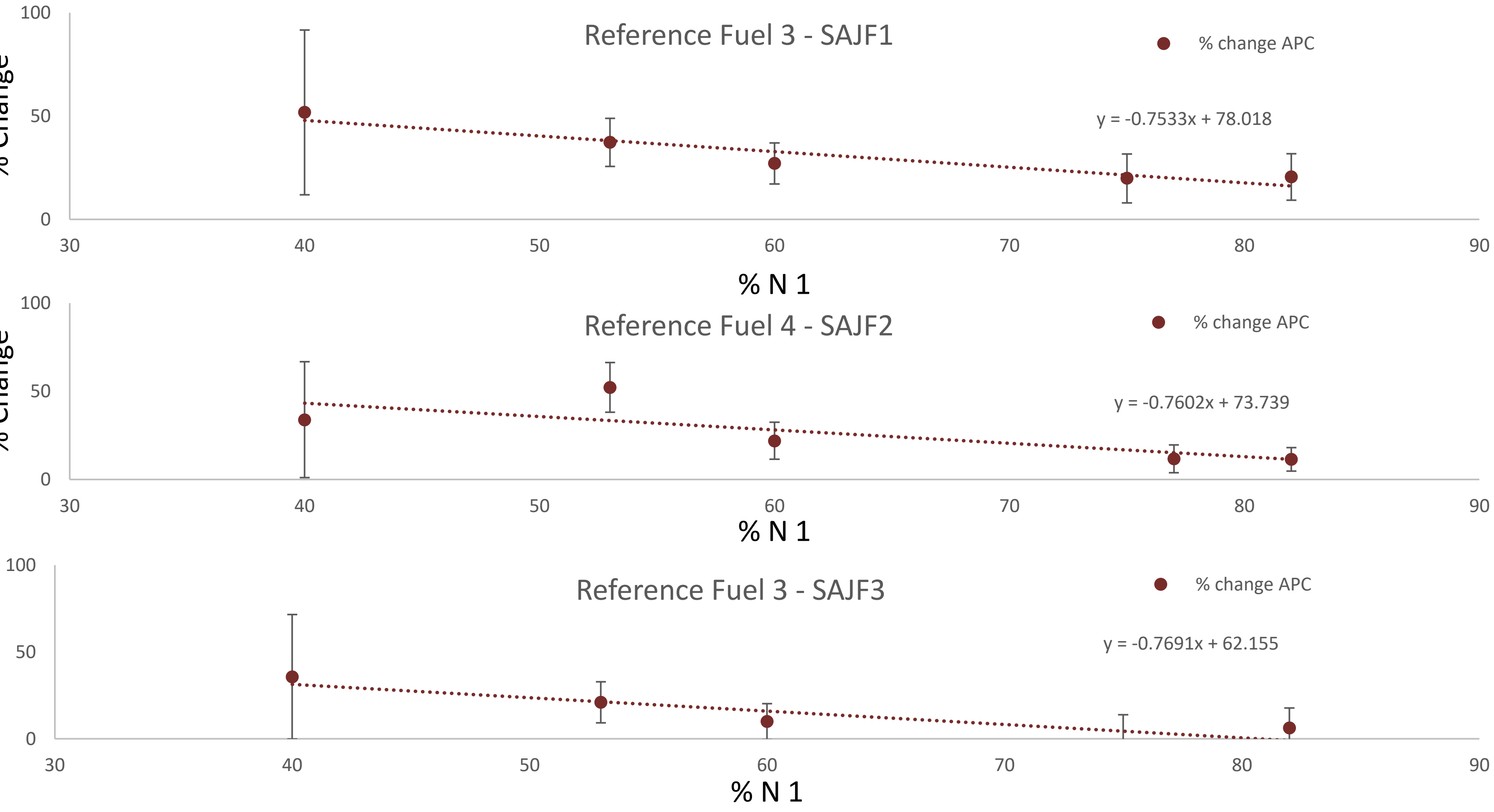
- Compare number and mass-based emissions measured with the NRC/DLR/NASA/ARI instruments to those from the NARS
  - Number: AVL APC, CPC
  - Mass: AVL MSS, LII-300, CAPS, PAX, Teflon filters, Quartz filters
- Validate the fuel composition correction model developed for WG3/PMTG
- Investigate BC optical properties as a function of fuel composition
  - CAPS
- Investigate primary particle size, aggregate size, and mobility size as a function of fuel composition
  - SMPS (with and without thermal denuder/catalytic stripper), EEPS, OPC, TEM, LII 300, DMS500
- Investigate organic PM and gas phase emissions and other gas phase properties
  - cTOF-AMS, PTR-ToF-MS, FTIR, LICOR (CO_2), NO_x

