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

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

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- FAA Award Number: 13-C-AJFE-MST Amendments: 002,003,005,008 and 010
- Period of Performance: 9/18/2014 – 12/31/2019
- Tasks:
    1. Ambient conditions corrections measurements using the NASA LDI combustor rig
    2. Ambient conditions corrections measurements using the GEAE combustor rig
    3. Engine to engine variability at Honeywell
    4. Ground-based nvPM emissions from an IAE V2527-A5 engine burning four different fuel types

Project Funding Level

PROJECT	FUNDING	MATCHING	SOURCE
13-C-AJFE-MST-002	1,288,836.30	1,288,836.30	EMPA LETTER
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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
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13-C-AJFE-MST-010	725,500.00	725,500.00	EMPA LETTER

Investigation Team
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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 (Missouri S&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 conditions corrections, engine-to-engine variability and fuel formulation sensitivity. During this reporting period work has been performed on two 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 sub-contract to MS&T. Technical oversight will be provided by the MS&T team.

Task 2
The North American Reference System (NARS) and its ancillary equipment has been used to characterize the 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 ND MAX campaign.

Task 1- Engine-to-Engine Variability at Honeywell

Missouri University of Science and Technology

Objective(s)

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 to derive characteristic nvPM emissions.

Research Approach

Experience has shown that manual calibration of the currently accepted standard systems for measuring nvPM from aero-engines is problematic. The current accepted method for assuring that nvPM measurements are valid is to perform a back-to-back measurement with a known good measurement system or "gold standard system." The North American reference system for nvPM, operated by MS&T has been compared with a similar European system and now serves as the reference "gold" system in the United States and Canada. In July and August, 2014, Honeywell performed a correlation test with the North American reference system at the Honeywell facility in Phoenix, Arizona. This test was performed on a development HTF7500 engine using the Honeywell Mobile Emissions Facility 2, (MES2). MES2 is equipped to measure nvPM, gaseous emissions and smoke. The North American reference system was plumbed in parallel to MES2 and nvPM results were measured sequentially from the Honeywell system and the MS&T system. Data were collected at the four International Civil Aviation Organization (ICAO) landing and take-off (LTO) conditions. Emissions samples were drawn from the Honeywell emissions sampling system (a cruciform mixed exhaust rake with 16 sampling ports on four arms at four radii) and two core engine sampling rakes with six radial ports per rake. Test results were analyzed and reported to the FAA.

In support of the anticipated 2019 ICAO/FAA Part 34 certification standard, Honeywell received a request for proposal from the FAA in January 2016 to measure engine-to-engine variability of non-volatile particulate matter emissions data from a sample of 20 Honeywell engines in order to assess the characteristic variability of these engines. The FAA proposed work included the following items:

(a) Obtain nvPM mass and number emissions from 20 turbofan engines, which contain the same model and type with 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).
(b) 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.
(c) Vary the rated thrust from idle to 100 percent at 10 percent increments. After the engine stabilizes at each thrust point, hold the throttle at that thrust point for approximately 3 minutes so that nvPM and gaseous emissions can be acquired.
(d) Use limited release Non-Disclosure Agreement (NDA) 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 (EIs) or any other emissions metric as needed.

In response to this request, Honeywell proposed conducting nvPM emissions sampling during break-in (green run) testing of new AS907-2-1A type production engines. This required the redesign of the HTF7500 sampling rake in order for it to be compatible with the AS907-2-1A engine short mixer design. During testing, two of the existing fixed AS907-2-1A Station 6 (core exit) thermocouple (TC) probes were replaced with these new core exhaust emissions sampling rakes.

Honeywell used their existing mobile emissions facility, MES2, certified for ICAO emissions testing. Under this program, Honeywell also procured one standardized draft Annex 16 Appendix 7 compliant nvPM mass measurement system and installed it in MES2 system to support this testing. Reference 2.

Task 1.1 – Procurement of nvPM Emissions Test Equipment
Honeywell shall design and fabricate nvPM emissions rakes required to gather data from new Honeywell AS907-2-1A engines. These are Station 6 (core exit) emissions sampling rakes compatible with the AS907-2-1A engine short mixer configuration. Two rakes were installed for testing, with each rake configured with six dial sampling ports. An exhaust sample from both rakes is averaged and analyzed through the compliant Honeywell emissions measurement system MES2. Honeywell completed design drawings for the engine Station 6 exhaust emissions rakes and fabricated four, which consists of two for testing with two spares. One standardized draft Annex 16 Appendix 7 compliant nvPM mass measurement system was purchased and installed in Honeywell's existing mobile emissions facility, MES2.

