Project 002 Ambient Conditions Corrections for Non-volatile PM Emissions Measurements

Missouri University of Science and Technology, Aerodyne Research Inc., and Honeywell

Project Lead Investigator

Philip D. Whitefield
Chancellor's Professor of Chemistry
Missouri University of Science and Technology
400 W 11th Street, Rolla, MO 65409
573-341-4420
pwhite@mst.edu

University Participants

Missouri University of Science and Technology

- PI: Philip D. Whitefield, Chancellor's Professor of Chemistry
- FAA Award Number: 13-C-AJFE-MST Amendments: 002, 003, 005, 008, 010, and 012
- Period of Performance: September 18, 2014, to February 28, 2021
- Tasks:
  - Task 1 - Engine-to-engine variability at Honeywell
  - Task 2 - Ground-based non-volatile particulate matter (nvPM) emissions from an IAE V2527-A5 engine burning four different fuel types
  - Task 3 - Re-examination of engine-to-engine particulate matter (PM) emissions' variability using an Aerospace Recommended Practice (ARP) reference sampling and measurement system

Project Funding Level

PROJECT	FUNDING	MATCHING	SOURCE
13-C-AJFE-MST-002	$1,288,836.34	$1,288,836.34	EMPA LETTER
	$284,613.66	$284,613.66	TRANSPORT CANADA
13-C-AJFE-MST-003	$500,000.00	$500,000.00	EMPA LETTER
13-C-AJFE-MST 005	$500,000.00	$500,000.00	EMPA LETTER
13-C-AJFE-MST-008	$579,234.00	$579,234.00	EMPA LETTER
13-C-AJFE-MST-010	$725,500.00	$725,500.00	EMPA LETTER
13-C-AJFE-MST-012	$1,217,221.00	$1,217,221.00	EMPA LETTER

Investigation Team

- Professor Philip Whitefield, Missouri University of Science and Technology
- Dr. Wenyan Liu, research chemist, Missouri University of Science and Technology
- Steven Achterberg, research technician, Missouri University of Science and Technology
- Max Trueblood, research technician, Missouri University of Science and Technology
- Dr. Richard Miake-Lye, subcontractor, Aerodyne Research Inc.
- Dr. Zenhong Yu, subcontractor, Aerodyne Research Inc.
- Rudy Dudebout, subcontractor, Honeywell Aerospace

- Paul Yankowich, subcontractor, Honeywell Aerospace

Project Overview

The International Civil Aviation Organization (ICAO) has approved publication of the revised ICAO Annex 16 Vol. II specifying a standardized sampling system for the measurement of non-volatile particulate matter (nvPM) from aircraft engines for use in certification. The Missouri University of Science and Technology (MS&T) owns and operates the ICAO Annex 16 Vol. II compliant North American mobile reference system (NARS) to measure nvPM emissions from the exhaust of aircraft engines. The work under this project exploits the use of the NARS to address issues associated with ambient condition corrections, engine-to-engine variability, and fuel formulation sensitivity. During this reporting period, work has been performed on three major tasks:

Task 1
Testing has taken place at Honeywell as part of a series of measurements to acquire certification-like data on a set of engines identified by ICAO Committee on Aviation Environmental Protection (CAEP) Working Group 3 (Emissions Technical) Particulate Matter Task Group (CAEP/WG3/PMTG) to be representative of the commercial fleet for entry into the nvPM values database. The engine-to-engine variability of nvPM emissions data from a sample of a large number of engines is required in order to assess the characteristic variability of these engines, which is critical in establishing a regulatory limit for nvPM number- and mass-based emissions. The measurement activity in this task has been undertaken by Honeywell personnel under subcontract to MS&T. Technical oversight was provided by the MS&T team.

Task 2
The NARS and its ancillary equipment have been used to characterize ground-based nvPM emissions from an IAE V2527-A5 engine burning four different fuel types. This work was conducted as part of the NASA/DLR Multidisciplinary Airborne Experiment (ND-MAX) campaign.

Task 3
The NARS and its ancillary equipment are being prepared to quantify the impact of changing conditions on nvPM emissions from a combustor rig and to develop methods for the use of inventory modeling.