Measurements Completed

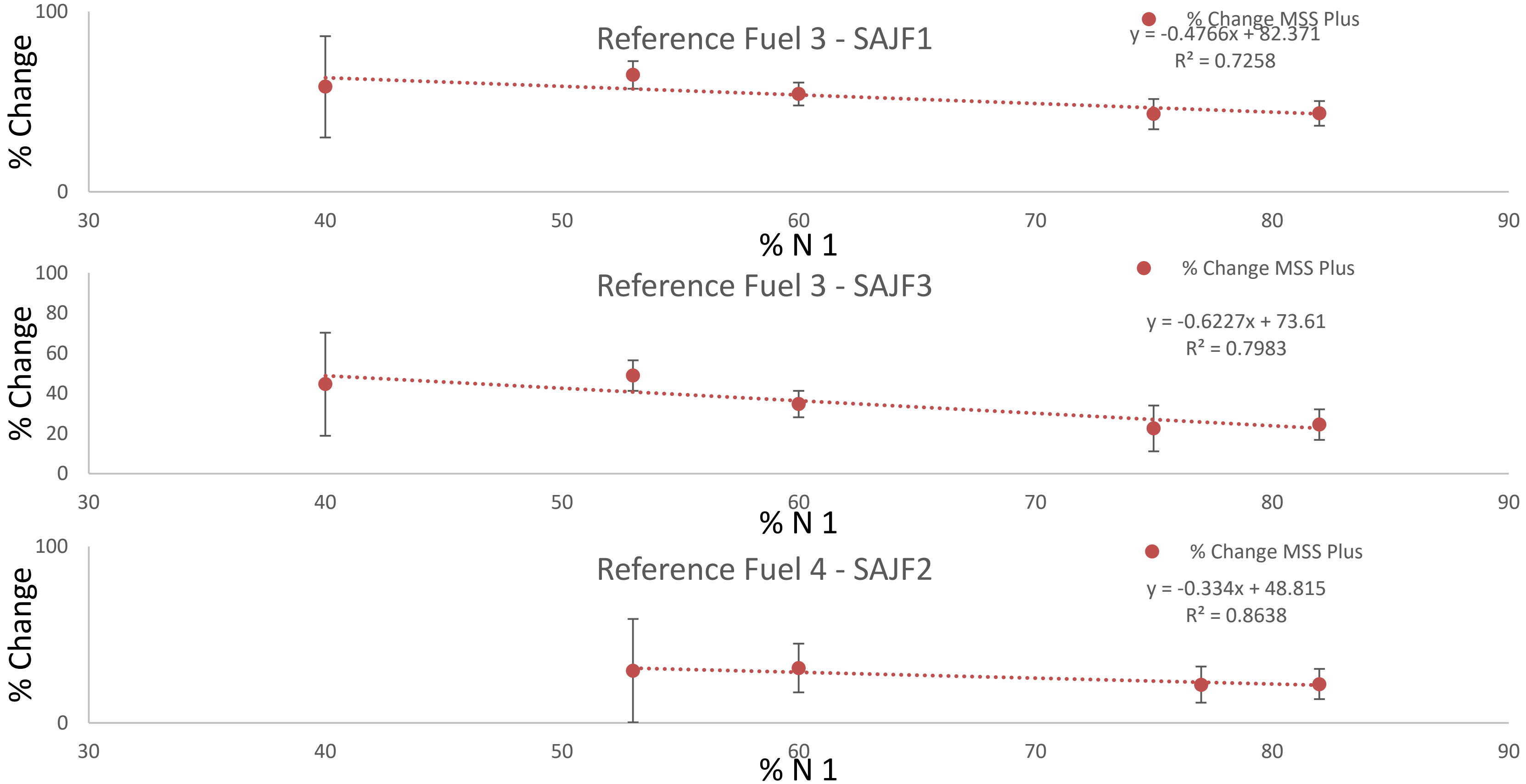
Run No.	Fuel	Duration
1	Ref3	45 min
2	SAJF2	60 + ~ 15 min*
3	JP-8 (C-17)	~ 20 min
4	SAJF1	60 min
5	JP-8 (DC8)	60 min
6	Ref3	60 min
7	SAJF1	60 min
8	SAJF3	60 min
9	Ref4	115 min

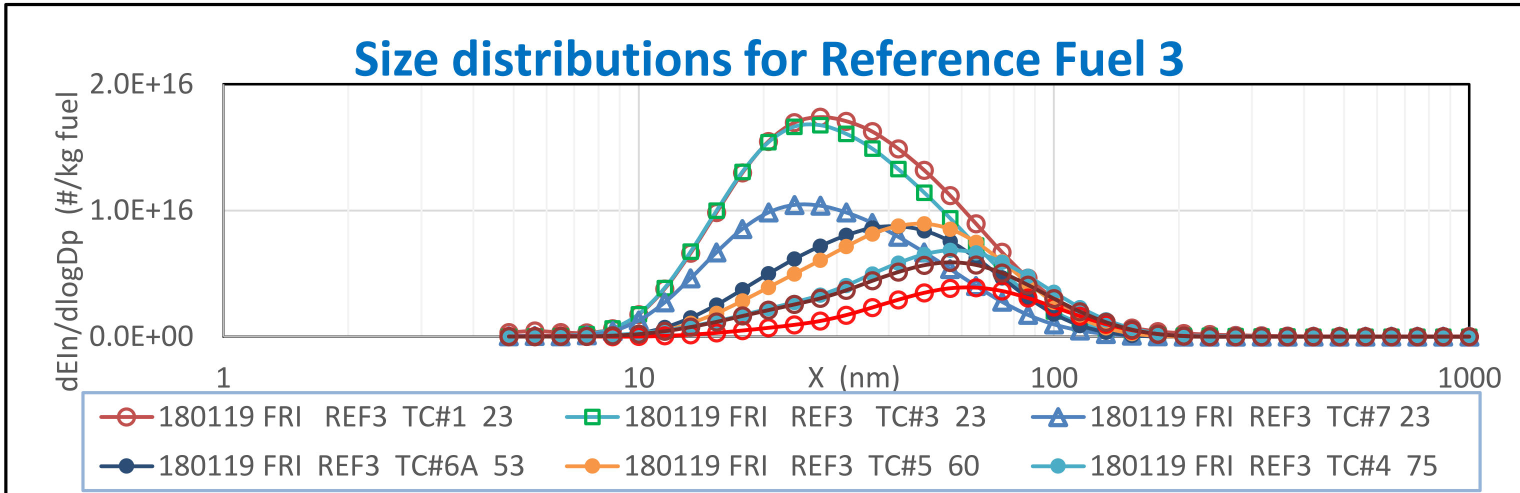
- For each of the four fuels under investigation, attempted two 60 min test sequences per fuel
- One additional test was performed, with Blend 3
- Two "unique opportunity" runs were also acquired
  - C17 / F117-PW-100; JP-8 (no data on thrust), fuel sample was collected
  - NASA DC-8 / CFM56-2C1 (#3 engine); JP-8

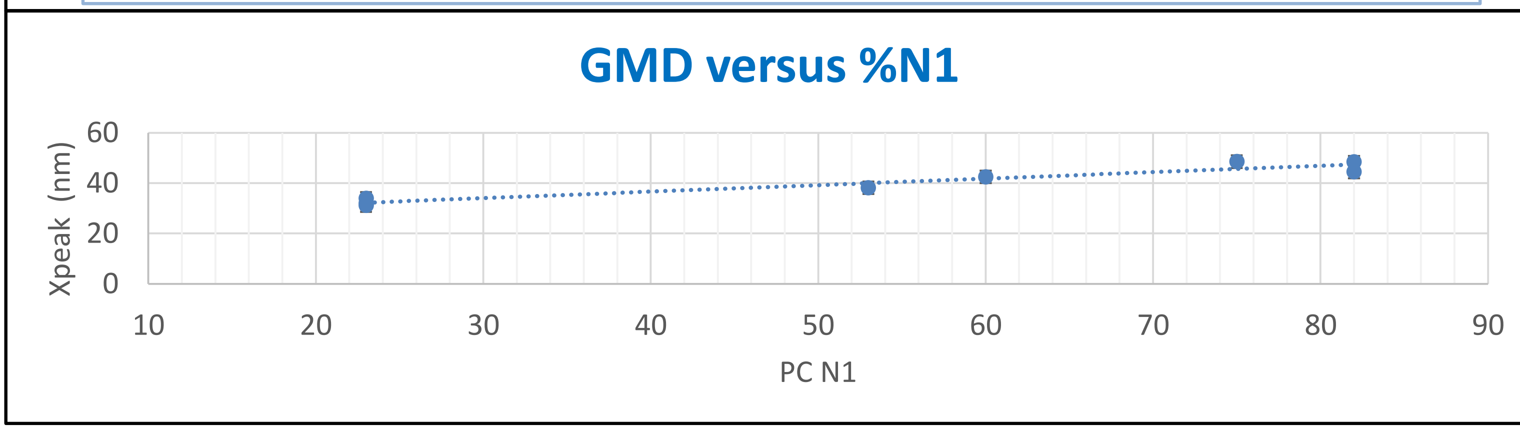
Percent Reduction in number - based emissions

