

INTERIM PARTICULATE MATTER TEST METHOD FOR THE DETERMINATION OF PARTICULATE MATTER FROM GAS TURBINE ENGINES

SERDP Project WP-1538
Final Report
29-July 2011

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 29-July 2011		2. REPORT TYPE Final Report		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Interim Particulate Matter Test Method for the Determination Of Particulate Matter from Gas Turbine Engines				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Robert P. Howard, Kathryn M. Stephens, Philip D. Whitefield, Donald E. Hagen, Steven L. Achterberg, Elizabeth A. Black, Scott C. Herndon, Michael T. Timko, Richard C. Miake-Lye, John S. Kinsey, Dave Gemmill				5d. PROJECT NUMBER SERDP Project WP-1538	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Aerospace Testing Alliance / Arnold Engineering Development, 1099 Schriever Avenue, Arnold AFB, TN 37389-9013				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program				10. SPONSOR/MONITOR'S ACRONYM(S) SERDP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The primary objective of this study was development of an EPA approved interim particulate matter (PM) test method for non-volatile PM that can be applied at the engine exit plane of military turbine engines. New particle (volatile) formation and condensation can occur in the sampling line as the sample gas temperature is lowered through interaction with the cooler sample line walls. A sampling process is defined by which non-volatile PM can be measured accurately by eliminating or accounting for the interference of new particle formation and condensation. A ground-level engine test campaign (Methodology Development Test) was conducted on an F100-220 military gas turbine engine in 2007 to experimentally investigate issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine data representativeness. The test measurement protocol was demonstrated during the Validation Test in late 2009 using a different F100-220 engine and the diagnostics, probe-rake system, and sampling system developed for JSF applications.					
15. SUBJECT TERMS PM measurement, particulate matter, turbine engine, non-volatile particles, test method					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 205	19a. NAME OF RESPONSIBLE PERSON Robert Howard
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) 931-454-4783

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Defense through the Strategic Environmental Research and Development Program (SERDP) and the Office of the Chief of Naval Operations (N45). It is a pleasure to acknowledge Mr. Bruce Sartwell, Dr. Jeffrey Marqusee, Mr. Charles Pellerin and Mr. Jeff Houff for their leadership and enthusiastic support of this project. We are thankful to the advisory council for their oversight and advice.

We appreciate the efforts of Mr. William Voorhees, Director of Science and Technology, Propulsion and Power Engineering Department of Naval Air Systems Command, for initiating this effort and Mr. Steven Hartle and Mr. Curtis Kimbel, Naval Air Systems Command, for their administration during the initial phases of this project.

Dr. Stephen O. Andersen, Director of Strategic Climate Projects, Office of Air and Radiation of the United States Environmental Protection Agency (EPA), is acknowledged for enthusiastically advocating and gaining the support of EPA.

We appreciate the efforts of the Air Force Management at Tinker AFB for making available piggy-back test opportunities for the Methodology Development Test; in particular Mr. David P. Hughes and Mr. Jeffrey L. Copeland and the staff who directly supported the research group.

And there are several organizations and individuals with valuable contributions that supported the planning, provided measurements or technical collaboration. We gladly acknowledge:

Mr. Triet Nguyen - Navy Aircraft Environmental Support Office (AESO), SAE E31
Dr. Xu Li-Jones, CTR FRC-SW, 08212, AESO, SAE E31
Ms. Jean Hawkins - Joint Program Office, JSF, Environmental, Safety and Health Manager
Dr. Anuj Bhargava - Pratt & Whitney (JSF PM Measurement Requirements), SAE E31
Dr. David Liscinsky - United Technologies Research Center, SAE E31
Dr. Chowen Wey - Army Research Lab, SAE E31
Dr. Bruce Anderson - NASA Langley Research Center
Dr. W. Berk Knightington - Research Professor – Montana State University
Dr. Wayne Miller - University of California-Riverside
Mr. Roy Carroll, Mr. Gary Storey and Mr. Brad Besheres - ATA/AEDC, Arnold AFB
Mr. Max Trueblood and Mr. Ben Baker - Missouri S&T
Mr. Ryan McGovern and Mr. Robert Prescott - ARI