Task 1 - Engine-to-Engine Variability at Honeywell

Missouri University of Science and Technology

Objective

The objective of this effort is to gather emissions data from at least 20 Honeywell commercial propulsion engines of the same type to assess engine-to-engine variability and derive characteristic nvPM emissions.

Research Approach

In support of the anticipated 2019 ICAO/FAA Part 34 certification standard, Honeywell has measured engine-to-engine variability of nvPM emissions data from a sample of 20 Honeywell engines to assess the characteristic variability of these engines. The FAA proposed work included the following items:

1. Obtain nvPM mass and number emissions from 20 turbofan engines, which contain the same model and type as the standardized draft ICAO Annex 16 Appendix 7 compliant nvPM measurement system, along with ICAO Annex 16 compliant gaseous emissions (possibly obtained during green runs).
2. Use a single-point probe positioned at a spot in the exhaust stream that is representative of the average emissions in the exit plane. A certification-type probe is preferable if the added cost is not prohibitive.
3. Vary the rated thrust from idle to 100% in 10-percentage-unit increments. After the engine stabilizes at each thrust point, hold the throttle at that thrust point for approximately 3 min so that nvPM and gaseous emissions can be acquired.
4. Use limited release non-disclosure agreement as needed. Ensure that the nvPM and gaseous emissions data are available from the 20 engines for analysis to derive characteristic nvPM mass and number emissions indices (EI) or any other emissions metric as needed.

Milestone(s)

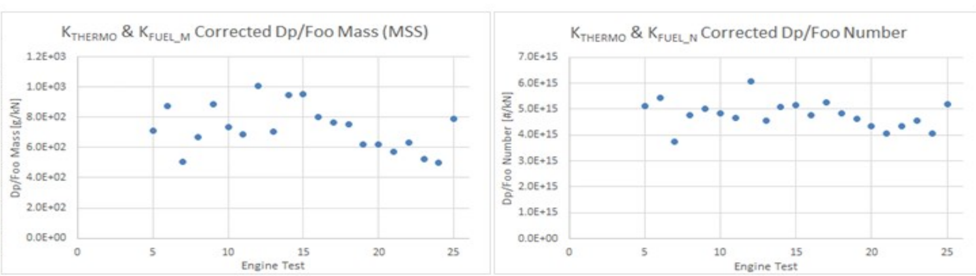
A final test report has been submitted by Honeywell to MS&T. It presents the results of a 25-engine test campaign to sample nvPM from production engines of the same model type. The sampling systems and analysis procedures used for this test campaign conform to the guidance set forth in SAE AIR6241 and the draft Appendix 7 to ICAO Annex 16. This work has directly informed CAEP/11 LTO nvPM Mass and Number Standards Development, permitting the development of characteristic coefficients for emissions as a function of number of engines tested.

Major Accomplishments

1. Total variation, including measurement system uncertainty, ambient condition variation, fuel variation, and engine-to-engine variation, has been assessed on one measurement train with two mass measurement systems (MMS).
2. The highest standard deviation was noted at 30% power, with standard deviation equal to 93% of average.
3. The lowest standard deviation was noted at 100% power, with standard deviation equal to 16% of average.
4. Modal standard deviation was higher at lower mean values.
5. Generally, lower variation was noted in number measurement.
6. Similar variation was noted between system loss–corrected and only thermophoretic loss–corrected data.
7. Excellent agreement was demonstrated between the laser induced incandescence instrument (LII) and micro soot sensor (MSS) (see Figure 2).
8. Fuel correction reduced variation by <1%.
9. No significant correlation was found for landing and take-off cycle (LTO) mass or number with ambient temperature or humidity.
10. Standard deviation divided by average for 21-engine testing with fuel correction (see Figure 1):
    - LTO mass standard deviation of mean (combined LII + MSS) = 20.4%.
    - LTO number standard deviation of mean = 11.0%.

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



Combined MSS & LII

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

- 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%

Fuel correction reduced standard deviation by < 1%

Honeywell

Figure 1. Summary of engine-to-engine variability data of 25 tests. nvPM, non-volatile particulate matter; LTO, landing and take-off cycle; LII, laser induced incandescence instrument; MSS, micro soot sensor; Dp/Foo, mass, in grams (Dp), of any pollutant emitted during the reference LTO cycle, divided by the rated output (Foo) of the engine.