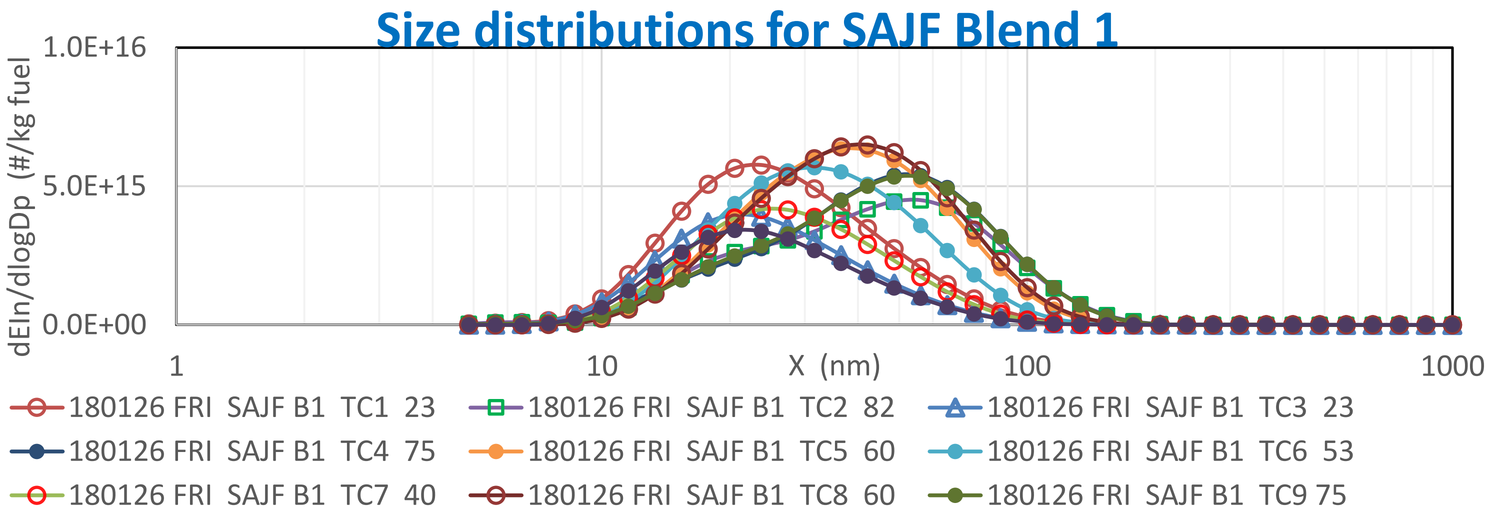


Percent Reduction in mass- based emissions

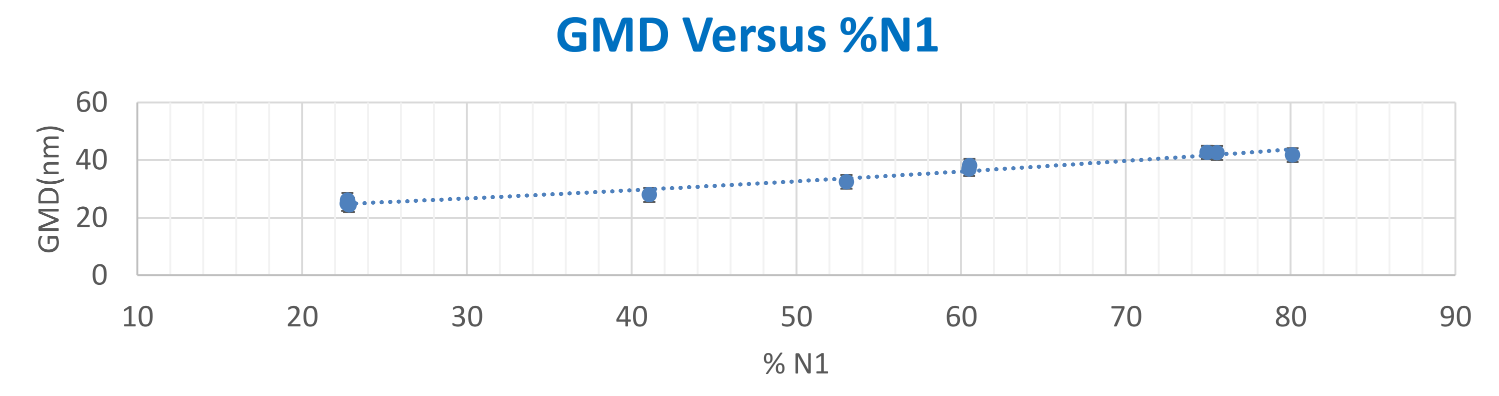



Size distributions for Reference Fuel 3
dEln/dlogDp (#/kg fuel
2.0E+16
1.0E+16
0.0E+00
1
10
100
1000
X (nm)
180119 FRI REF3 TC#1 23
180119 FRI REF3 TC#3 23
180119 FRI REF3 TC#7 23
180119 FRI REF3 TC#6A 53
180119 FRI REF3 TC#5 60
180119 FRI REF3 TC#4 75


