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

Missouri University of Science and Technology
Aerodyne Research Inc.

Project Lead Investigator

Philip D. Whitefield
Professor and Department Chair
Chemistry
Missouri University of Science and Technology
142 Schrenk Hall, 400 W 11th Street, Rolla, MO 65409
573-341-4420
pwhite@mst.edu

University Participants

Missouri University of Science and Technology

- P.I.(s): Philip D. Whitefield
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- Task(s):
    - Task 1 Ambient conditions corrections for nv PM
    - Task 2
        - (a) NARS Upgrade for gaseous emissions and smoke number
        - (b) NARS Upgrade for Canadian electrical standards compliance
    - Task 3 - nv PM measurements at RR Indianapolis
    - Task 4 - nv PM measurements at P&W
    - Task 5 - nv PM measurements at the VARIANT 2 Campaign
    - Task 6 - nv PM measurements at Honeywell
    - Task 7 - Engine to Engine Variability and Derivation of Characteristic nvPM Emissions

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Investigation Team

Philip D. Whitefield PI
Donald E. Hagen Co-PI
Prem Lobo Co-PI
Richard Miake-Lye Co-PI
Max Trueblood Research Associate
Steven Achteberg Research Associate

Project Overview

The Society of Automotive Engineers (SAE) Aircraft Exhaust Emissions Measurement Committee (E-31) has published an Aerospace Information Report (AIR) 6241 detailing the sampling system for the measurement of non-volatile particulate matter (nvPM) from aircraft engines (SAE 2013). 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). Based on the AIR 6241, ICAO has specified in Annex 16, Vol. II, a standardized nvPM measurement system for demonstrating compliance with the new CAEP/10 nvPM standard for gas turbine engines. The engine certification measurements of nvPM emissions will be performed using the Annex 16 compliant nvPM sampling system.

The Missouri University of Science and Technology (Missouri S&T) owns and operates an Annex 16 compliant mobile system to measure nvPM emissions from the exhaust of aircraft engines. The MST system based on past measurement campaigns and data inter-comparisons is the North American Reference System and is one of the three reference systems in the world. The other two reference systems are: a) The Swiss FOCA Measurement System; and b) The EASA SAMPLE System.

The nvPM system consists of three sections – collection, transfer, and measurement – connected in series (Figure 1). A description of each section is provided below.

