Non-volatile PM Emissions Measurements

Project 002

Lead investigator: Phil Whitefield, MS&T
Project manager: Daniel Jacob, FAA

October 22-23 2019
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 on open issues related to the CAEP/11 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 to address the requirements 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

- **Near term**

  – Close coordination with and feedback from SAE E-31 committee
  – Common agreement on way forward
  – Develop international standard atmosphere (ISA) corrections for NVPM measurements.
  – Process data to evaluate cruise nvPM models
  – Contribute to the development of certification methods improvements particularly with PM mass calibration approaches

Approach

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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

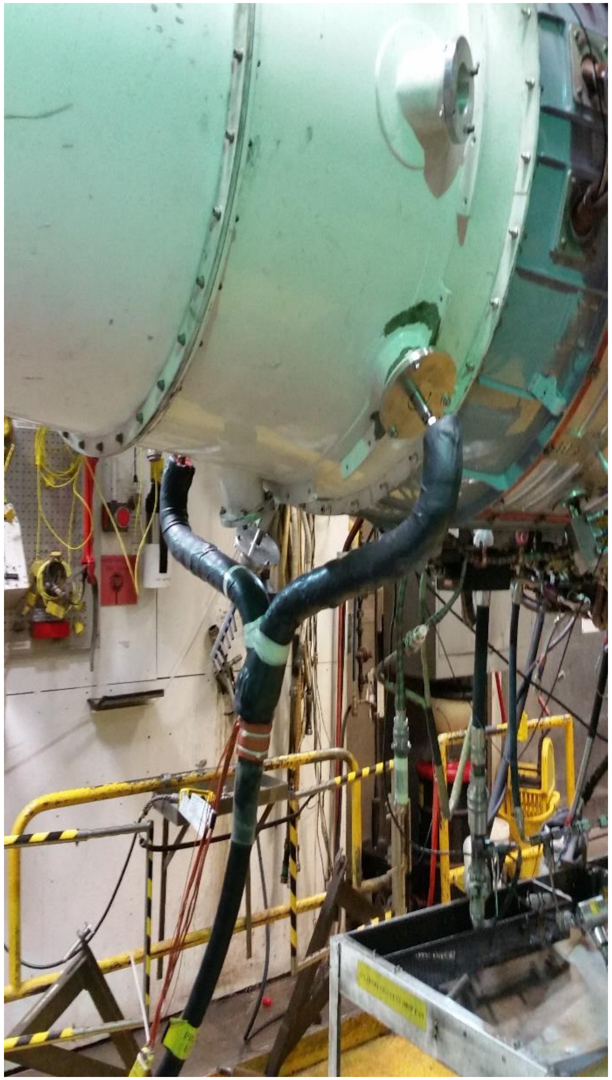
- ND MAX 2017 - 2020
- Honeywell Comb/rig/alt fuels 2018 - 2020

Proposed

- Mass Cal. Standard Development 2019 - 2020

Recent Accomplishments and Contributions

- Informed CAEP/11 LTO nvPM Mass and Number Standards Development
  - Engine to Engine Variability – development of characteristic coefficients
  - Ambient Conditions Corrections development
- NDMAX/ECLIF-11
- Combustor Rig Test & Analysis for Determining nvPM Ambient Corrections at Honeywell – In Progress
  - nvPM emissions from aircraft engines are affected by changing inlet conditions. A combustor rig test provides the most flexibility to quantify the impact of changing conditions on the nvPM emissions and to develop methods for use inventory modeling.



NVPM EMISSIONS: ENGINE TO ENGINE VARIABILITY TEST RESULTS SYNOPSIS FROM ICAO CAEP11-WG3-PMTG7-IP01

Oct 26, 2017

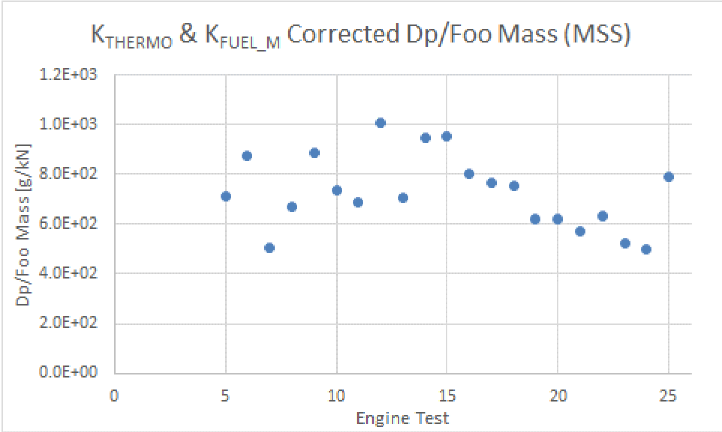
Rudy Dudebout and Rich Bohman, Honeywell