GMD versus %N1
Xpeak (nm)
60
40
20
0
10
20
30
40
50
60
70
80
90
PC N1

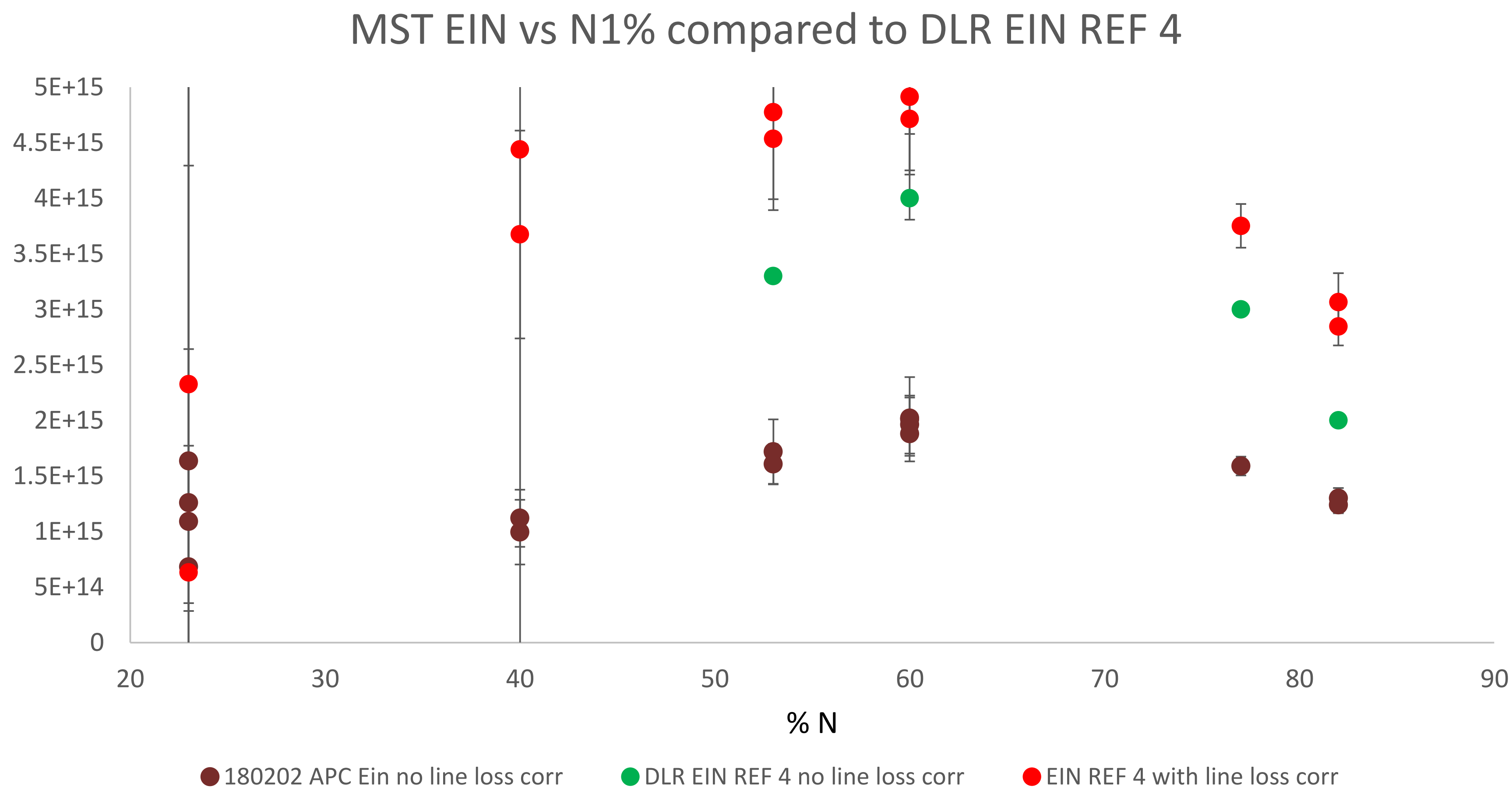


Size distributions for SAJF Blend 1
dEln/dlogDp (#/kg fuel
1.0E+16
5.0E+15
0.0E+00
1
10
100
1000
X (nm)
180126 FRI SAJF B1 TC1 23
180126 FRI SAJF B1 TC2 82
180126 FRI SAJF B1 TC3 23
180126 FRI SAJF B1 TC4 75
180126 FRI SAJF B1 TC5 60
180126 FRI SAJF B1 TC6 53
180126 FRI SAJF B1 TC7 40
180126 FRI SAJF B1 TC8 60
180126 FRI SAJF B1 TC9 75



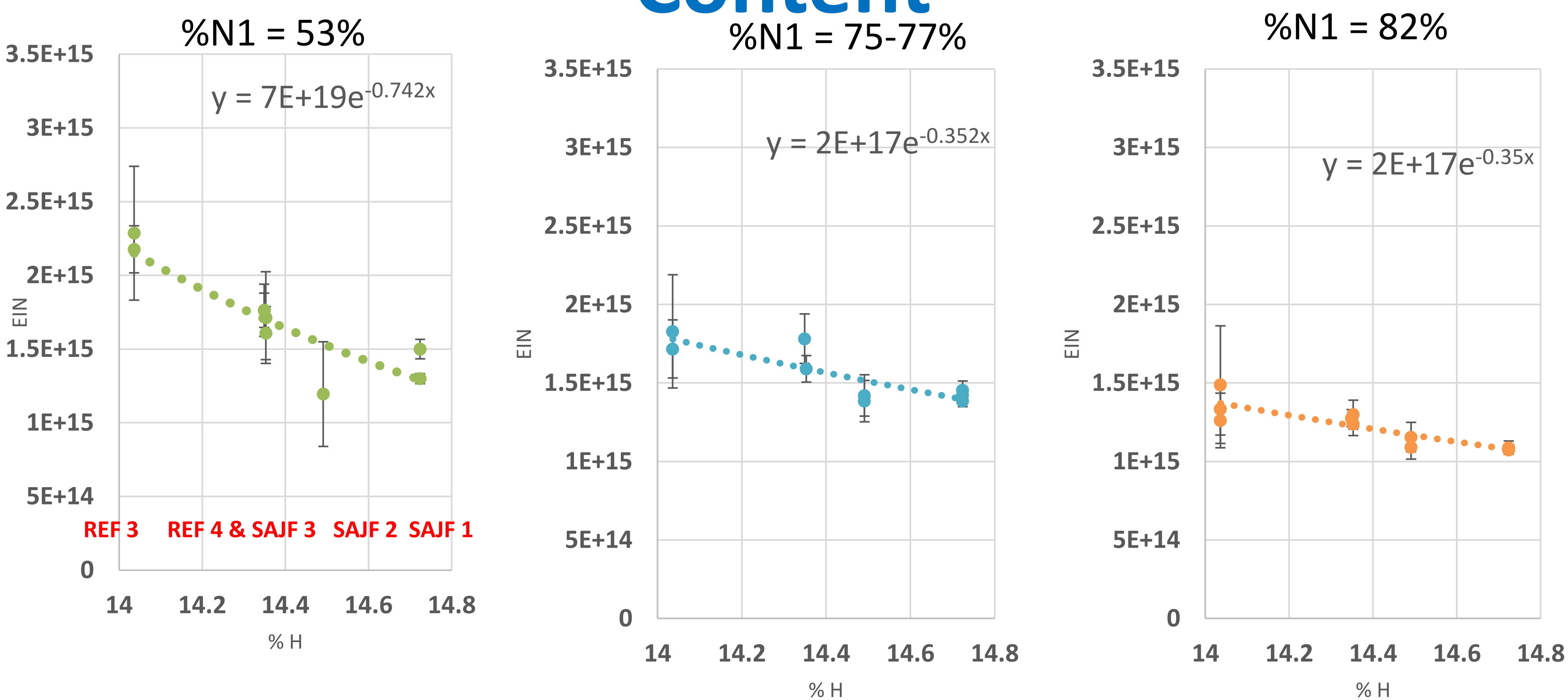
GMD Versus %N1
GMD(nm)
60
40
20
0
10
20
30
40
50
60
70
80
90
% N1