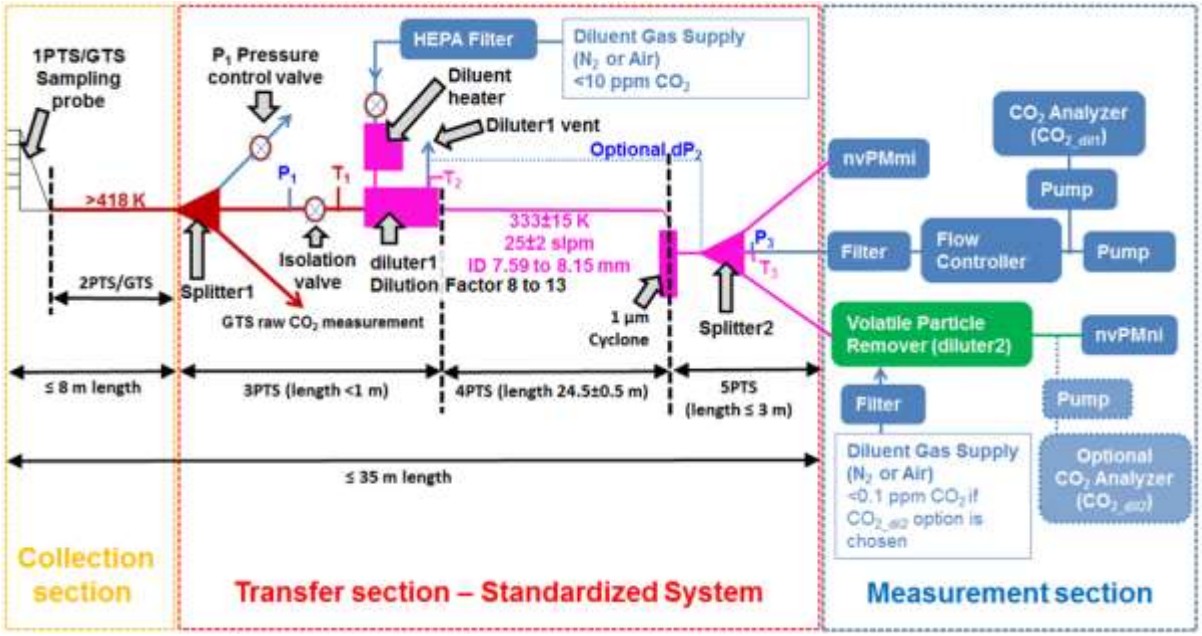

Figure 1: Components of an AIR6241 nvPM system

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 (McCaldon, 2013; Lobo and Condevaux, 2014) as well as the SR Technics maintenance facility in Zurich, Switzerland (Lobo et al., 2015). 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 (Lobo and McKinney, 2014). 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.

Task 1 Ambient conditions corrections for nv PM

Missouri University of Science and Technology

Objective(s)

1. Conduct combustor rig testing to determine ambient condition corrections for non-volatile PM Emissions measurements
    - Perform combustor rig tests at GE Aviation facilities using an AIR6241 compliant Sampling System for the measurement of non-volatile PM (nvPM) emissions
    - Evaluate the influence of ambient conditions on PM production
    - Determine appropriate corrections to standard atmospheric conditions for aircraft nvPM

Research Approach

Missouri S&T and ARI will coordinate with GE Aviation to secure access to altitude test cells at which nvPM emissions can be acquired for varying ambient temperature, pressure, and relative humidity. To evaluate the effects of ambient conditions on PM production, a multi-sector combustor will be used as the PM emissions source.

Missouri S&T will work with GE Aviation to plan and prepare for the nvPM measurements in the altitude test cell. During the planning process, a detailed plan for the test will be developed in collaboration with the OEMs. The plan will include details of the sample extraction system, interfacing with the North American AIR6241 mobile reference system, simulating a range of ambient conditions for the test, measurement protocol, and data analysis. A site visit will also be undertaken as part of the planning process to have face-to-face discussions with the OEM facility engineers and technicians and also determine essential details regarding placement of sampling and measurement system, interfacing with existing probe-rake hardware, power and air requirements, etc.

After the test plan has been developed and approved, and a test window identified, Missouri S&T will begin preparation for deploying the system to the GE Aviation facility, including but not limited to, calibration of instruments, checkout of various system components, and preparing the system for transport. The nvPM system will be deployed alongside Annex 16 Volume II certification-grade gaseous and smoke measurement systems to obtain the full complement of gaseous and nvPM data.

The testing itself will be conducted in accordance with the test plan developed during the planning phase. Data for nvPM mass, number, and gaseous emissions and smoke number will be acquired for simulated ambient conditions spanning the full realistic parameter space using a multipoint probe similar to those used for gaseous emissions certification. The OEMs will be responsible for providing the probe system to be used for these tests. Following the test, the data will be analyzed and appropriate correlations will be developed for nvPM data acquired under different ambient conditions. A correction of nvPM data to standard atmospheric conditions will then be developed based on these correlations.

Milestone(s)

Testing scheduled for January/February 2017.

Major Accomplishments
Test plan completed and testing date scheduled for January 2017.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
Conduct test, analyze data and report findings.

Task 2:
(a) NARS Upgrade for gaseous emissions and smoke number
(b) NARS Upgrade for Canadian electrical standards compliance

Missouri University of Science and Technology

Objective(s) and Research Approach
Missouri S&T will procure a portable emissions cart designed for raw exhaust measurement for gaseous emissions such as NO/NOx, UHC, CO and CO_2. Figure 3 shows the portable unit and the analyzers available from California Analytical Instruments (CAI). OEMs such as GE, Pratt and Whitney, and Honeywell all use gaseous emissions analyzers manufactured by CAI during the emissions tests, including certification tests.

Figure 2: Portable emissions cart designed for raw exhaust measurement for engine gaseous emissions

Missouri S&T will also procure a smoke meter from Chell Instruments. Figure 4 shows a smoke meter manufactured by Chell Instruments. This smoke meter has also been used by Rolls-Royce, UK for emissions measurements.