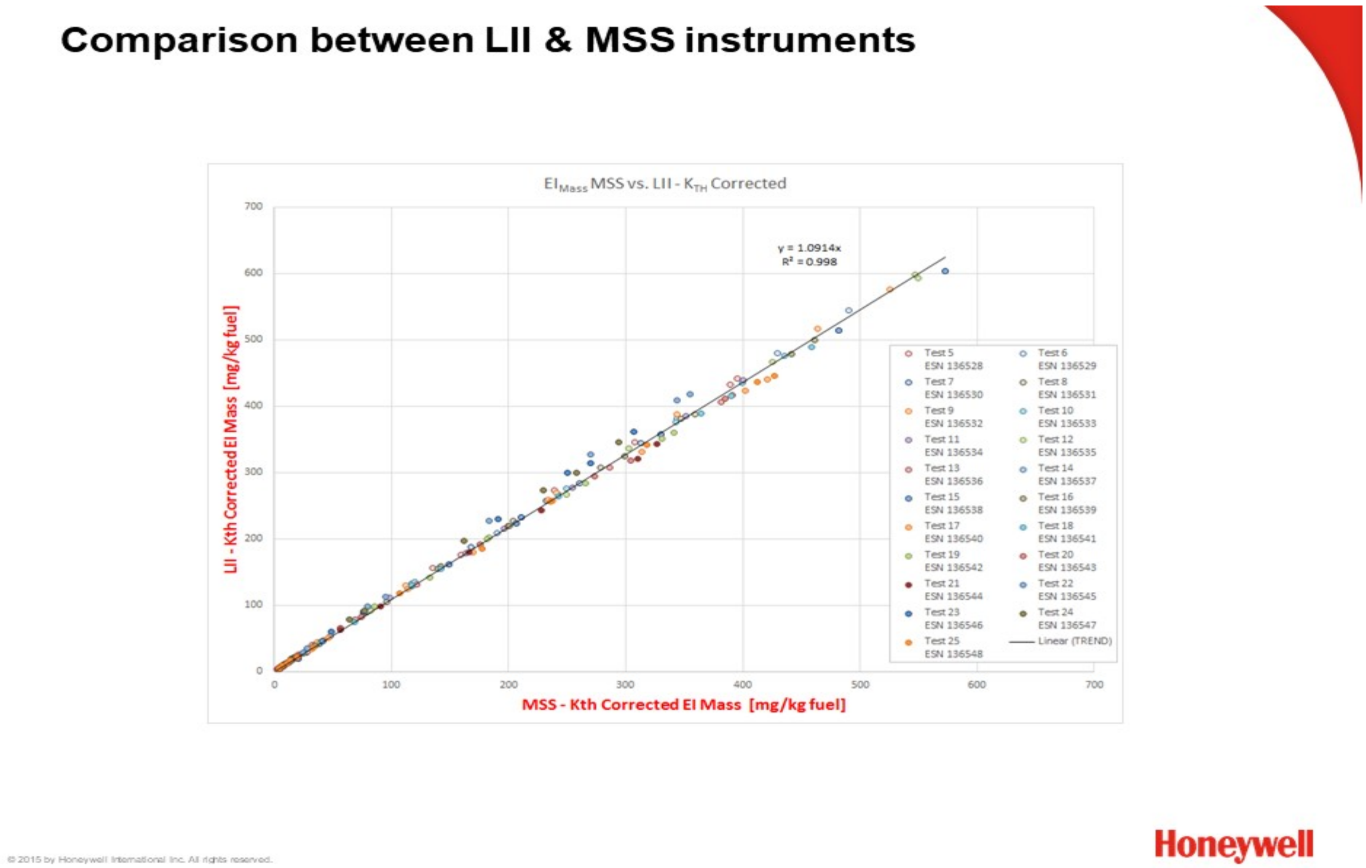


Figure 2. Comparison between micro soot sensor (MSS) and laser induced incandescence instrument (LII) data.

Publications

N/A

Outreach Efforts

This work was reported at the ASCENT advisory board meetings held in Cambridge, MA, in April 2018.
Data were provided to the ICAO CAEP/WG3/PMTG in paper CAEP11-WG3-PMTG7-IP01.

Awards

None.