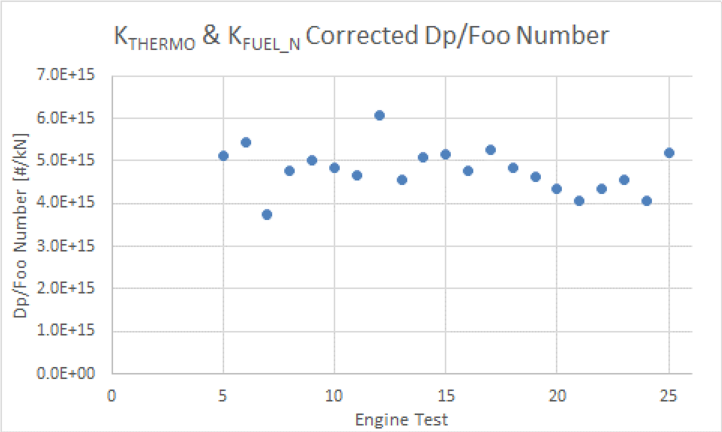
Honeywell

Engine-to-Engine nvPM Variability Testing Program – 25 Engines Tested

Dp/Foo Summary for nvPM Mass and Number (Fuel correction)

	With K_{THERMO} & K_{FUEL_X}		
	Dp/Foo MSS	Dp/Foo LII	Dp/Foo Num
Test	g/kN	g/kN	#/kN
5	7.14E+02	7.97E+02	5.13E+15
6	8.75E+02	9.74E+02	5.44E+15
7	5.07E+02	5.56E+02	3.73E+15
8	6.71E+02	6.84E+02	4.77E+15
9	8.87E+02	9.99E+02	5.03E+15
10	7.37E+02	8.07E+02	4.84E+15
11	6.89E+02	7.55E+02	4.65E+15
12	1.01E+03	1.10E+03	6.06E+15
13	7.08E+02	7.57E+02	4.55E+15
14	9.50E+02	1.01E+03	5.09E+15
15	9.53E+02	1.02E+03	5.17E+15
16	7.99E+02	8.69E+02	4.77E+15
17	7.64E+02	8.03E+02	5.25E+15
18	7.54E+02	8.05E+02	4.84E+15
19	6.19E+02	6.53E+02	4.62E+15
20	6.23E+02	6.58E+02	4.33E+15
21	5.73E+02	5.97E+02	4.06E+15
22	6.35E+02	7.51E+02	4.36E+15
23	5.24E+02	6.13E+02	4.55E+15
24	4.99E+02	5.83E+02	4.06E+15
25	7.92E+02	8.31E+02	5.20E+15
Avg	727.8	791.1	4.79E+15
StDev	148.5	157.8	5.27E+14
StDev / Avg	0.204	0.199	0.110





- **Based on 21 engine tests:**
  - **LTO mass (MSS) standard deviation/average = 20.4%**
  - **LTO mass (LII) standard deviation/average = 19.9%**
  - **LTO mass (LII & MSS) standard deviation/average = 20.4%**
  - **LTO number standard deviation/average = 11.0%**

Combined MSS & LII

	Dp/Foo MSS + LII
Avg	759.5
StDev	154.7
StDev / Avg	0.204

Fuel correction reduced standard deviation by < 1%

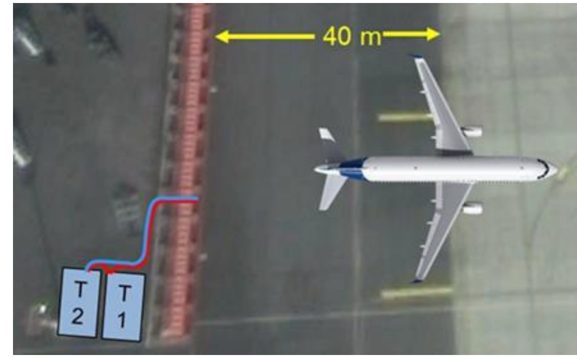
Outcome

- nvPM Mass and Number Characteristic Factors for CAEP/11 nvPM Standards Compliance in Annex 16 Vol.II Appendix 6