Task 1.2 – Engine nvPM Emissions Testing

Honeywell shall obtain nvPM and gaseous emissions from a minimum of 20 AS907-2-1A type turbofan engines during production break-in testing, using MES2. This facility is fully compliant with the draft ICAO Annex 16 Appendix 7 nvPM measurement system and is also ICAO Annex 16 compliant for the gaseous emissions system. In addition, with nvPM and gaseous emissions, Honeywell will report derived smoke number (SN) from the optical smoke meter (OSM). Honeywell did not perform or report filter smoke measurements to minimize the analysis time per engine condition. To minimize impact on the critical HTF7000 production engine break-in test schedule, the nvPM emissions test plan aligns with the existing break-in run test schedule which includes a 3-minute hold at the end of each power point tested. This program obtained nvPM mass and gaseous emissions samples at the end of these 3-minute periods. The proposed 11-point nvPM and gaseous emissions sampling test matrix is shown in Table 1. Prior to each green run test, technicians replaced two of the fixed AS907-2-1A Station 6 (core exit) TC probes with the exhaust emissions sampling rakes.

Table 1. nvPM Mass and Emissions Sampling Test Matrix.

Test Condition/	Approximate Maximum Thrust, Percent	Stabilizing Time Prior to nvPM Sampling, minutes
Ground idle (GI)	4	3
17,600	8	3
20,600	16	3
22,600	29	3
23,600	38	3
24,600	52	3
25,600	72	3
26,300	90	3
26,900	97	3
Maximum takeoff (MTO)	100	3
1,100 lb/hr	33	3
GI	4	3

Since agreement with production is contingent on not significantly impacting or delaying the production test schedule, this task plans to gather data from 25 green run engine tests, anticipating the risk that some tests may have issues that are not identified during the test and thus will not produce acceptable data. Honeywell will reduce the analysis results following every test to validate the data, but the production engine tests cannot be delayed while waiting for data validation completion.

The engine rated thrust was varied in increments from idle to 100 percent MTO per Table 1. The steady-state engine condition were stabilized at each point for approximately 3 minutes before obtaining the exhaust emissions data.

Task 1.3 - Data Reduction and Analysis

Honeywell will reduce and analyze the data following every test to validate that the data set is acceptable.

Task 1.4 - Project Management and Reporting

Honeywell shall manage the program activities and finances in accordance with standard Honeywell practice and provide monthly status reports to MS&T.

Honeywell is proposing completion of this work within 11 months after contract award. Honeywell estimates that it will require four months to procure, install, and check out the required nvPM test equipment before initiating nvPM engine testing.

Current production projections indicate that a sufficient number of AS907-2-1A engines will be produced during the proposed contract period to be able to conduct the 25 planned exhaust emissions tests during planned green runs. Honeywell estimates that this testing will be completed within a four-month period after the nvPM equipment has been cleared for testing.

Following these tests, Honeywell shall compile the data and prepare a draft final report documenting the test results and hold a final briefing to present results to MS&T and FAA representatives. Honeywell shall prepare a limited release draft final report, and make available the nvPM and gaseous emissions data from the engines tested for additional analysis to derive characteristic nvPM mass and number, EIs or any other emissions metrics as needed.

Honeywell shall then submit a draft final report to MS&T, and allocate 30 days for review and feedback. Honeywell shall then incorporate the comments and submit the final report to MS&T.

Milestone(s)

A final test report has been submitted by Honeywell to MS&T. It presents the results of a twenty-five-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 AIR 6241 and the draft Appendix 7 to ICAO Annex 16.