Student Involvement

No graduate students were employed in this task; however, four undergraduate research assistants (Christian Hurst, Nicholas Altese, Davis Strassner, and Susan Donaldson) were employed in pre- and post-test activities, including individual component testing and calibration and data reduction and interpretation. Hurst, Altese, and Donaldson have not graduated; Strassner has graduated (current status unknown).

Plans for Next Period

With completion of the engine testing described above, additional scope is proposed in the form of a series of new tasks for MS&T and Honeywell to perform combustor rig testing with alternate fuels to establish nvPM ambient corrections designed specifically to address a set of FAA objectives (see Task 3 below):

- Set up a rich-quench-lean (RQL) full annular combustor rig and standardized nvPM measurement system

- Vary combustor inlet air conditions (range of ambient conditions on the ground and at altitude) and measure nvPM emissions
- Use probe designs that minimize losses and sample representatively
- Develop isokinetic sampling techniques such that particles are not over- or under-sampled
- Perform rig testing using Jet A fuel and three alternative fuels
- Analyze data to inform performance-based nvPM emissions modeling for all altitudes

Because the 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 ambient or altitude conditions on nvPM mass and number emissions and to develop correlations for use in inventory modeling or for regulatory purposes.

Task 2 - Ground-Based non-volatile Particulate Matter (nvPM) Emissions from an IAE V2527-A5 Engine Burning Four Different Fuel Types

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Objective(s)

1. Measure engine emissions from four different fuel types on the ground using NARS and its ancillary equipment and compare it with the NASA measurement system and, where appropriate, quantify differences. Specifically, the research team will
    a. Deploy to Europe
    b. Make measurements and analyze data
2. Contribute to planning the emissions measurements at various altitudes and evaluate cruise nvPM models

Research Approach

In this task, MS&T and subcontractor Aerodyne Research Inc. have used the NARS to measure engine emissions from four different fuel types on the ground and compared the resulting data with that acquired by other ground-based and airborne NASA/DLR measurement systems. The NARS was used to conduct the following tasks:

Task A: Contribute to planning emissions measurements at various altitudes and evaluate cruise nvPM models

In this task, the primary objective of the MS&T team was to work closely with the ND-MAX PIs to plan the logistics and test matrices of the proposed emission measurements at ground level and altitude, including an inter-comparison of the NARS data with that acquired with the NASA/DLR-deployed nvPM measurement systems. The secondary objective of this task will be to evaluate models predicting cruise nvPM emissions by comparing the model results with in situ and ground-based measurements.

Task B: The NARS and ancillary equipment were prepared for deployment to test site in Germany

In this task, the NARS subsystems were laboratory tested at MS&T and Aerodyne to ensure they met operational specifications as defined in SAE AIR6241/SAE ARP 6320. On completion of laboratory testing, the NARS and ancillary equipment were packaged and shipped to the test site in Germany.

Task C: Deployment was undertaken to set up the NARS at an airfield in Germany

In this task, the MS&T team deployed to the test site in Germany, set up the NARS and ancillary equipment, and undertook subsystem check-out procedures in preparation for emissions testing.

Task D: Ground-based emissions measurements on four different aviation fuels were acquired

In this task, the MS&T team used the NARS and ancillary equipment to characterize the nvPM component of emissions from four fuels to be defined by the test matrix established in the work described in task A.

Task E: Tear-down and ship NARS and ancillary equipment to MS&T

In this task, the MS&T team tore down the NARS and ancillary equipment and packaged it for return shipment to the United States.

Task F: Reduce, analyze, and report nvPM data
In this task, the raw emissions data acquired during task D were reduced and analyzed using the methods described in AIR6241/ARP 6320. These data have been reported to the FAA and shared with ND-MAX participants.

Milestone(s)
The airborne and ground-based phases of the ND-MAX campaign have been successfully executed. Data analysis and interpretation are underway.