ABSTRACT

Standards enacted under the United States Clean Air Act (CAA) require accurate estimates of particulate matter (PM) less than 2.5 micrometers in diameter (PM 2.5) emitted from military aircraft. The US Department of Defense (DoD) needs accurate PM 2.5 data to demonstrate conformity in any National Ambient Air Quality Standards (NAAQS) Non-Attainment area where military aircraft will be based. The Joint Strike Fighter (JSF) will replace a wide range of aging military aircraft currently flying in the U.S. and numerous countries. Characterization of the JSF PM emissions is necessary for JSF aircraft basing decisions. The EPA Method 5 formerly used for PM measurements of test facility and turbine engine PM emissions is cumbersome, costly and offers limited PM characterization data. The primary objective of this study was development of an EPA approved PM test method that can be applied at the engine exit plane in a manner similar to regulatory measurements of gas species on commercial engines specified by the International Civil Aviation Organization ANNEX16. The exhaust exiting the engine contains non-volatile PM and volatile gas constituents (precursors) that have a propensity, as the gas cools, to nucleate and form volatile particles (new particle formation) and/or condense and coat non-volatile particles (condensation). There are no volatile particles in the exhaust at the engine exit plane, only their gas phase precursors. New particle formation and condensation occur naturally in the downstream exhaust plume as the exhaust gas mixes (and cools) with the engine bypass and ambient air. New particle formation and condensation can also occur in the sampling line as the sample gas temperature is lowered through interaction with the cooler sample line walls. The objective was to define a sampling process by which non-volatile PM can be measured accurately by eliminating or accounting for the interference of new particle formation and condensation. The approach pursued in this study adds dilution gas to the exhaust sample as it enters the sampling probe (probe-tip dilution) to eliminate, or mitigate, new particle formation and condensation in the sampling line over all engine power level conditions. A ground-level engine test campaign, called the Methodology Development Test, was conducted on an F100-220 military gas turbine engine in 2007 to experimentally investigate issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine data representativeness. The test data provided assessment of minimally acceptable sample dilution for diluting at the probe tip, the effects of probe-tip versus downstream sample dilution sample line velocity, and the impact of engine power level on PM sampling parameters. Also, there was significant progress on development of a field method for sample line penetration, PM instrument calibration issues, and defining system performance checks. The test measurement protocol, referred to as the Interim PM Test Method, was successfully demonstrated during the Validation Test in late 2009, again using an F100-220 engine and the diagnostics, probe-rake system, and sampling system developed for JSF applications. This study has successfully developed and demonstrated a PM test methodology for accurate non-volatile PM emissions characterization measurements that can be applied at the exit plane of non-afterburning military engines. The hardware was developed and validated on an F100-220 engine for future application to the JSF F135 engine and will be available for other military engines as required. This research has been shared with the Society of Automotive Engineers (SAE) E-31 Aircraft Exhaust Emissions Measurement Committee to aid in the development of an International PM measurement procedure for certification of commercial engines. Further research is needed to simplify the extractive sampling methodology and possible development of non-intrusive diagnostics for quantitative measurements of PM mass and number in turbine engine exhaust.

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LIST OF ACRONYMS

AEDC	Arnold Engineering Development Center
AESO	Aircraft Environmental Support Office
AFB	Air Force Base
AMS	Aerosol Mass Spectrometer
APEX	Aircraft Particle Emissions eXperiment
ARI	Aerodyne Research Incorporated
ATA	Aerospace Testing Alliance
CAA	Clean Air Act
CNC	Condensation Nuclei Counter
CPC	Condensation Particle Counter
DMA	Differential Mobility Analyzer
DMS	Differential Mobility Spectrometer