Comparison with DLR Data and Line Loss Adjustments

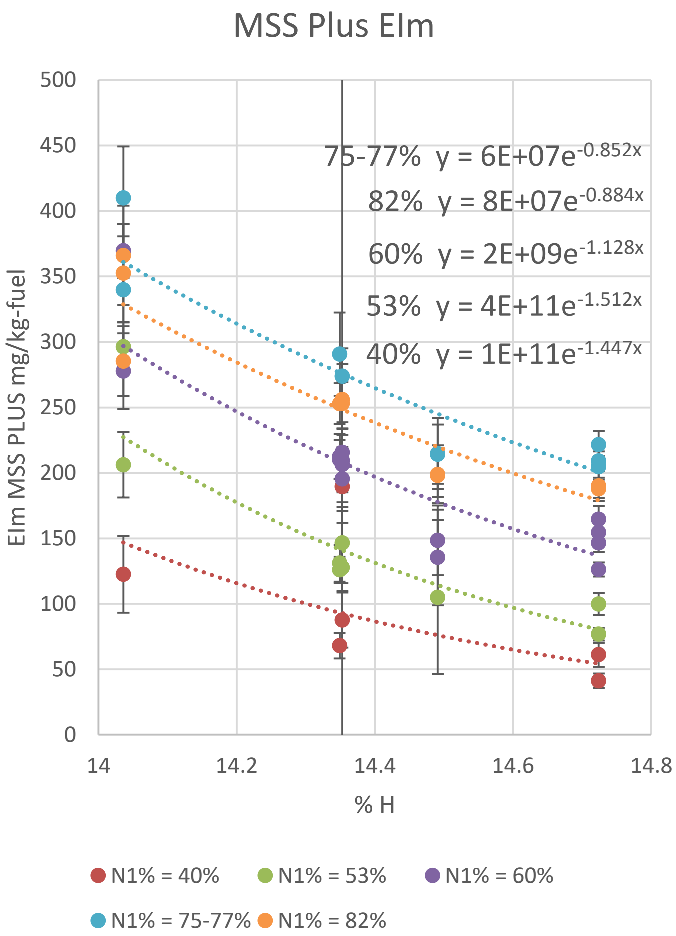


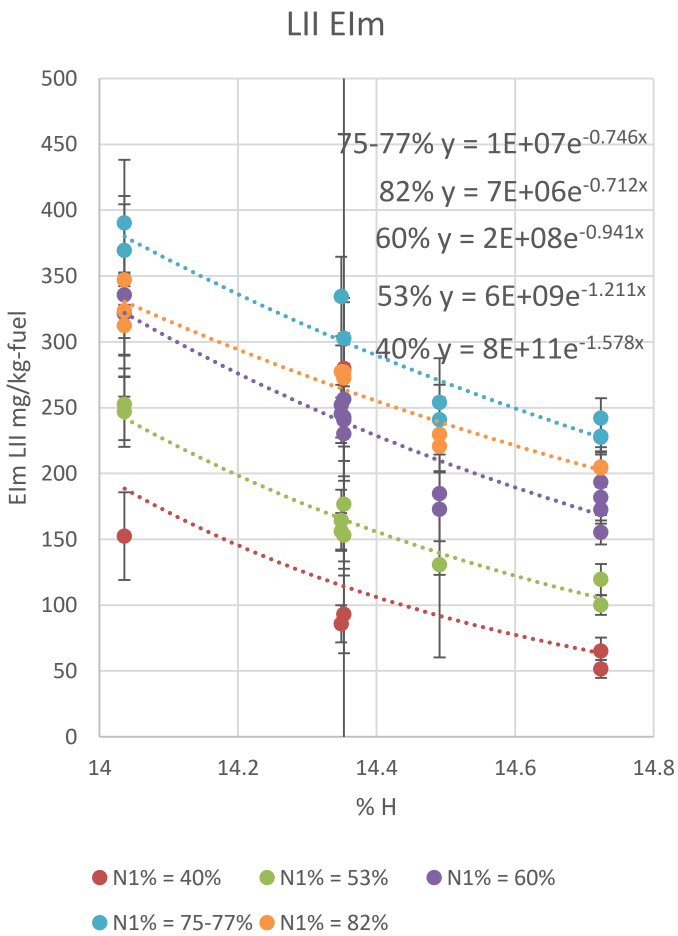
Data for reference fuel 4 from MST with (red symbol) and without line loss correction (brown symbol)
Data for reference fuel 4 from DLR without line loss correction (green symbol)
The NARS methodology deployed by MST requires an additional 25m of sample line