Number of engines tested (i)	CO	HC	NOx	SN	nvPM mass concentration	nvPM LTO mass	nvPM LTO number
1	0.814 7	0.649 3	0.862 7	0.776 9	0.776 9	0.719 4	0.719 4
2	0.877 7	0.768 5	0.909 4	0.852 7	0.852 7	0.814 8	0.814 8
3	0.924 6	0.857 2	0.944 1	0.909 1	0.909 1	0.885 8	0.885 8
4	0.934 7	0.876 4	0.951 6	0.921 3	0.921 3	0.901 1	0.901 1
5	0.941 6	0.889 4	0.956 7	0.929 6	0.929 6	0.911 6	0.911 6
6	0.946 7	0.899 0	0.960 5	0.935 8	0.935 8	0.919 3	0.919 3
7	0.950 6	0.906 5	0.963 4	0.940 5	0.940 5	0.925 2	0.925 2
8	0.953 8	0.912 6	0.965 8	0.944 4	0.944 4	0.930 1	0.930 1
9	0.956 5	0.917 6	0.967 7	0.947 6	0.947 6	0.934 1	0.934 1
10	0.958 7	0.921 8	0.969 4	0.950 2	0.950 2	0.937 5	0.937 5
more than 10	$1- \frac{0.130\ 59}{\sqrt{i}}$	$1- -\frac{0.247\ 24}{\sqrt{i}}$	$1- \frac{0.096\ 78}{\sqrt{i}}$	$1- \frac{0.157\ 36}{\sqrt{i}}$	$1- \frac{0.157\ 36}{\sqrt{i}}$	$1 - \frac{0.197\ 78}{\sqrt{i}}$	$1 - \frac{0.197\ 78}{\sqrt{i}}$

Recent Accomplishments and Contributions

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)

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:

Transport Canada Transports Canada

Experiment Plan MS&T team Contributions

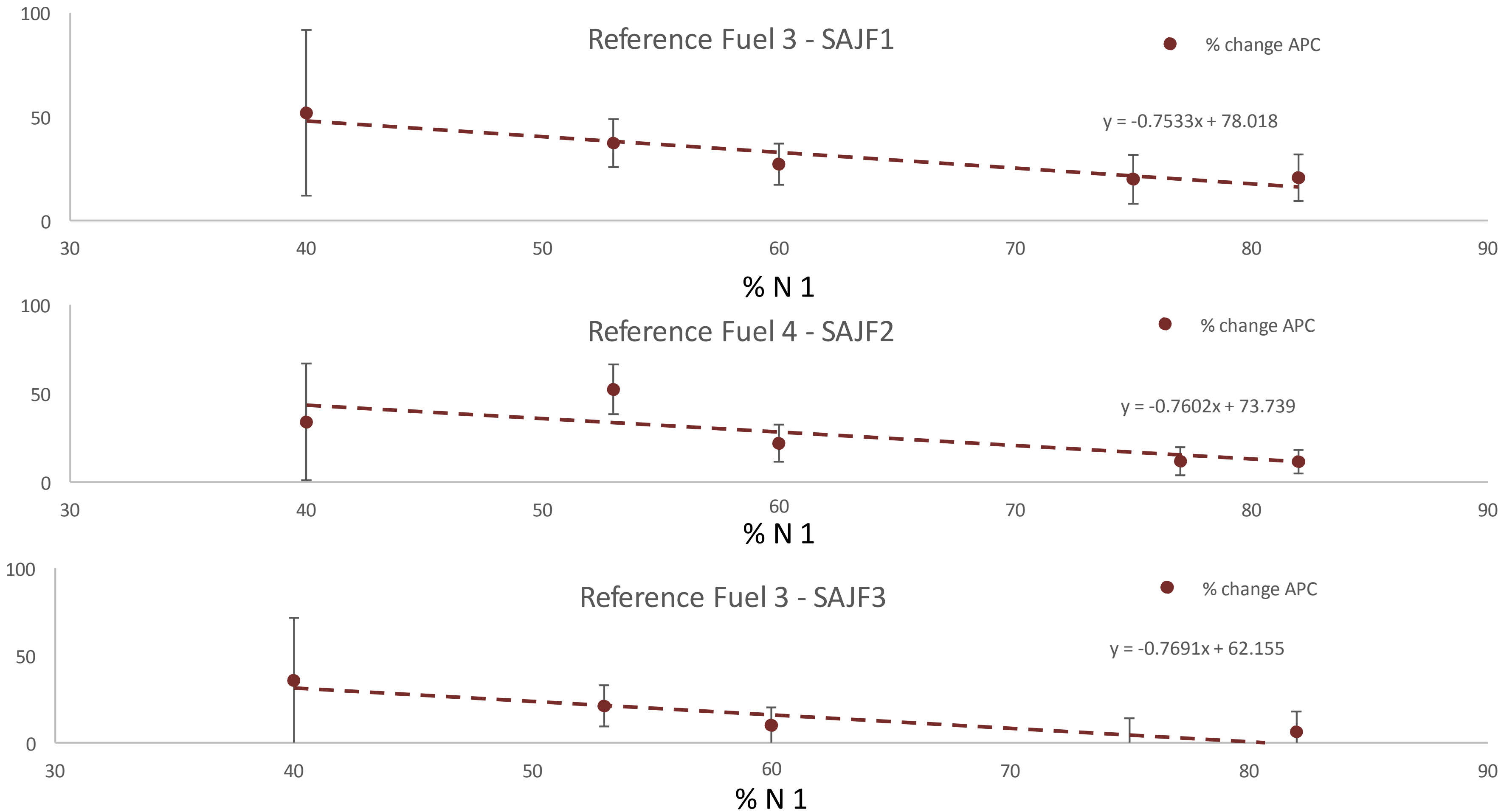
- Compare number and mass-based emissions measured with the NRC/DLR/NASA/ARI instruments to those from the NARS
  - Number: AVL APC, CPC
  - Mass: AVL MSS, LII-300, CAPS, PAX, Teflon filters, Quartz filters
- Validate the fuel composition correction model developed for WG3/PMTG
- Investigate BC optical 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