DoD	Department of Defense
D _p	Particle Diameter
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FTIR	Fourier Transform Infrared
HEPA	High-Efficiency Particulate Air (as HEPA Filter)
HFID	Heated Flame Ionization Detector
ICAO	International Civil Aviation Organization
IPMTM	Interim Particulate Matter Test Method
JSF	Joint Strike Fighter
MAAP	Multi-Angle Absorption Photometer
MASS	Mobile Aerosol Sampling System
MGA	MultiGas™ Analyzer
Missouri S&T	Missouri University of Science and Technology
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NRMRL	National Risk Management Research Laboratory
PM	Particulate Matter
PTR-MS	Proton-Transfer Reaction Mass Spectrometer
PTFE	Polytetrafluoroethylene, Teflon®
RAOS	Reno Aerosol Optics Study
QC-TILDAS	Quantum-Cascade Tunable Infrared Laser Differential Absorption Spectrometer
SAE	Society of Automotive Engineers
SAE E-31	SAE E-31 Aircraft Exhaust Emissions Measurement Committee
SERDP	Strategic Environmental Research and Development Program
THC	Total Hydrocarbons
TILDAS	Tunable Infrared Laser Differential Absorption Spectrometer
VOC	Volatile Organic Compound

LIST OF TERMS AND SYMBOLS

D_{va}	Aerodynamic Particle Diameter
EI	Emission Index
EIm	Mass-based Emission Index [g/kg-fuel]
EIm-nvPM	Mass-based Emission Index for non-volatile PM [g/kg-fuel]
EIm-organic	Mass-based Emission Index for the organic component of volatile PM [g/kg-fuel]
EIm-vPMorganic	Mass-based Emission Index for the organic component of volatile PM [g/kg-fuel]
EIn	Number-based Emission Index [number/kg-fuel]
EIn-nvPM	Number-based Emission Index for nonvolatile PM[number/kg-fuel]
EIn-organic	Number-based Emission Index for the organic component of volatile PM [number/kg-fuel]
EIn-vPMorganic	Number-based Emission Index for the organic component of volatile PM [number/kg-fuel]
EIm-total	Mass-based Emission Index for total non-volatile and volatile PM
EIn-total	Number-based Emission Index for total non-volatile and volatile PM
M	(Total) particle mass concentration (derived from integral of number size distribution)
n	(Logarithmic) differential number concentration
N	(Total) number concentration of the particle size distribution
NFF	Normalized Fuel Flow
SN	Smoke Number

1.0 BACKGROUND AND INTRODUCTION

Standards enacted under the United States Clean Air Act (CAA) require accurate estimates of particulate matter (PM) less than 2.5 micrometers in diameter (PM 2.5) emitted from military aircraft. The US Department of Defense (DoD) needs accurate PM 2.5 data to demonstrate conformity in any National Ambient Air Quality Standards (NAAQS) Non-Attainment area where military aircraft will be based. The Joint Strike Fighter (JSF), a new multi-mission aircraft designed to replace a wide range of aging military aircraft currently flying in numerous countries, will be deployed several years before the implementation of a final PM testing methodology. In lieu of EPA Method 5 [California Air Resources Board, 1997] that has been used for reporting PM emissions from military engines and sea-level test facilities, this report describes a PM test method for the Joint Strike Fighter (JSF) Program that implements modern particle measurement techniques. These techniques are to be applied at the engine exit plane in a manner similar to regulatory measurements of gas species on commercial engines. Modern particle measurement techniques offer improved accuracy in PM reporting, provide additional information such as the particle size distribution, and require shorter engine run times at significantly reduced costs. The overall program objective is development of an Interim PM Test Method (IPMTM) for use in measuring PM emissions for the JSF Program.

Investigators from the Air Force-Arnold Engineering Development Center (AEDC), Missouri University of Science and Technology (Missouri S&T) and Aerodyne Research, Incorporated (ARI) were responsible for the research and development of the IPMTM. The work was conducted in collaboration with the Naval Air Systems Command (NAVAIR), the United States Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), the Navy Aircraft Environmental Support Office (AESO), the Federal Aviation Administration (FAA), and the Society of Automotive Engineers (SAE) E-31 Aircraft Exhaust Emissions Measurement Committee.

In early 2006, the project team seized an opportunity to “piggy back” modern PM measurements on a JSF F-135 engine test to assess implementation issues that should be addressed in the development of the IPMTM. This effort, called the PM “Quick-Look” test, showed that:

- The general instrument suite and methodology employed are well suited to characterize the PM emissions associated with F-135 type engines and are suitable for the JSF measurements.
- The probe-rake system functioned properly in extracting sample from the hot high-speed flow for all engine power settings. However, lessons learned regarding implementation of the probe-rake system in the extreme thrust and temperature exhaust environment should be considered in a new rake design planned for future JSF exhaust emission measurements.
- The maximum measured number based emission index was comparable to that reported for comparable modern commercial engines. However, for low power conditions, the number based emission indices were significantly lower than those of comparable modern engines.
- The range of measured mass based emission indices were generally lower than those reported for comparable modern engines and at low power were down by at least an order of magnitude.

