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

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

Project Lead Investigator

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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	1,573,000.00	1,288,836.34	EMPA LETTER
		300,000.00	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

Investigation Team

Professor Philip Whitefield (all tasks), Dr. Prem Lobo, Research Scientist (tasks 1,2), Dr. Wenyan Liu, Research Chemist (task 4), Steven Achterberg, Research Technician (tasks 1,2,4), Max Trueblood, Research Technician (tasks 1,2,4), Dr. Richard Miake-Lye and Dr. Zenhong Yu, sub-contractors (tasks 1,2,3,4) and (tasks (1,2,4) respectively.

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.

Task1 and Task 2
Ambient Conditions Corrections measurements. A key consideration for the development of the nvPM emissions standard is the impact of ambient condition variability on the nvPM emissions. Combustor rigs at: (1) the NASA Glenn Research Center, Cleveland, OH and (2) GEAE Cincinnati, OH, have been identified as a suitable test vehicle for these types of measurements. Since we had an imminent opportunity at NASA in the late summer of 2016 and at GEAE in March/April 2017, funds were redirected from the original Engine to Engine Variability Study to support these tests. The redirection of funds allowed us to complete both tests and provide valuable information to the ICAO/CAEP process as they develop the nvPM emissions standard.

Task 3
Additional 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 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 will be undertaken by Honeywell personnel under sub-contract to MS&T. Technical oversight will be provided by the MS&T team.

Task 4
The North American Reference System (NARS) and its ancillary equipment will be used to characterize the ground-based nvPM emissions from an IAE V2527-A5 engine burning four different fuel types. This work will be conducted as part of the NASA/DLR ND MAX campaign.

Task #1: Ambient Conditions Corrections for nvPM – NASA LDI Combustor Rig

Missouri University of Science and Technology

Objective(s)

As part of the standard setting process, corrections for measured nvPM emissions at various ambient conditions, similar to those employed for gaseous species, will need to be developed. Missouri S&T is currently working with NASA to conduct an nvPM emissions measurement campaign in NASA's LDI (Lean Direct Injection) combustor rig to acquire data that will be used to develop first order ambient conditions corrections of nvPM number- and mass-based emissions. These first order corrections will need to be validated in subsequent tests to evaluate their applicability to a range of turbofan engines. Missouri S&T will review data from this and other engines tests conducted over a wide range of ambient conditions to validate the methodology and the model developed in previous campaign with GE Aviation.

Research Approach

The system is designed to operate in parallel with existing International Civil Aviation Organization (ICAO) Annex 16 compliant combustion gas sampling systems used for emissions certification from aircraft engines captured by conventional (Annex 16) gas sampling rakes (ICAO, 2008). The certification measurements of nvPM emissions will be performed using the SAE defined nvPM sampling system.

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.