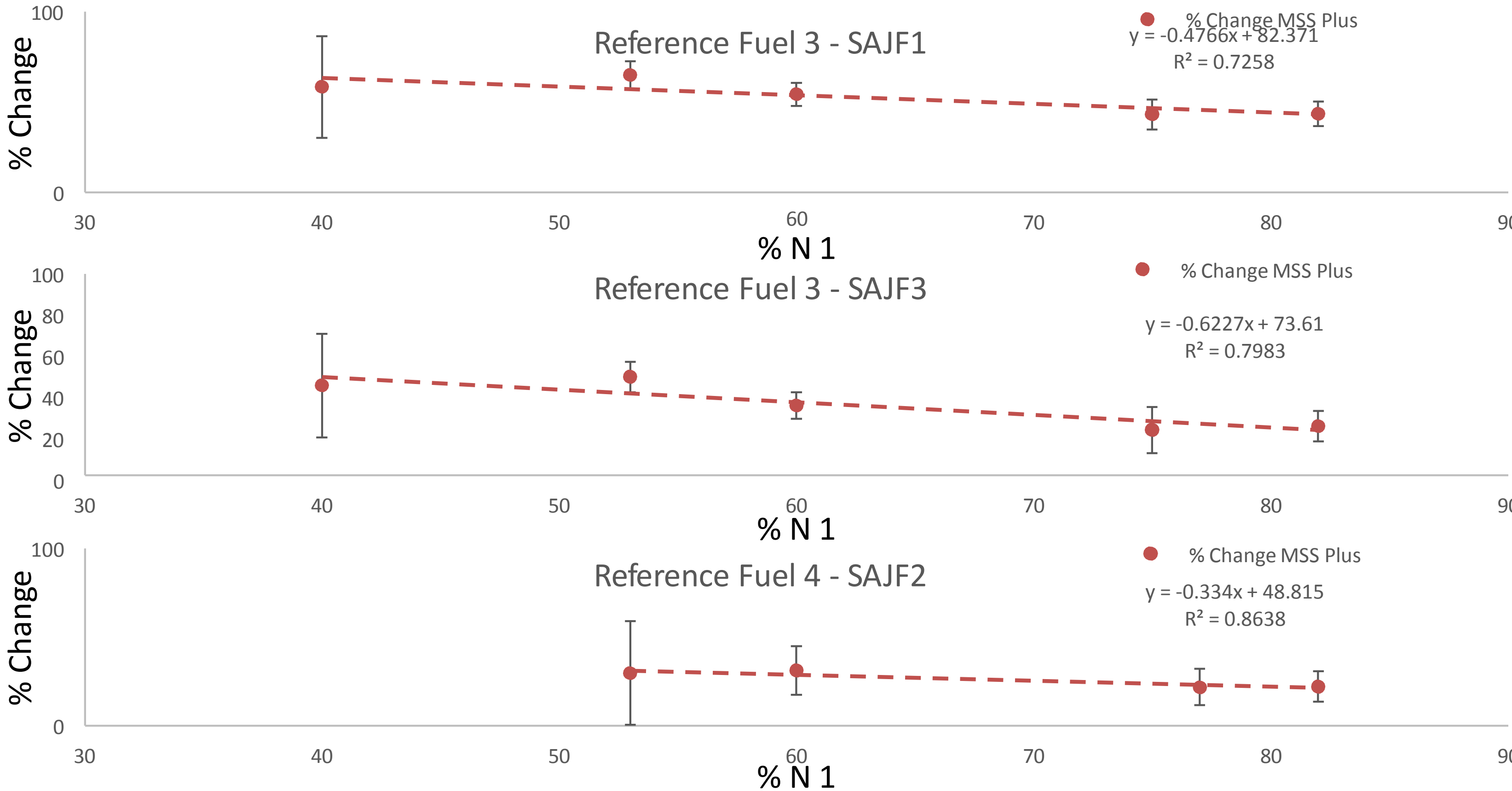
Run No.	Fuel	Duration
1	Ref3	45 min
2	SAJF2	60 + ~ 15 min*
3	JP-8 (C-17)	~ 20 min
4	SAJF1	60 min
5	JP-8 (DC8)	60 min
6	Ref3	60 min
7	SAJF1	60 min
8	SAJF3	60 min
9	Ref4	115 min