A ground-level engine test campaign, called the Methodology Development Test, was conducted in 2007 on an F100-220 military gas turbine engine to experimentally investigate unresolved measurement issues identified during prior NASA PM characterization studies. The draft

IPMTM used for this test was based on the approach developed for the former NASA gas turbine PM characterization studies and the results of the Methodology Development Test. The IPMTM was successfully demonstrated during a second F100-220 engine test in late 2009, called the Validation Test, using the diagnostics, probe-rake system, and sampling system developed for JSF applications.

The main body provides an overview summary of the IPMTM sampling and PM measurement approach and recommendations and a summarized overview and results of the Methodology Development Test and Validation Test. Full descriptions are given in the appendices of this report. It is anticipated that the IPMTM will be applied to the JSF Program for reporting PM emissions and will be available for use on other military engines as necessary to meet PM reporting requirements.

1.1 OBJECTIVE

The primary objective of this project was development of an EPA approved interim PM test method for the JSF Program that will provide defensible emission data required for JSF basing decisions. The interim test protocol will be used to characterize JSF emissions using state-of-the-science PM emissions testing instrumentation and will serve as a test bed to advance the scientific basis of environmental decision-making and provide an alternative approach to EPA Test Method 5 [California Air Resources Board, 1997] which does not measure particle size and particle number density. Multi-Agency collaboration on the development of this new test method helps improve the accuracy of estimating PM emissions from aircraft gas turbine engines while reducing the cost and time required for testing. The collaborative work provides input to the SAE E-31 Aircraft Exhaust Emissions Measurement Committee that is developing long-term recommended practices for measurements of gas turbine PM emissions of commercial aircraft for adoption by the United Nations International Civil Aviation Organization (ICAO) and the United States EPA.

2.0 INTERIM PM TEST METHOD

The Interim PM Test Method is a document that describes the recommendations for characterizing PM emissions from gas turbine engines using extractive sampling techniques near the nozzle exit plane and modern PM measurement techniques. This section summarizes the principals, approach and recommendations. The reader is referred to the full IPMTM document in Appendix A for detailed explanations.

2.1 PRINCIPLE

Particles emitted at the exhaust nozzle exit plane of aircraft are small, typically less than a few tenths of a micron, and result from the combustion of hydrocarbon fuels. These particles are classified as non-volatile PM. Non-volatile particles are comprised primarily of carbonaceous particles (optically black carbon), and metal particles from engine erosion and trace metals in the fuel. The IPMTM is expected to provide an accurate measure of the non-volatile particle size, number and mass concentrations in non-afterburning plumes within one half of an exit nozzle diameter. All PM diagnostic techniques recommended rely on a gas sampling system to deliver exhaust gas to the analyzer. Figure 2.1 illustrates the sampling system approach consisting of a probe-rake mounted to a traverse stand that would be installed behind the nozzle exit of a gas

turbine engine. Exhaust gas enters the tip of a particle probe designed to preserve sampled-particle integrity by affording sample dilution at the probe tip as illustrated in Figure 2.2.