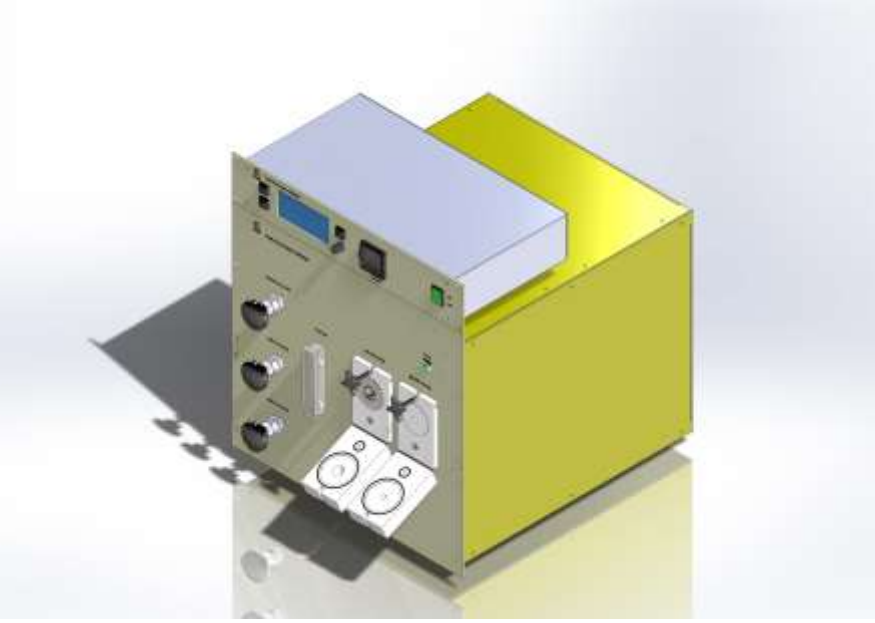

Figure 3: Smoke meter

The North American mobile reference system will need to comply with the Canadian electrical standards. To gain approval for use in Canada, the system must pass a field evaluation (FE) performed by a third party recognized by ESA. This field evaluation will take place on location at Missouri S&T, and will necessitate paid travel and time of an ESA recognized inspector. The field evaluation process follows CSA SPE-1000 standard, which requires three mandatory tests; these tests are non-destructive and ensure the electrical safety requirements meet CEC standards and the equipment can be operated safely. During the field evaluation process, the Missouri S&T team will be provided documentation of failures, and will be required to make modifications as necessary. Once modifications are complete, inspections will resume until the field evaluator is satisfied and the North American mobile reference system is deemed electrically safe according to ESA and CEC standards. It is projected that a minimum of three trips will be required by an ESA recognized inspector: initial inspection with the Missouri S&T team and electrician to identify necessary upgrades, follow-up inspections to critique and further guide the Missouri S&T team and electrician, and final inspection. Once deemed safe, a serialized FE label will be put on each individual piece of equipment.

Milestone(s)

Completed

Major Accomplishments

Upgrades were completed. The North American Reference System can now be used in Canada without any limitation.

Publications

None

Outreach Efforts
None.

Awards
None

Student Involvement
None.

Plans for Next Period
With these tasks being completed the NARS has been upgraded to include gaseous and smoke emissions measurement capabilities and has been certified as compliant for use in Canada.

Task 3 nv PM measurements at RR Indianapolis
Missouri University of Science and Technology

Objective(s)
To gather emissions data on a RR engine, an engine identified by PMTG for inclusion in their nvPM emissions database to develop a metric to regulate nvPM.

Research Approach
Missouri S&T will deploy the North American nvPM mobile reference system at an OEM facility (Rolls-Royce, Indianapolis, IN) to gather emissions data on the engine. This engine is a mixed turbo-fan engine and one that has been identified by PMTG for inclusion in their nvPM emissions database to develop a metric to regulate nvPM. The data from this test will also be valuable to the SAE E-31 committee as they draft a nvPM ARP.

Missouri S&T will work with Rolls-Royce to plan and prepare for the nvPM measurements. During the planning process, a detailed plan for the test will be developed in collaboration with Rolls-Royce. The plan will include details of the sample extraction system, interfacing with the North American nvPM mobile reference system, measurement protocol, and data analysis. Essential details regarding placement of sampling and measurement system, interfacing with existing probe-rake hardware, power and air requirements, etc. will also be discussed.

After the test plan has been developed and approved, and a test window identified, Missouri S&T will begin preparation for deploying the system to the Rolls-Royce facility in Indianapolis, including but not limited to, calibration of instruments, checkout of various system components, and preparing the system for transport. The nvPM system will be deployed alongside Annex 16 Volume II certification-grade gaseous and smoke measurement systems to obtain the full complement of gaseous and nvPM data.