Major Accomplishments
- We measured the emissions from four different fuels—two conventional sources of Jet A-1 and two specifically designed sustainable alternative jet fuels (SAJFs) blended to 50% with each of the conventional fuels. The SAJFs were designed to have naphthalene contents that differed by an order of magnitude.
- The two SAJFs yielded substantial reductions in soot emissions compared with the two unblended conventional Jet A-1 fuels. The percentage reductions decreased with fuel flow rate (%N1). See Figure 3.
- The PM emissions were observed to decrease with increasing fuel hydrogen content. See Figure 4.
- Organic PM emissions were found to be insensitive to fuel type and had a distinct mode at 268 nm. Compositional analysis revealed the organic PM to be due to vented lubrication oil and not a product of combustor emissions. See Figures 5 and 6.
- H% serves as a useful proxy for EI of SAJF fuels.
- Black carbon or "nvPM" instruments generally perform consistently for SAJF fuels compared with traditional fuels. Filter-based instruments require source-specific calibrations when sources produce particles of a different composition or size, compared with the calibration of those instruments. The calibration factors of such instruments must not be treated as universal constants.

Publications
N/A

Outreach Efforts
Presentations on the data analysis and interpretation to date have been made at
- ASCENT advisory board meetings Washington, DC, in October 2018
- Aviation Emissions Characterization (AEC) Roadmap Meeting held in Washington, DC, in May 2019
- American Geophysical Union (AGU) Fall Meeting in session A33K: Improving the Science of Emissions through Inventories, Observations and Models III, 12 December 2018, Washington, DC

Awards
NASA Group Achievement Award to ND-MAX.

Student Involvement
No graduate students were employed in this task; however, four undergraduate research assistants (Christian Hurst, Nicholas Altese, Davis Strassner, and Susan Donaldson) were employed in pre- and post-test activities, including individual component testing and calibration and data reduction and interpretation. Hurst, Altese, and Donaldson have not graduated; Strassner has graduated (current status unknown).

Plans for Next Period
Continue with instrument inter-comparisons especially between other ground-based systems and their in-flight equivalents. Present papers at American Association of Aerosol Research Meeting October 2019.

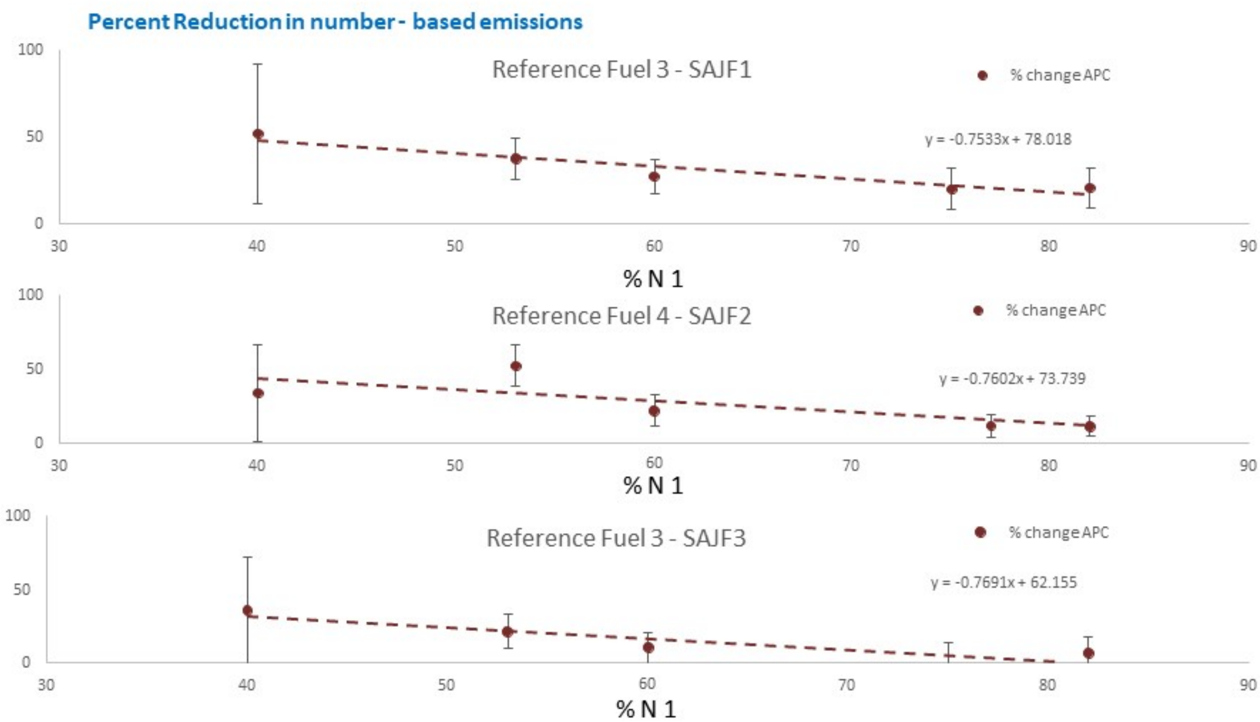

Figure 3. Example data of measured percentage reductions in particulate matter (PM) number-based emissions comparing blend emissions and reference fuel emissions. N1, rotational speed of the low-pressure compressor in a jet engine; APC, AVL particle counter (AVL, Graz, Austria).