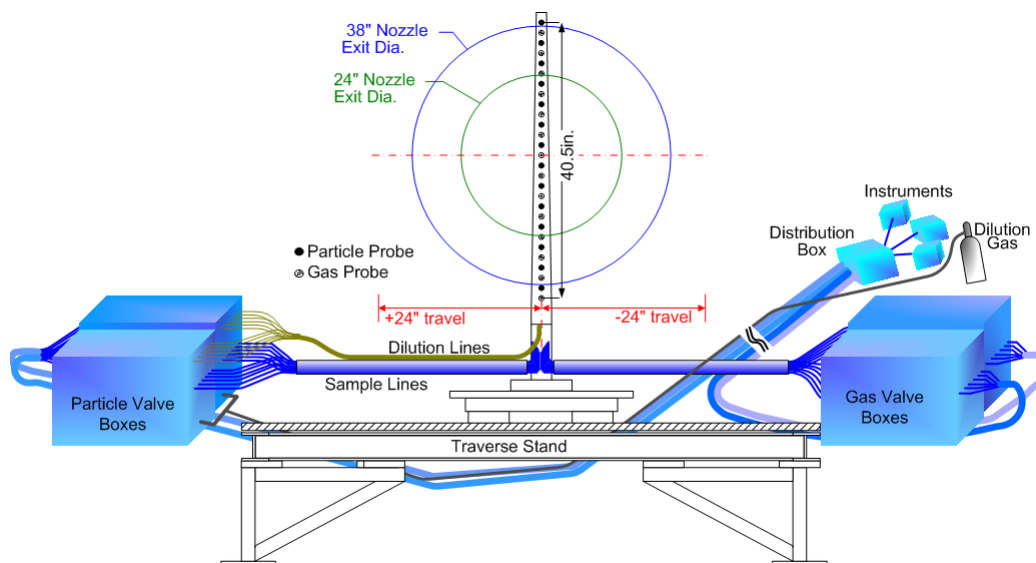


Figure 2.1 The AEDC and Missouri S&T sampling components.

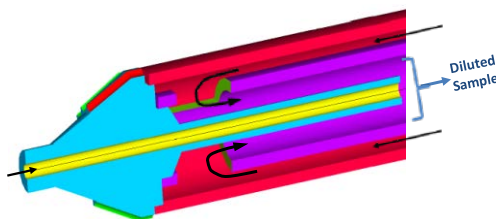


Figure 2.2 Cross-section view of the particle probe sampling concept.

Diluting the sample suppresses modification of the PM that might occur through gas to particle conversion, agglomeration and condensation of volatile gases, and reduces sample system particle losses. The diluted sample is transported through sample lines to a suite of diagnostic instruments located at a safe distance (up to 30 meters) from the engine. A multi-angle absorption photometer (MAAP) is recommended for measuring non-volatile particle mass concentration and offers data on-line and in near real-time. A differential mobility analyzer (DMA) in combination with a condensation particle counter (CPC) is recommended for measuring particle size distribution, particle number density, and a secondary indirect measure of mass concentration. The sample dilution gas (nitrogen) helps preserve the PM sample integrity, but unfortunately does not eliminate particle losses through sample extraction and transport. The sample system throughput losses are measured as a function of particle size and the test data corrected accordingly. The sample line penetration curve shown in Figure 2.3 was measured during the Validation Test.

For selected power conditions from idle to maximum non-afterburning, spatially resolved data are acquired across the nozzle exit plane. These PM measurements are corrected for line loss and reported for the engine.

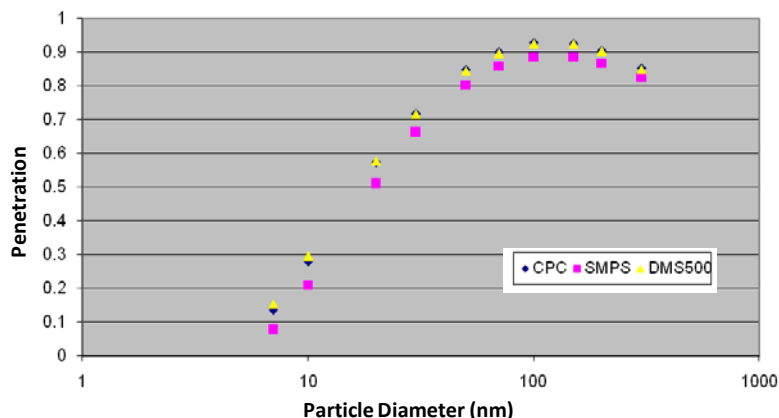


Figure 2.3 Size dependent sample line penetration curve for the Validation Test.