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.
2. Highest standard deviation noted at 30% power, standard deviation equal to 93% of average
3. Lowest standard deviation noted at 100% power, standard deviation equal to 16% of average
4. Modal standard deviation is higher at lower mean values
5. Generally lower variation in number measurement noted
6. Similar variation noted between system loss corrected and only thermophoretic loss corrected data
7. Excellent agreement between LII and MSS demonstrated
8. Fuel correction reduced variation by <1%
9. No significant correlation on LTO mass or number with ambient temperature or humidity
10. Standard Deviation divided by average for 21 engine testing with fuel correction:
    - LTO mass standard deviation % of mean (combined LII + MSS) = 20.4%
    - LTO number standard deviation % of mean = 11.0%

Publications

None

Outreach Efforts

This work was reported at the ASCENT advisory board meetings held in Cambridge MA in April 2018

Data provided to ICAO working group 3 Particulate Matter Task Group in paper CAEP11-WG3-PMTG7-IP01

Awards
None

Student Involvement
None

Plans for Next Period
Having completed the engine testing described above additional scope is proposed in the form of a series of new tasks for Missouri S&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:

- Set up an 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-sampled 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

Since 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 the nvPM mass and number emissions and to develop correlations for use in inventory modeling or regulatory purposes.

In order to successfully complete these new tasks, the existing contracts will need an extended period of performance and will result in additional cost.

Task 2- Ground-based nvPM Emissions from an IAE V2527-A5 Engine Burning Four Different Fuel Types
Missouri University of Science and Technology

Objective(s)

1. Measure engine emissions from four different fuel types on the ground using NARS and its ancillary equipment and compare it to 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
The Missouri University of Science and Technology (Missouri S&T) owns and operates an Annex 16 compliant, North American mobile reference system to measure nvPM emissions from the exhaust of aircraft engines. The nvPM system consists of three sections – collection, transfer, and measurement – connected in series (Figure 1). A description of each section is provided below.

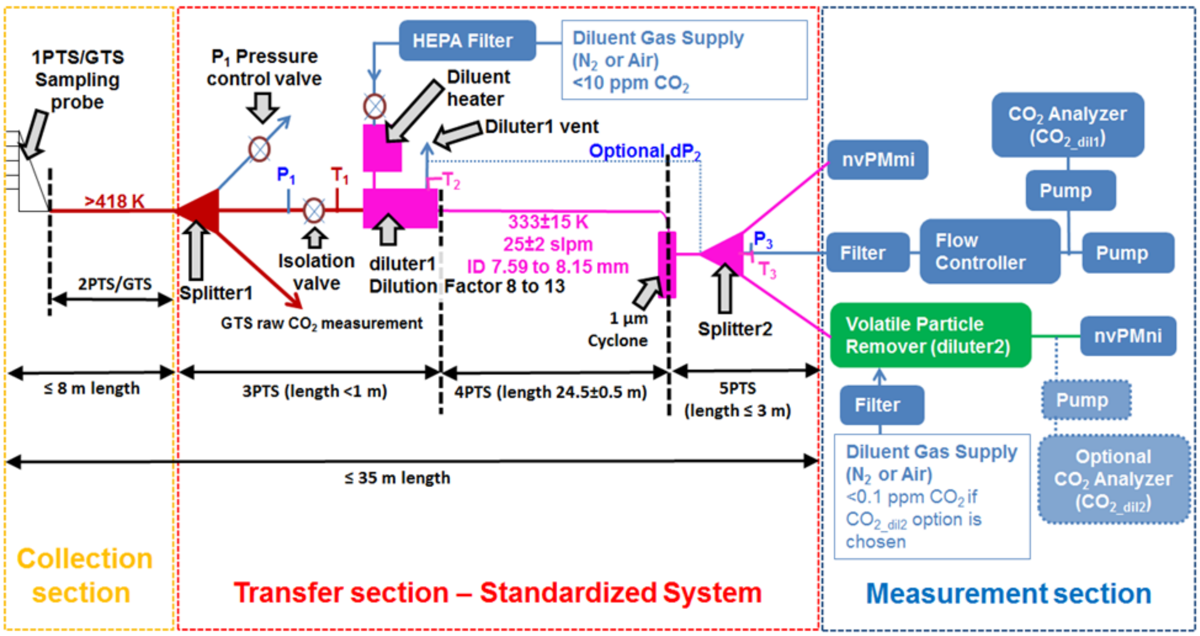

Figure 1. Components of an ICAO Annex 16 Vol.II Appendix 7 Compliant nvPM system

Collection section
The collection section consists of the probe rake system and up to 8m of stainless sample line heated to 160˚C.