Emissions Variation with Fuel Hydrogen Content

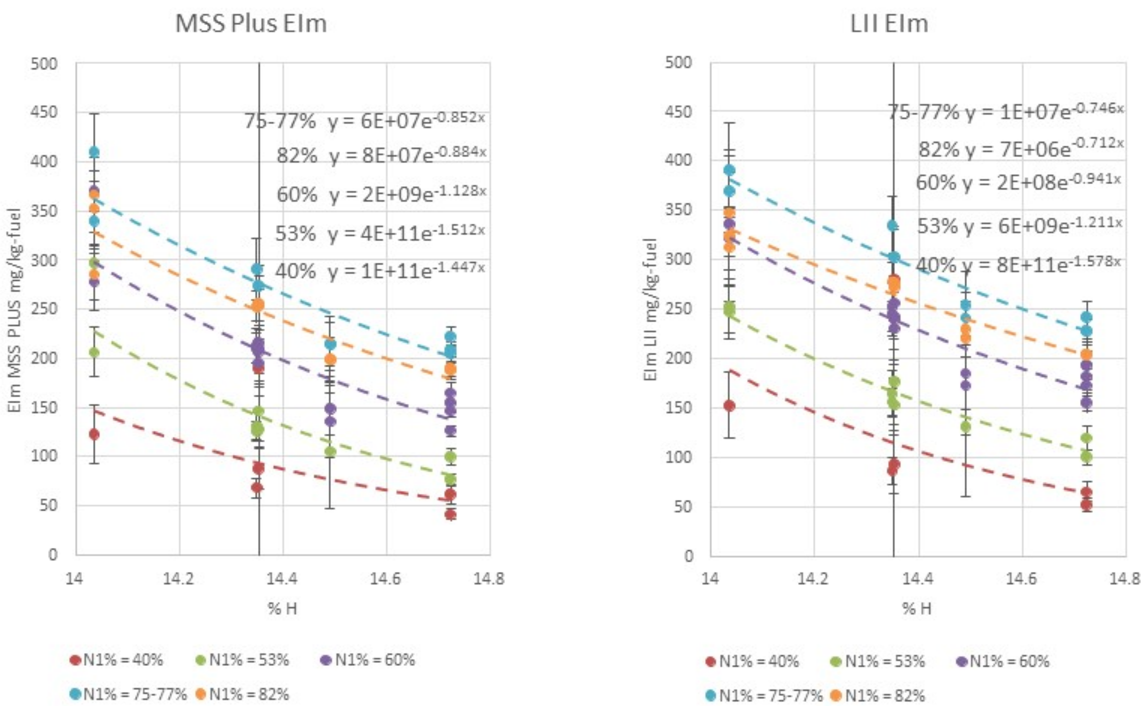

Figure 4. Example emission index values for the mass-based emission index (EI_m) as a function of fuel hydrogen content (% H) using the micro soot sensor (MSS) and laser induced incandescence instrument (LII) mass measurement techniques.