The exhaust exiting the engine contains non-volatile PM and volatile gas constituents (precursors) that have a propensity, as the gas cools, to nucleate and form volatile particles (new particle formation) and/or condense and coat non-volatile particles (condensation). There are no volatile particles in the exhaust at the engine exit plane, only their gas phase precursors. New particle formation and condensation occur naturally in the downstream exhaust plume as the exhaust gas mixes (and cools) with the engine bypass and ambient air. New particle formation and condensation can also occur in the sampling line as the sample gas temperature is lowered through interaction with the cooler sample line walls. The objective of the interim PM test method is to define a sampling process by which non-volatile PM can be measured accurately by eliminating or accounting for the interference of new particle formation and condensation. The IPMTM approach adds dilution gas as the exhaust sample enters the sampling probe (probe-tip dilution, Figure 2.2) to eliminate, or mitigate, new particle formation and condensation in the sampling line over all engine power level conditions.

2.2 PARTICLE PROBE RECOMMENDATIONS

The particle probe is the apparatus used to extract exhaust sample from the flow field for subsequent transport through the sample system to the PM analyzers. The particle probe concept is shown in Figure 2.2 and recommendations summarized here:

- The particle probes should accommodate sample dilution near the probe tip
- The particle probe should be capable of more than 10:1 sample dilution; preferably allowing up to 20:1 dilution
- The particle probe should be actively cooled (not expected to be a general recommendation for engines with lower temperature exhaust)
- There should be independent dilution level control to each particle probe

2.3 PROBE-RAKE SYSTEM

Spatial mapping of the PM across the nozzle exit plane should be performed using these recommendations:

- A linear rake of particle probes that span the nozzle exit plane
- Particle probe spacing ≤ 7.62 cm (3.0 in)
- The rake installed on a traverse with sufficient travel to span the nozzle exit plane

2.4 SAMPLE LINE RECOMMENDATIONS

Sample lines are specified in four sections, but with overall stipulations that follow:

- Segment 1: Probe exit to the base of the rake
 - Length ≤ 2 m
 - Stainless steel
 - Internal diameter ≥ 3.8 mm (0.15 in)
- Segment 2: Base of the rake to the particle valve box
 - Length ≤ 4 m
 - Stainless steel preferred; but optional flexible conductive PTFE to simplify traversing of the probe or probe rake system
 - Internal diameter ≥ 7.6 mm (0.30 in)
- Segment 3: Particle valve box to the distribution box (main trunk line)
 - Length ≤ 30 m with a residence time ≤ 6 sec (calculated time for plug flow)
 - Stainless steel preferred; but optional flexible conductive PTFE to simplify traversing of the probe or probe rake system
 - Internal diameter ≥ 12.7 mm (0.50 in)
- Segment 4: Distribution box to the instruments
 - Length ≤ 3 m
 - Stainless steel
 - Internal diameter ≥ 7.6 mm (0.30 in)
- Overall: The total sample line length from probe tip to the instruments should be as short as possible but not exceed 35 m and a sample residence time of less than 8 sec (calculated time for plug flow). All stainless steel lines should be seamless and have a minimum number of bends, fittings and valves. All valves should be full-bore (i.e., the internal diameter of the valve matches as much as possible the internal diameter of the tubing). All bends should have radii of curvature greater than 10 times the internal sample line diameter.

2.5 SAMPLE SYSTEM OPERATION

Trade-offs must be considered in sample system operation to balance sufficient dilution to mitigate new particle formation and condensation of volatile gases within the sample system, but maintain a sufficient non-volatile PM concentration within the detectable range of the PM analyzers. Following are sample system recommendations:

- The valve box should be located near the rake with remotely actuated valves to select the probe(s) to sample.
- Use a mass flow controller on the dilution line to allow faster and more accurate control of the dilution level.
- Back purge sample line segments with nitrogen gas for probes not sampled,
- The extracted exhaust sample should be diluted with dry, particle-free (HEPA-filtered) nitrogen near the probe tip.