Transfer section
The transfer section consists of a three-way sample splitter, a PM sample eductor/dilutor, flow controllers, and sample line heater controllers. The first sub-component of the transfer section is a three-way sample splitter which divides the total exhaust gas sample from the rake into three flow streams. The first is the required flow of exhaust for the Annex 16 combustion gas sample. The second is the PM sample and the third is an excess flow dump line controlled with a pressure relief valve. The PM sample is diluted by a factor 8-13 with dry nitrogen (heated to 60˚C) by means of an eductor/dilutor. The diluted PM sample with a flow rate 25 ± 2 SLPM is transferred by an electrically heated, temperature controlled conductive, grounded, carbon loaded PTFE PM sample transfer line 25m in length, maintained at 60˚C to a 1µm cyclone and then a second three-way splitter to direct the sample to the number and mass measurement devices in the measurement system.

Measurement section
The measurement section consists of a volatile particle remover and a particle number measurement device, a mass measurement device and a mass flow controller, pump and CO_2 detector as specified by Annex 16
As part of evaluating the methodology and the robustness of the system described in Annex 16, the North American nvPM reference system has been deployed at several OEM facilities in North America as well as the SR Technics maintenance facility in Zurich, Switzerland. These demonstration/inter-comparison studies served to provide information regarding the variability of the individual sampling and measurement systems. Additional testing at OEM facilities has also be conducted to acquire QL2 data on a set of engines identified to be representative of the commercial fleet for entry into the nvPM values database. Datasets from these initial measurement activities are being used by the ICAO Committee on Aviation Environmental Protection (CAEP) and their PM Task Group (PMTG) as they consider future aviation PM regulations. The data will be used by PMTG to develop a metric on which the regulation for nvPM emissions will be based. In this task Missouri S&T and its sub-contractor Aerodyne Research Inc. will use the North American Reference System to measure engine emissions from four different fuel types on the ground using NARS and its ancillary equipment and compare it to the NASA measurement system. And where appropriate quantify differences.

Task 4.1- Contribute to planning the emissions measurements at various altitudes and evaluate cruise nvPM models
In this task the primary objective of the MS&T team will be to work closely with the ND-MAX principal investigators to plan the logistics and test matrices of the proposed emission measurements at ground level and at 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 the in-situ and ground-based measurements.

Task 2.2- Prepare the NARS and ancillary equipment for deployment to test site in Germany
In this task the NARS sub-systems will be laboratory tested at Missouri S&T and Aerodyne to assure they meet operational specification as defined in AIR6241/ARP 6320. On completion of laboratory testing the NARS and ancillary equipment will be packaged and shipped to the test site in Germany.

Task 2.3- Deploy to and set up the NARS at an airfield in Germany
In this task the MS&T team will deploy to the test site in Germany and set up the NARS and ancillary equipment and undertake sub-system check-out procedures in preparation for emissions testing.

Task 2.4- Conduct ground-based emissions measurements on four different aviation fuels
In this task the MS&T team will use the NARS and ancillary equipment to characterize the nvPM component of emissions from four separate fuels to be defined by the test matrix established in the work described in task 6.

Task 2.5- Tear-down and ship NARS and ancillary equipment to MS&T
In this task the MS&T team will tear down the NARS and ancillary equipment and package it for return shipment to the US.

Task 2.6- Reduce, analyze and report nvPM data
In this task the raw emissions data acquired during task 3 will be reduced and analyzed using the methods described in AIR6241/ARP 6320. These data will be reported to the FAA and shared with the ND-MAX participants.

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

Major Accomplishments
Measured the emissions from 4 different fuels – 2 conventional sources of Jet A1 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 when compared to the two unblended conventional Jet A-1 fuels. The percent reductions decrease with fuel flow rate (%N1).

The PM emissions were observed to decrease with increasing fuel hydrogen content.

No statistically significant differences in PM emissions were observed when the two SAJF blends were compared.

Organic PM emissions were found to be insensitive to fuel type and had a distinct mode at 268nm. Compositional analysis revealed the organic PM to be due to vented lubrication oil and not a product of combustor emissions.

Publications
None

Outreach Efforts
Presentations on the data analysis and interpretation to date have been made at:

- ASCENT advisory board meetings held in Cambridge MA in April 2018 and Washington DC October 2018
- AEC Roadmap Meeting held in Washington DC in May 2018

- It is scheduled to be presented at the AGU Fall Meeting in session A33K – Improving the Science of Emissions through Inventories, Observations and Models III, 12 December 2018, Washington DC.

Awards
None

Student Involvement
No graduate students were employed in this task however four undergraduate research assistants were employed in pre- and post-test activities including individual component testing and calibration and data reduction and interpretation.

Plans for Next Period
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.