Emissions Variation with Hydrogen Content

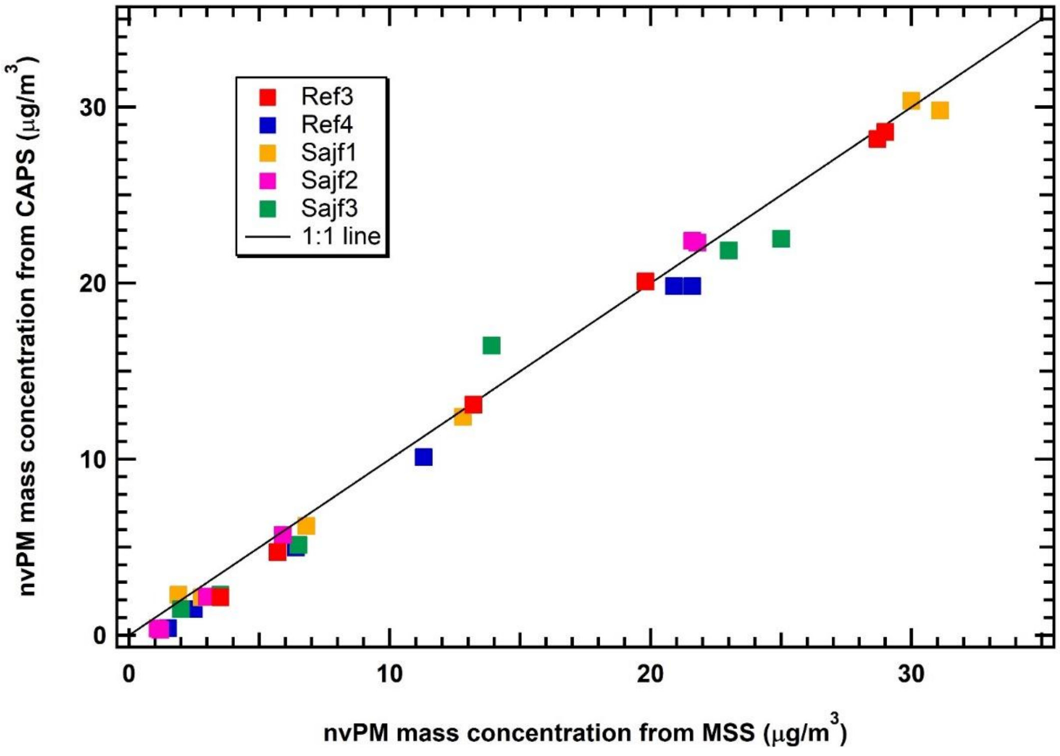


Emissions Variation with Fuel Hydrogen Content



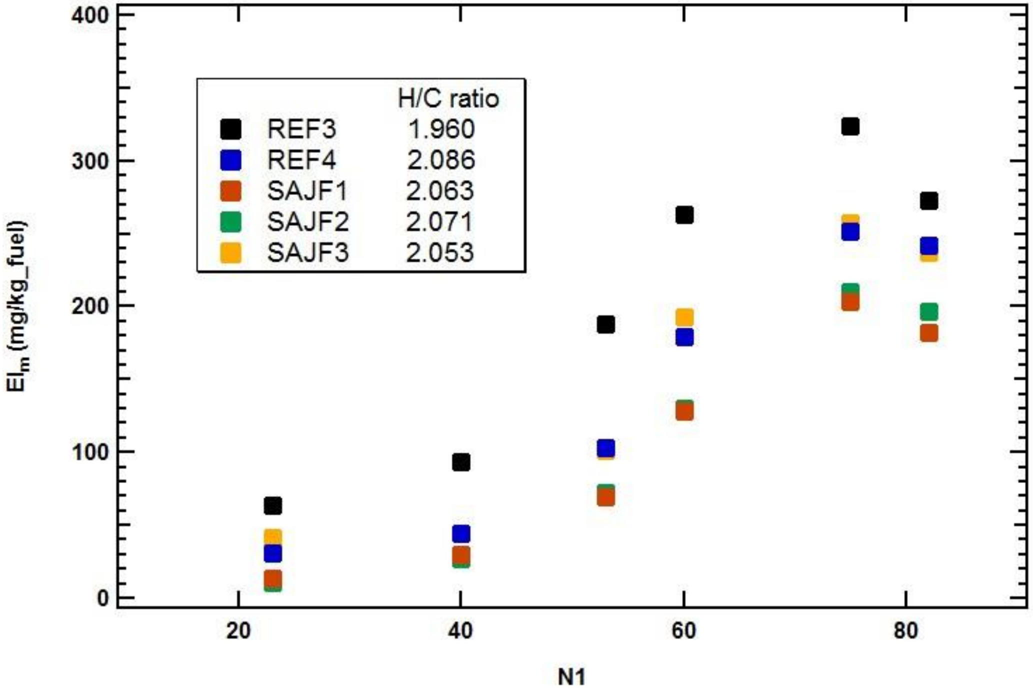


CAPS ssa monitor gives the similar results as MSS in nvPM mass measurements



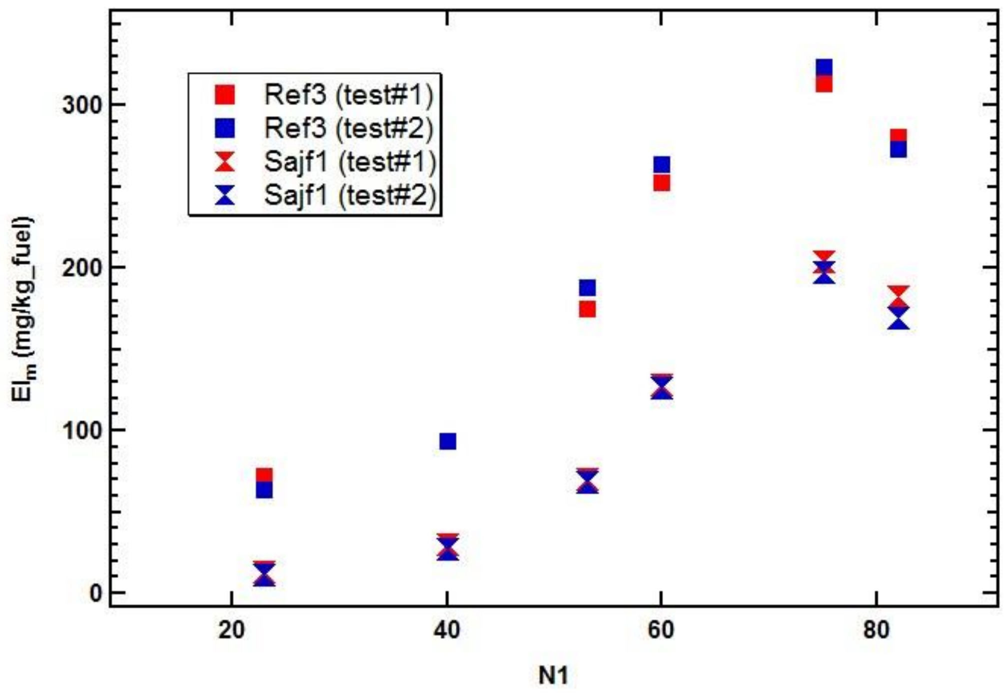
- nvPM mass concentrations from the CAPS ssa measurements are calculated from the determined absorption coefficients by assuming MAC (mass absorption coefficient) = 6.5 m^2/g at 635nm (Bond & Bergstrom, AST 2006)
- The agreement between CAPS ssa and MSS instruments are good for each fuel type