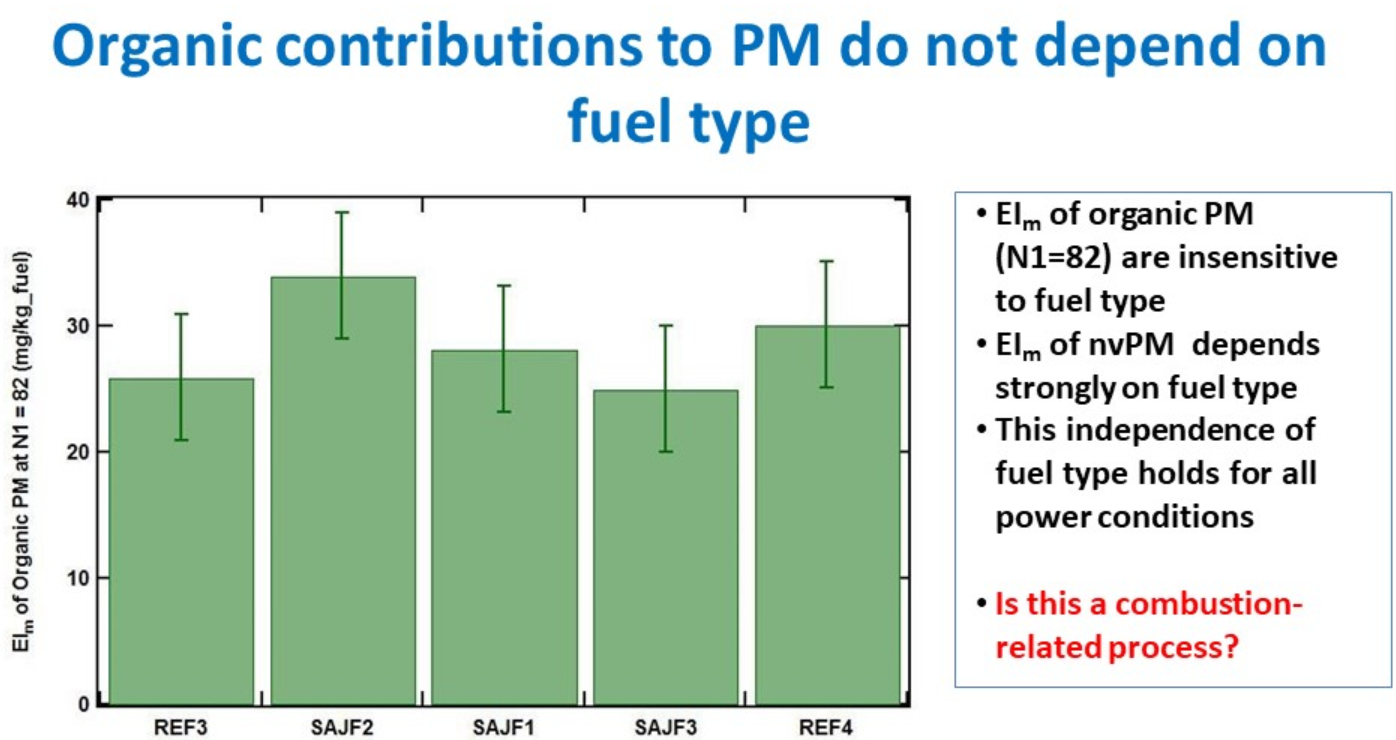

Figure 5. Data revealing that the mass-based emission index (EI_m) values for organic particulate matter (PM) are insensitive to fuel type. SAJF, sustainable alternative jet fuel; nvPM, non-volatile PM.