- 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

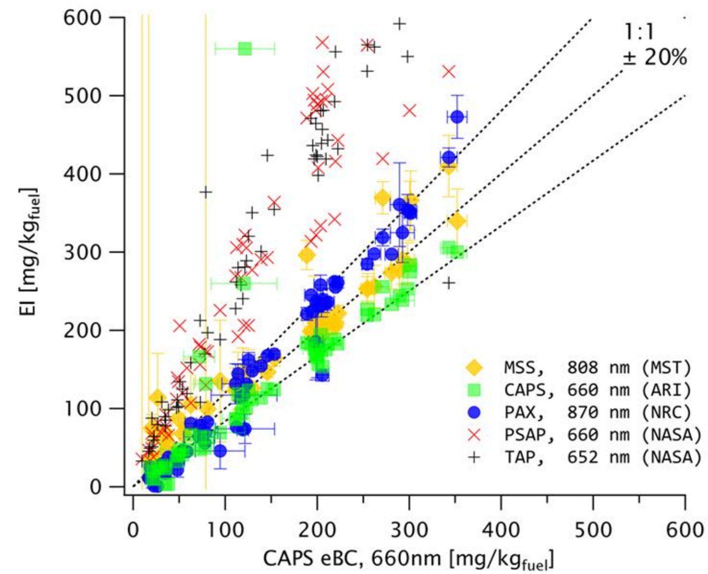


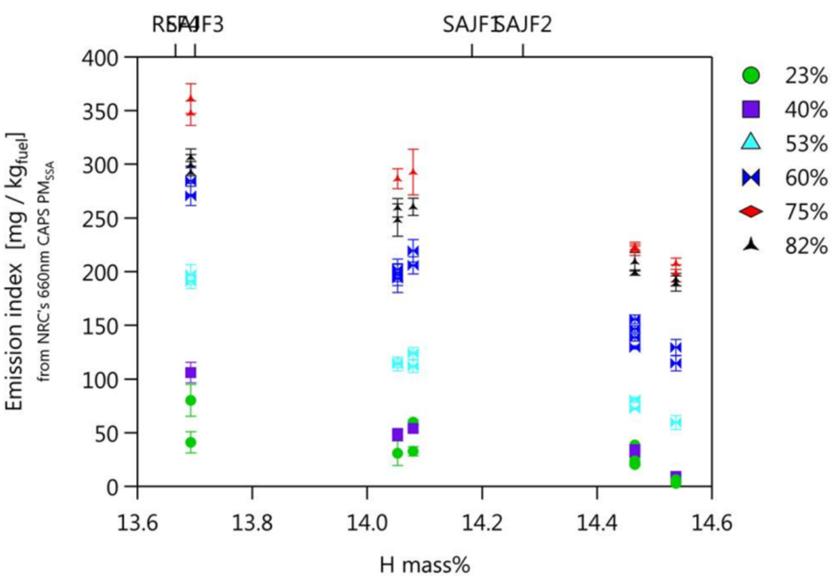
Percent Reduction in mass- based emissions



H% Correlations and Mass instrument Comparisons

Fuel Property	REF3	REF4	SAJF1	SAJF2	SAJF3
Aromatics [vol%] (ASTM D1319) PetroLab	18.6	15.4 *(ASTM D6379)*	9.6	10.8	15.2
Hydrogen H [mass%] (NMR ASTM D7171) VT-CHA	13.65	14.08	14.40	14.51	14.04
Sulphur [ppm] (ISO 20884) ASG	105	5.7	56.8	4.1	58.6
Naphthalenes [mass%] (ASTM D1840) PetroLab	1.17	0.07	0.61	0.042	0.64
Smoke point [mm] (ASTM D1322) PetroLab	23.0	26.5	29.0	28.0	28.0





- H% serves as a useful proxy for emission indices of SAJF fuels.
- BC or "nvPM" instruments generally perform consistently for alternative SAJF fuels compared to traditional fuels.
- Filter-based instruments require source-specific calibrations when sources produce particles of a different composition or size, compared to the calibration of those instruments. The calibration factors of such instruments must not be treated as universal constants.