EI_m from CAPS ssa shows the similar trends on emission reduction as MSS and LII



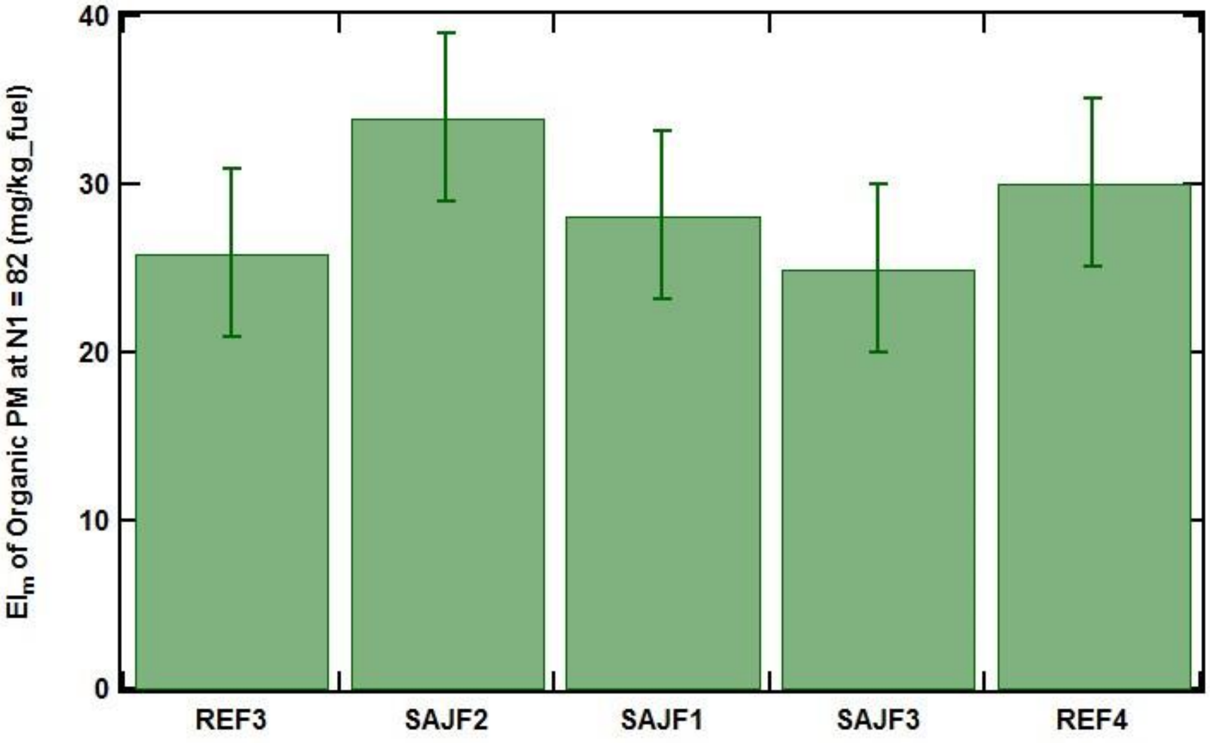
- Relative reduction in EI_m by mixing alternative fuel with Jet A fuel decreases with the increasing engine power.
- Reduction in EI_m compared to Ref3 fuel is more significant than that compared to Ref4 fuel
- Determination of H/C ratio with a higher precision seems necessary to better interpret the dependence of emission reduction on fuel composition

EI_m from CAPS ssa shows good test repeatability for each fuel



EI_m from the CAPS ssa measurements demonstrates the variation between test # 1 and 2 at each engine power condition is less than experimental uncertainty (~15%) for each fuel

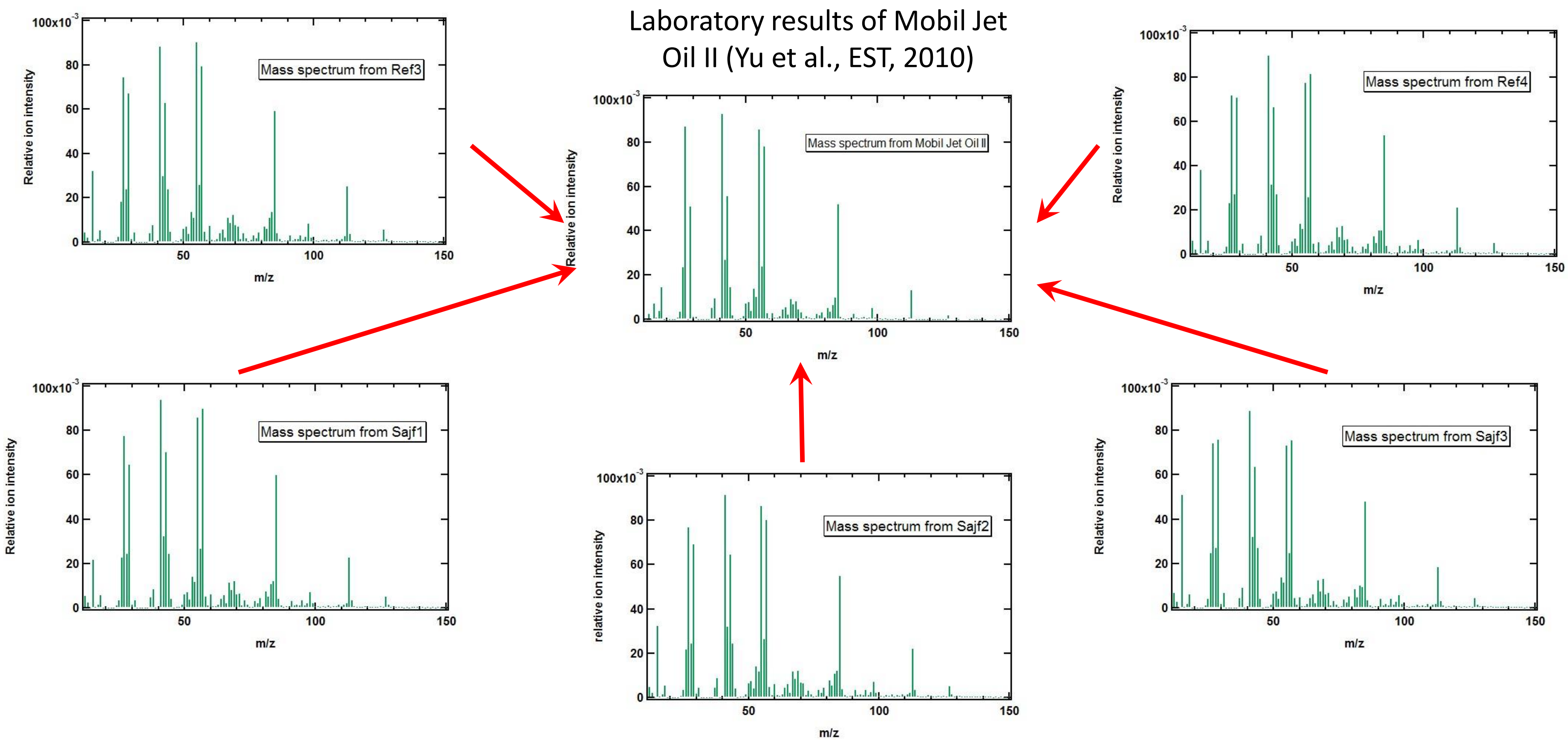
Organic contributions to PM do not depend on fuel type