The testing itself will be conducted in accordance with the test plan developed during the planning phase. Data for nvPM mass, number, and gaseous emissions and smoke number will be acquired for a range of engine power conditions, spanning the full realistic parameter space using a multipoint probe similar to those used for gaseous emissions certification. The OEMs will be responsible for providing the probe system to be used for these tests. Following the test, the data will be analyzed and reported.

Milestone(s)
Task completed

Major Accomplishments
Measurements and analysis completed. RR-Indy has provided the data to ICAO Committee on Aviation Environmental Protection for an LTO based nvPM mass and number standards.

Publications

None.

Outreach Efforts
This test afforded RR-Indy testing personnel to experience firsthand the deployment of the NARS for nvPM emissions characterization.

Awards
None.

Student Involvement
None.

Plans for Next Period
None.

Task 4 nv PM measurements at P&W
Missouri University of Science and Technology

Objective(s)
To gather emissions data on a P&W engine, an engine identified by PMTG for inclusion in their nvPM emissions database to develop a metric to regulate nvPM.

Research Approach
Missouri S&T will deploy the North American nvPM mobile reference system at an OEM facility (Pratt and Whitney) to gather emissions data on the P&W engine. This engine has been identified by PMTG for inclusion in their nvPM emissions database to develop a metric to regulate nvPM. The data from this test will also be valuable to the SAE E-31 committee as they draft a nvPM ARP.

Missouri S&T will work with P&W to plan and prepare for the nvPM measurements. During the planning process, a detailed plan for the test will be developed in collaboration with P&W. The plan will include details of the sample extraction system, interfacing with the North American nvPM mobile reference system, measurement protocol, and data analysis. Essential details regarding placement of sampling and measurement system, interfacing with existing probe-rake hardware, power and air requirements, etc. will also be discussed.

After the test plan has been developed and approved, and a test window identified, Missouri S&T will begin preparation for deploying the system to the P&W facility in Connecticut, including but not limited to, calibration of instruments, checkout of various system components, and preparing the system for transport. The nvPM system will be deployed alongside Annex 16 Volume II certification-grade gaseous and smoke measurement systems to obtain the full complement of gaseous and nvPM data.

The testing itself will be conducted in accordance with the test plan developed during the planning phase. Data for nvPM mass, number, and gaseous emissions and smoke number will be acquired for a range of engine power conditions, spanning the full realistic parameter space using a multipoint probe similar to those used for gaseous emissions certification. The OEMs will be responsible for providing the probe system to be used for these tests. Following the test, the data will be analyzed and reported.

Milestone(s)
Testing completed December 14, 2016. Data analysis underway.

Major Accomplishments
None.

Publications

None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
Complete data analysis and prepare report.

Plans for Next Period
None.

Task 5 nv PM measurements at the VARIANT 2 Campaign
Missouri University of Science and Technology

Objective(s)
a) Upgrade the measurement capability of the North American reference system to sample nvPM emission from mixed flow engines certified in the mixed flow configuration

b) Participate in the VAriable Response In Aircraft nvPM Testing (VARIAnT) 2 campaign

Research Approach
The VAriable Response In Aircraft nvPM Testing (VARIAnT) campaign was conducted in Aug/Sep 2014 to (1) better understand variability within a single measurement system versus the allowable range of operational parameters, (2) better understand variability between (two) measurement systems and (3) better define variability among instruments of the same and different types. The PM sources used during the study included a miniCAST burner and a small GE J-85 turbojet engine. The study concluded that the system specifications for the sampling system and number measurement instrument were sufficiently robust. In terms of the mass measurement instruments the LII was found to be consistently lower than the NIOSH 5040 EC concentration by ~20% while using the miniCAST as the source and ~40% on J-85 engine emissions.

A subsequent study – MANTRA (Mass Assessment of nvPM Technology Readiness for Aviation) was conducted during Dec 2014 – April 2015 to further explore the differences in mass concentration reported by LII to that of MSS and NIOSH using laboratory and gas turbine emission sources. The primary objective of this study was to investigate the calibration source criterion impact on differences observed between LII and MSS mass instruments when applied to aviation engine PM measurements. The data from this study is being processed and will be reported on during the SAE E-31 Annual meeting in June 2015.