Recent Accomplishments and Contributions

Progress on rig testing at Honeywell

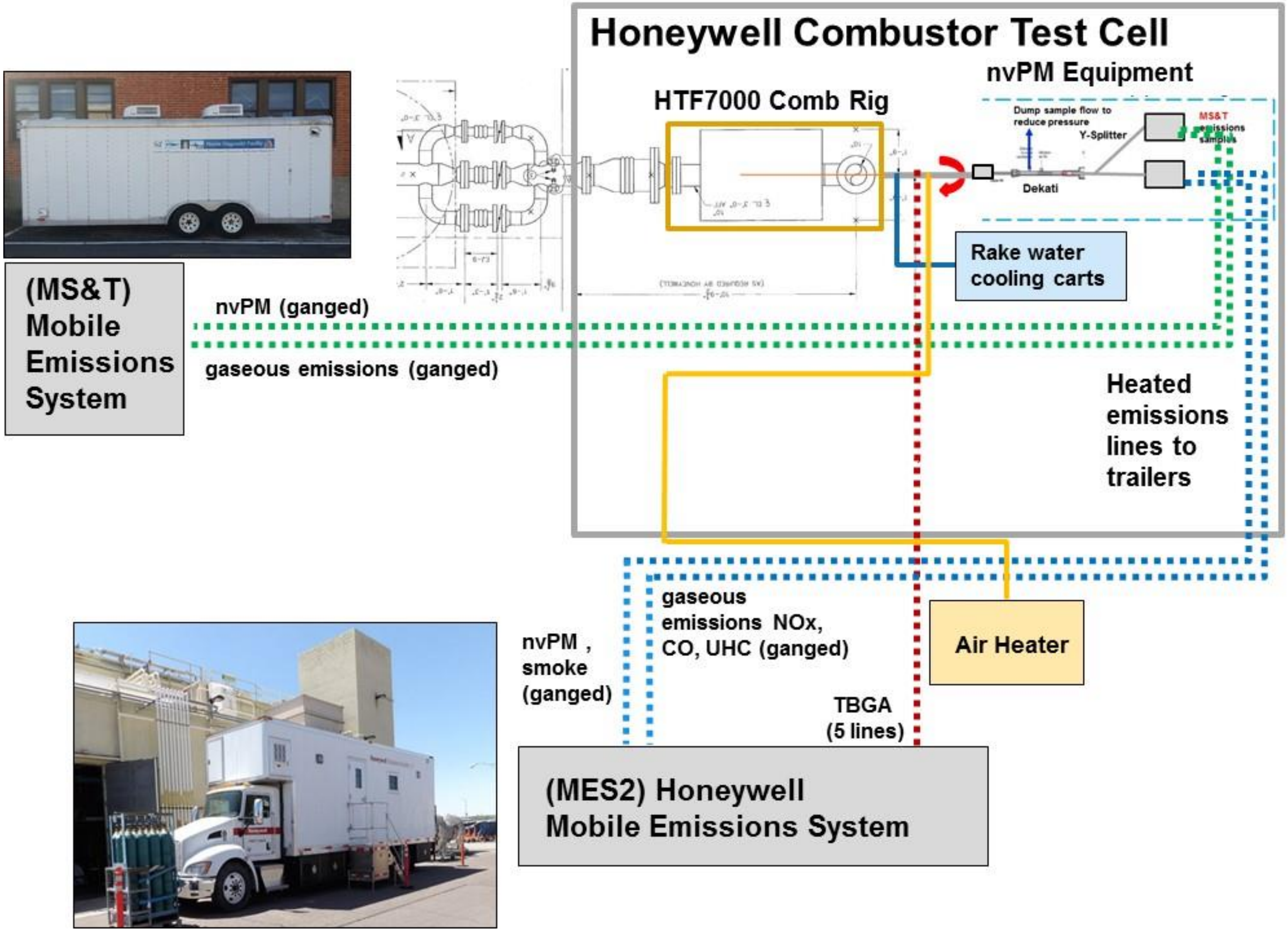
- **Objectives**
- Set up an RQL full annular combustor rig and standardized nvPM measurement system
- *An nvPM emissions measurement system and combustor rig adaptive hardware is to be assembled, tested and validated by Honeywell to enable nvPM and gaseous emissions data to be acquired from a Combustor 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

NVPM EMISSIONS: COMBUSTOR RIG MEASUREMENT SYSTEM

Acknowledgements: Rudy Dudebout, David Christie and Rich Bohman, Honeywell

Honeywell

Test Cell Arrangement



Honeywell & MS&T Mobile Emissions Systems will sample nvPM

Summary

Progress to date:

- Adaptive rig nvPM sampling hardware completed
- Calibration of Instruments is in Progress
- Standardized system will be in place for testing by November 2019

Next Steps:

- Perform Performance Analysis to define the rig test matrix
- Complete pre-test setup and shakedown of nvPM combustor rig measurement system with rig in test cell
- Conduct initial rig test with Jet-A, following system shakedown and availability of test cell

Conclusions and Next Steps

- Summary statement

  Demonstrations, inter-comparisons and methodology validation for determining compliance with the regulatory standard for aircraft engine nvPM

- Next steps?
  - ❑ analysis of results obtained during ND-MAX/ECLIF-II
  - ❑ 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.
  - ❑ Undertake performance evaluation of CERMS mass standard
  - ❑ Design, perform and analyze data - Honeywell combustor rig tests

  – 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

Assessment of PM losses in Sampling and Measurement Systems Part 1 NDMAX ECLIF Special Symposium, Aircraft Emissions Characterization Roadmap Meeting, National Academy of Sciences, Washington DC, May 2019

Whitefield, P. Hagen, D, Missouri University of Science and Technology in association with Soucacos, P. Booz Allen Hamilton, Webb, S, Environmental Consulting Group and Csonka, S. Csonka Aviation consultancy, **Quantifying E missions Reductions at Airports from the Use of Alternative Jet Final Report** prepared for ACRP 02-80 Transportation Research Board of the National Academies, March 2019

P. Whitefield, R. Miake-Lye, S. Achterberg, Z. Yu, M. Trueblood and W. Liu, **Ground-based In-Situ PM Emissions Characterization during NASA's NDMAX Campaign Using SAE Aerospace Recommended Practice,** American Geophysical Union Fall Meeting paper number A33K-3306, Washington DC, December 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)