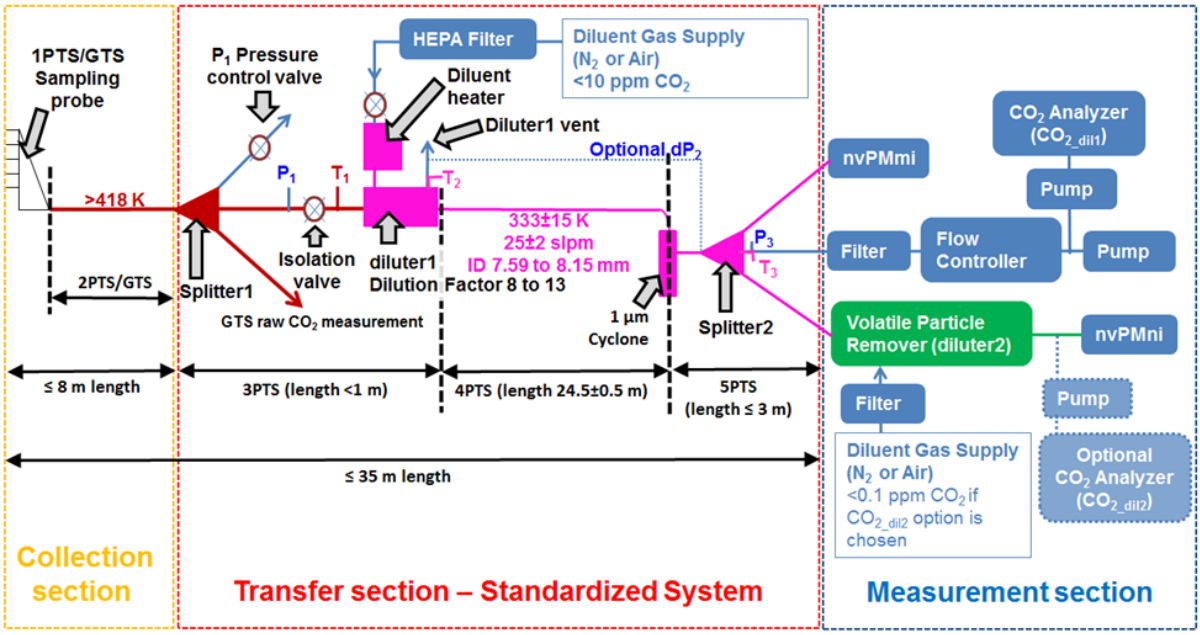

Figure 1: Components of an ICAO Annex 16 Vol.II Appendix 7 Compliant nvPM system

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 as described above to develop a dataset for the development of an ambient conditions corrections methodology validation. Representative data and a summary of conclusions from the study can be found in reference 1.

Ref 1 – Presentation on Project 2 at the ASCENT Advisory board Meeting in Washington DC, April 2017.

Milestone(s)
Measurement campaign completed (October 2016)
Data delivered to NASA (October 2016)
NASA/MS&T team presented results to CAEP (spring 2017)
NASA final report in preparation.

Major Accomplishments
Critical data on nvPM ambient conditions corrections was acquired using the NASA LDI combustor. These data were used to inform CAEP WG3 as it strives to establish regulatory standards for nvPM emissions from commercial transport aircraft.

Publications
None

Outreach Efforts
A summary of the findings from this task was presented at:
(1) The SAE E31 Meeting in Madrid, Spain, January 2017
(2) ASCENT Advisory Board Meeting in April 2017

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
Additional ambient condition correction testing is anticipated during the next year. Potential test vehicles are being pursued at Pratt and Whitney, Rolls Royce and Honeywell.

Task #2: Ambient Conditions Corrections for nvPM – GE Combustor Rig
Missouri University of Science and Technology

Objective(s)
As part of the standard setting process, corrections for measured nvPM emissions at various ambient conditions, similar to those employed for gaseous species, will need to be developed. Missouri S&T is currently working with GE Aviation to conduct an nvPM emissions measurement campaign in GEAE combustor rig to acquire data that will be used to develop first order ambient conditions corrections of nvPM number- and mass-based emissions. These first order corrections will need to be validated in subsequent test to evaluate its applicability to a range of turbofan engines. Missouri S&T will review data from other engines tests conducted over a wide range of ambient conditions to validate the methodology and the model developed in previous campaign with GE Aviation.

Research Approach
ICAO has published Annex 16 Vol II Appendix 7 detailing the sampling system for the measurement of non-volatile particulate matter (nvPM) from aircraft engines. The system is designed to operate in parallel with existing International Civil Aviation Organization (ICAO) Annex 16 compliant combustion gas sampling systems used for emissions certification from aircraft engines captured by conventional (Annex 16) gas sampling rakes (ICAO, 2008). The certification measurements of nvPM emissions will be performed using the SAE defined nvPM sampling system.

The Missouri University of Science and Technology (Missouri S&T) owns and operates the 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.