- EI_m of organic PM (N1=82) are insensitive to fuel type
- EI_m of nvPM depends strongly on fuel type
- This independence of fuel type holds for all power conditions

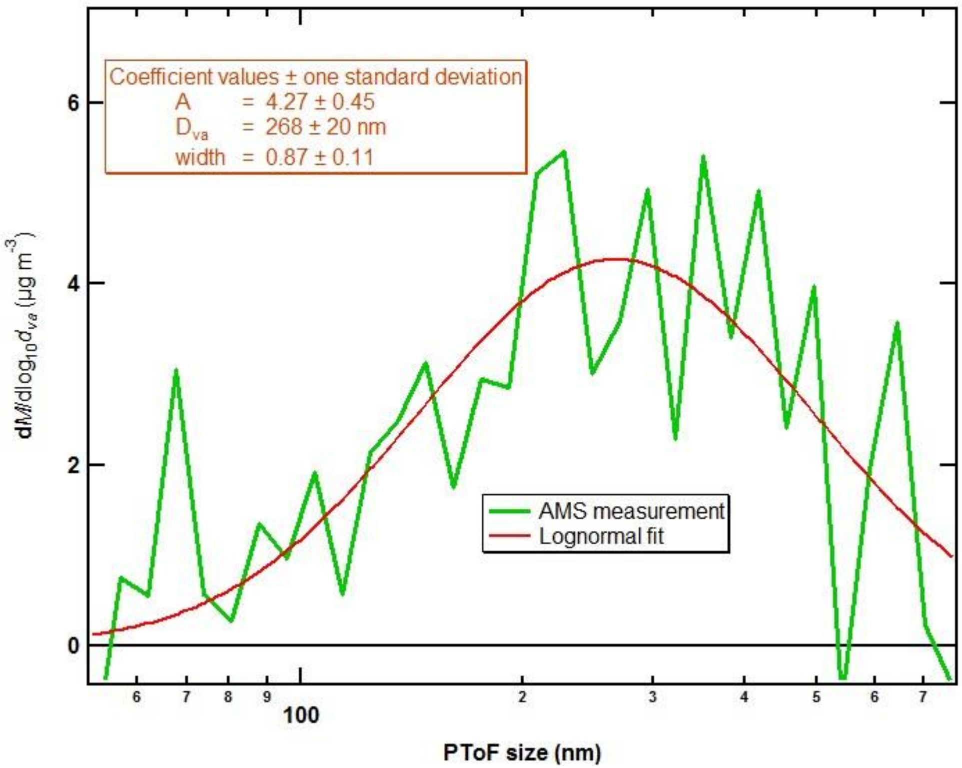
- Is this a combustion-related process?

Mass spectra of organic PM emissions from all fuels match the spectrum of aviation oil



Organic PM in a distinct mode: Externally mixed

Larger than soot particles, and consistent with oil vent particles measured previously



Particle size distribution (PSD) of organic PM (N1=82) is consistent with our previous study on lubrication oil emissions from aircraft engines (Yu et al., EST 2010)

PSD of organic PM from SAJF1 fuel at N1 = 75 peaks around 268 nm in vacuum aerodynamic diameter (D_{va}), which is very different from that of the nvPM emissions that peaks about 60 nm in electrical mobility diameter (D_m)

We conclude that organic PM is vented oil and not combustion-related

Next Steps for ND MAX

- Attend ND MAX workshop in Hampton VA 17-19 October 2018.
- Continue with instrument inter-comparisons especially between other ground-based systems and their in-flight equivalents.
- Present paper at AGU Fall Meeting in DC 10-14 December 2018.
- Publish results Spring 2019

Conclusions and Next Steps

- Summary statement
  - Demonstrations, inter-comparisons and methodology validation for informing the development of a LTO based nvPM mass and number aircraft engine emissions standard and determining compliance with a new regulatory standard for aircraft engine nvPM
- Next steps?
  - analysis of results obtained during ND-MAX/ECLIF-II and Honeywell Rig Testing
  - Continue close coordination with SAE E31
  - Review data, correlate, and build upon current knowledge with other programs i.e. VARIANT, ND-MAX follow on etc.
  - Opportunities in consideration for the development of nvPM measurements to quantify fuel composition, ambient conditions and cruise effects.
- Key challenges/barriers
  - Complex interaction with multiple stakeholders

Publications and Presentations

- Emissions Measurements (ND MAX/ECLIF2) Annual Emissions Characterization (AEC) Research Roadmap Meeting, National Academy of Science, Washington DC, 22-24 May 2018.
- SAE E31 ND MAX Presentation, SAE E31 International Meeting, Los Angeles CA, 4-8 June 2018.
- Tandem DMA Approach for Real Time Measurements of Deliquescence and Volatility of Plume Processed Jet Engine PM Exhaust. Cambridge Particle Meeting, Cambridge University, UK, 15 June 2018

Participants

- Phil Whitefield, Steven Achterberg, Max Trueblood, David Satterfield, Wenyan Liu (MST)
- Rick Miake-Lye, Zhenhong Yu (ARI)
- Greg Smallwood, Prem Lobo, Joel Corbin (NRC)
- Bruce Anderson, Ewan Crosbie NASA
- Hans Schlager, Tobias Schripp (DLR)
- Rudy Dubedout, Paul Yankowich, Dave Christie (Honeywell)