The VAriable Response In Aircraft nvPM Testing (VARIAnT) 2 campaign is currently scheduled for August 17-31, 2015 with a primary goal to determine the performance of the LII (with new firmware) and MSS using both miniCAST and gas turbine exhaust. This campaign will attempt to reproduce selected results from the MANTRA study with respect to both instrument performance and calibration protocol.

Milestone(s)
Analysis complete.

Major Accomplishments
Analysis completed and reported to ASCENT advisory board.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
None.

Task 6 nv PM measurements at Honeywell
Missouri University of Science and Technology

Objective(s)
a) Conduct non-volatile PM Emissions measurements of a turbofan engine at Honeywell

b) Validate ambient condition corrections for non-volatile PM Emissions measurements

Research Approach
Missouri S&T will deploy the North American nvPM mobile reference system at the Honeywell facility (Phoenix/San Tan, AZ) to gather emissions data on a mixed turbofan engine that has been identified by PMTG for inclusion in their nvPM emissions database to develop a metric to regulate nvPM. The data from this test will also be valuable to the SAE E-31 committee as they draft a nvPM ARP.

Missouri S&T will work with Honeywell to plan and prepare for the nvPM measurements. During the planning process, a detailed plan for the test will be developed in collaboration with Honeywell. The plan will include details of the sample extraction system, interfacing with the North American nvPM mobile reference system, measurement protocol, and data analysis. Essential details regarding placement of sampling and measurement system, interfacing with existing probe-rake hardware, power and air requirements, etc. will also be discussed. Honeywell will deploy their nvPM system in parallel and the data obtained will be used to compare the performance of the Honeywell nvPM system with the North American mobile reference system.

After the test plan has been developed and approved, and a test window identified, Missouri S&T will begin preparation for deploying the system to the Honeywell facility in Arizona, including but not limited to, calibration of instruments, checkout of various system components, and preparing the system for transport. The nvPM system will be deployed alongside Annex 16 Volume II certification-grade gaseous and smoke measurement systems to obtain the full complement of gaseous and nvPM data. In addition to measurements of nvPM number and mass-based emissions, ancillary instruments will also be deployed to characterize the nvPM in terms of particle size and composition.

All testing will be conducted in accordance with the test plan developed during the planning phase. Data for nvPM mass, number, and gaseous emissions and smoke number will be acquired for a range of engine power conditions, spanning the full realistic parameter space using a multipoint probe similar to those used for gaseous emissions certification. Honeywell will be responsible for providing the probe system to be used for these tests. Following the test, the data will be analyzed and reported.

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 conduct

an nvPM emissions measurement campaign in an altitude test cell 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. Such validation is planned during the engine tests scheduled for Honeywell. Missouri S&T will review the Honeywell data and 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.

Milestone(s)
Analysis completed

Major Accomplishments
Analysis completed and reported to agencies participating in the NDA associated with this task. Honeywell has provided the data to ICAO Committee on Aviation Environmental Protection for an LTO based nvPM mass and number standards.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
None.

Task 7 Engine to Engine Variability and Derivation of Characteristic nvPM Emissions
Missouri University of Science and Technology

Objective(s)
a) Conduct non-volatile PM Emissions measurements of a large number of turbofan engines at Honeywell

b) Analyze the data acquired to assess the characteristic variability of these engines for nvPM emissions

Research Approach
Honeywell will deploy their nvPM and gaseous emissions measurement system. Honeywell will work with Missouri S&T to plan and prepare for the nvPM measurements. During the planning process, a detailed plan for the test will be developed. The plan will include details of the sample extraction system, measurement protocol, and data analysis. Essential details regarding placement of sampling and measurement system, interfacing with existing probe-rake hardware, power and air requirements, etc. will also be discussed.

After the test plan has been developed and approved, and a test window identified, the Honeywell nvPM measurement system will be setup at the engine test facility in Phoenix, AZ. All testing will be conducted in accordance with the test plan developed during the planning phase. Data for nvPM mass, number, and gaseous emissions will be acquired for a range of engine power conditions, spanning the full realistic parameter space using a multipoint probe similar designed

to sample engine exhaust from the core flow. Honeywell will be responsible for providing the probe system to be used for these tests.

Following the emissions measurement tests, all the data collected will be reduced and analyzed. The nvPM number- and mass-based emissions data for each engine at each engine operating condition will be compared. This dataset will then be used to assess the characteristic variability in nvPM emissions for this particular engine type.

Milestone(s)
None

Major Accomplishments
None

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
None.