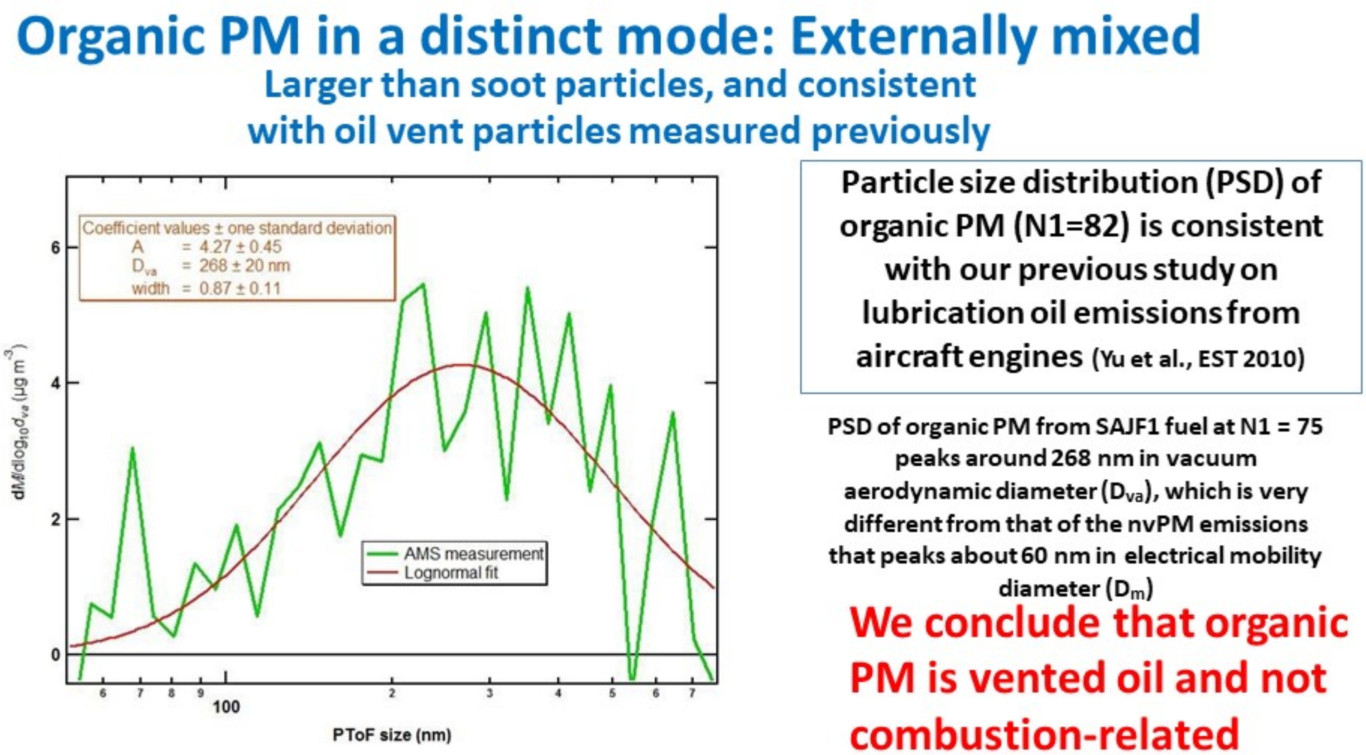

Figure 6. Size distribution data for organic particulate matter (PM) revealing that organic PM is vented oil. SAJF, sustainable alternative jet fuel.

Task 3 - Re-Examination of Engine-to-Engine Particulate Matter (PM) Emissions Variability Using an Aerospace Recommended Practice (ARP) Reference Sampling and Measurement System

Missouri University of Science and Technology

Objective(s)

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 nvPM emissions and to develop methods for use in inventory modeling. The MS&T/Aerodyne team will work with Honeywell to conduct combustor rig tests, collect nvPM mass and number emissions data, and analyze data to determine nvPM ambient corrections.

Research Approach

- Define and assemble a standardized nvPM measurement system that will include the same MMS that was used to sample nvPM from 25 Honeywell HTF7350 production engines in 2017
- Design and fabricate nvPM emissions rakes and combustor rig adaptive hardware required to enable nvPM and gaseous emissions data to be acquired from Honeywell's existing HTF7000 Combustor Test Rig
- Perform four combustor rig tests with Jet A and three alternative fuels
- Vary combustor test conditions (derived from engine cycle performance analysis, covering a range of engine ambient inlet conditions on the ground and at altitude) and measure nvPM emissions
- Analyze data to inform performance-based nvPM emissions modeling for all altitudes

Milestone

The funding for the Honeywell and Aerodyne subawards is in place and work is underway to prepare for testing at Honeywell's combustor rig facilities in Phoenix, AZ.

Major Accomplishments

- Honeywell and the MS&T/Aerodyne team have assembled two standardized nvPM emissions measurement systems. Key components are in the process of being recalibrated.
- Honeywell has completed design and fabrication of rakes and adaptive rig hardware required to enable nvPM emissions measurements in the HTF7000 Combustor Test Rig.

Publications

N/A

Outreach Efforts

Presentations on the project plan to date have been made at

- ASCENT advisory board meetings held in Alexandria, VA, in October 2018
- AEC Roadmap Meeting held in Washington, DC, in May 2019

Awards

None.

Student Involvement

No graduate students were employed in this task; however, four undergraduate research assistants (Christian Hurst, Nicholas Altese, Davis Strassner, and Susan Donaldson) were employed in pre- and post-test activities, including individual component testing and calibration and data reduction and interpretation. Hurst, Altese, and Donaldson have not graduated; Strassner has graduated (current status unknown).

Plans for Next Period

- Conduct 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