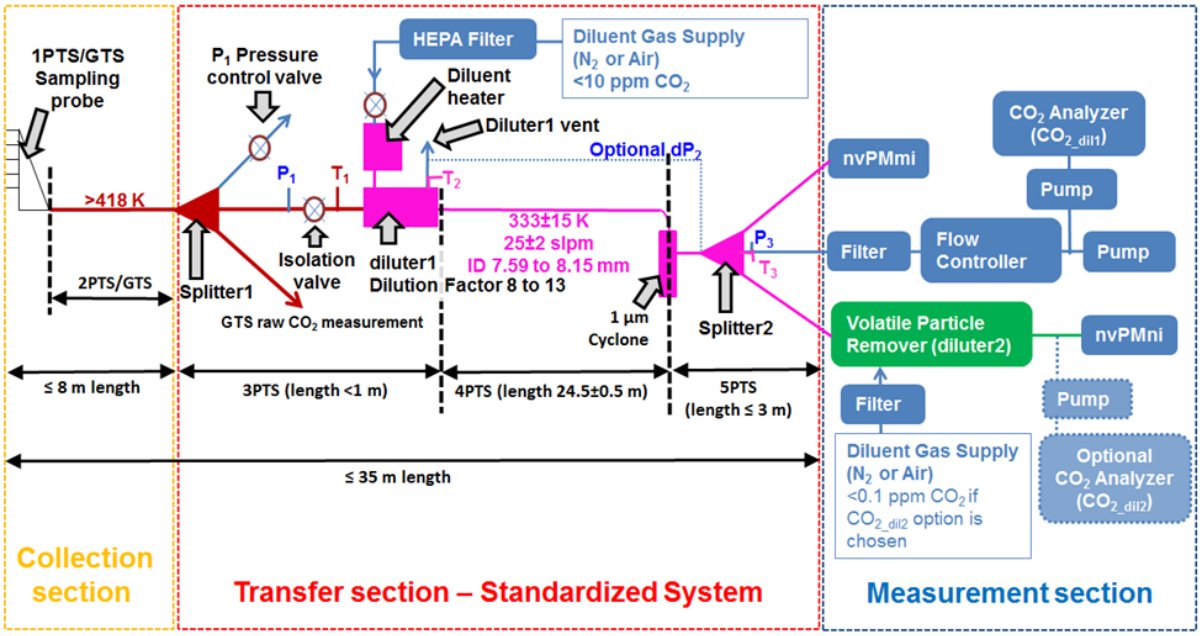

Figure 2: Components of an ICAO Annex 16 Vol.II Appendix 7 Compliant nvPM system

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 AIR6241.

As part of evaluating the methodology and the robustness of the system described in AIR6241, 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. with use the North American Reference System as described above to develop a dataset for the development of an ambient conditions corrections methodology. Reference 1.

Milestone(s)
Measurement campaign completed (April 2017)
NARS Data delivered to GE (April 2017)
Ancillary size distribution data to GE (October 2017)

Major Accomplishments
Critical data on nvPM ambient conditions corrections was acquired using the GE combustor. These data were used to inform CAEP WG3 as it strives to establish regulatory standards for nvPM emissions from commercial transport aircraft.

Publications
None

Outreach Efforts
This work was reported at the ASCENT advisory board meetings held in Washington DC in April and September 2017

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
Additional ambient condition correction testing is anticipated during the next year. Potential test vehicles are being pursued at Pratt and Whitney, Rolls Royce and Honeywell.

Ref 1 – Presentation on Project 2 at the ASCENT Advisory board Meeting in Washington DC, April 2017.

Task #3: 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 was sampled 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 3.1 – 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 will be 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 will complete design drawings for the engine Station 6 exhaust emissions rakes and fabricate four, which consists of two for testing with two spares. One standardized draft Annex 16 Appendix 7 compliant nvPM mass measurement system shall be purchased and installed in Honeywell's existing mobile emissions facility, MES2.

Task 3.2 – 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 also report derived smoke number (SN) from the optical smoke meter (OSM). Honeywell will 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 will align with the existing break-in run test schedule which includes a 3-minute hold at the end of each power point tested. This program will obtain 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 will replace 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 will be varied in increments from idle to 100 percent MTO per Table 1. The steady-state engine condition will be stabilized at each point for approximately 3 minutes before obtaining the exhaust emissions data

Task 3.3 - Data Reduction and Analysis

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

Task 3.4 - 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.

Ref 2 – Presentation poster on Project 2 at the ASCENT Advisory board Meeting in Washington DC, September 2017.

Milestone(s)
Engine testing on 25 engines has been completed – September 2017
Data being reduced analyzed and reviewed – September 2017

Major Accomplishments
With data on 25 engines acquired this project is more than 75% completed.

Publications
None

Outreach Efforts
This work was reported at the ASCENT advisory board meetings held in Washington DC in April and September 2017.

Awards
None

Student Involvement
None

Plans for Next Period
Consult with Honeywell engineers on the interpretation of the data.

Task #4: 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. Quantify differences
    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

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 intercomparison 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 4.2: 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 4.3: 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 4.4: 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 4.5: 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 4.6: 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.

Ref 2 – Presentation poster on Project 2 at the ASCENT Advisory board Meeting in Washington DC, September 2017.

Milestone(s)
None during this reporting period

Major Accomplishments
None during this reporting period

Publications
None during this reporting period

Outreach Efforts
None during this reporting period

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
Complete the Tasks 4.1through 4.6 described in the research approach for Task 4. The measurement campaign is expected to take place at Ramstein Air Force Base in Germany during the period January 12 through February 4, 2018.