- Sample lines should be leak checked from the probe tip to the instrument and demonstrated to yield less than 5 particles/cc measured with a CPC when drawing ambient air through a HEPA filter at the probe tip.
- Sample line penetration as a function of size should be measured and should be greater than 80% for particle sizes greater than 80 nm. Full penetration should be performed pre- and post test.
- Sample line integrity with respect to leaks and penetration should be checked at least on a daily basis.
- The CO₂ concentration on the diluted and undiluted sample lines should be measured and monitored for real-time assessment and recording of the dilution ratio.
- Dilution ratios from 10 to 20 are recommended; the higher dilution ratios (approaching 20:1) are preferred and usually achievable at low engine power (idle) and help maintain a smaller sample residence time; lower dilution ratios are acceptable at high engine power conditions where precursors are minimal. Overall, recognize the tradeoff in sample system operation to balance sufficient dilution to mitigate new particle formation and condensation of volatile gases within the sample system, but maintain a sufficient concentration within the detectable range of the PM analyzers. The dilution ratio should never be allowed to drop below a level that would allow condensation of water in the sample line; typically in the range of 4 to 6.
- Through dilution, the particle number concentration should be kept below $5 \times 10^6 \text{ cm}^{-3}$ to avoid particle coagulation effects in the sample line.
- If multiple probe tips are sampled simultaneously (ganged), the specified dilution ratio must be maintained per probe tip.
- Sample line pressure at the instrument end of the sample line should be maintained between about 0.85 and 1.02 atm; venting excess flow at the instrument end of the sampling system.
- Active heating of the sample lines is not recommended as long as the ambient temperature during measurements is $25 \pm 15 \text{ }^\circ\text{C}$.

2.6 DIAGNOSTIC INSTRUMENTATION

Diagnostic needs for the IPMTM include characterization of non-volatile PM number density, non-volatile PM size distribution and non-volatile PM mass density. Other diagnostic instruments are recommended to assure data quality through real-time monitoring of the sampling system operation and assessment of gaseous emissions for assurance the engine performance is on par with historical manufacturer's data for that engine.

2.6.1 Particulate Matter Species

The Condensation Particle Counter (CPC) and Differential Mobility Analyzer (DMA) instruments are recommended for PM size and number characterization. The Multi-angle Absorption Photometer (MAAP) [Petzold and Schonlinner, 2004; Petzold et al., 2005] is recommended for PM mass characterization. (See Appendix A)

CPC: Saturator-condenser type Condensation Particle Counters (CPCs) are recommended for number concentration measurements. Typical models are TSI 3022A and 3025A (see Section A-5.1).

DMA: Commercial Differential Mobility Analyzers (DMAs) are available from several vendors, e.g. TSI (St. Paul, MN), Hauk (Vienna), and Grimm (Douglasville, GA – US office). Typical

models are TSI 3071 or 3081 (Long), TSI (short), TSI 3085 (nano), used in the scanning mode (See Section A-5.2).

MAAP: The Multi-Angle Absorption Photometer (MAAP, Thermo Electron Corp.) provides real-time (modified from the commercial version to provide up to a 1 second data stream), continuous non-volatile mass measurements. A rigorous data inversion algorithm (Petzold and Schönlinner; 2004) converts optical transmission and scattering measurements on non-volatile PM collected onto a filter to an equivalent non-volatile mass. The manufacturer cites a detection limit of 100 ng m^{-3} (on a 2 min average), which is adequate for exhaust measurements ($>500 \text{ ng m}^{-3}$). Figure 2.4 depicts the principle of MAAP operation. Petzold and Schönlinner (2004) provide more detail on the fundamental aspects of MAAP operation, while Petzold et al. (2005) demonstrate its use as part of the Reno Aerosol Optics Study (RAOS). In brief, aerosol sample at a controlled mass flow rate is introduced into a sample chamber. Particles deposit on a section of filter tape (99.98% retention efficiency) and alter its optical properties. A 670-nm light source illuminates the filter paper and a battery of optical sensors to monitor the forward (180° for transmission) and back (135° and 160° for scattering) to analyze the optical properties modifications which accompany particle deposition. Sampled aircraft exhaust can contain mixed aerosol particles (volatile and non-volatile) and the back-scattering optical measurements serve to correct the transmission measurement to account for light scattering and focusing from particle coatings. As part of an extensive instrument inter-comparison, Slowik et al. (2007) precisely coated soot particles with nanometer layers of oleic acid and found the MAAP measurements to be unaffected by the coating. The data inversion algorithm requires the black carbon absorption coefficient; the test method takes the absorption coefficient to be $6.6 \text{ m}^2 \text{ g}^{-1}$, in agreement with Petzold and Schönlinner's (2004) various measurements of black carbon optical properties. The MAAP must be interrupted periodically (roughly every 30 min) to advance manually a filter tape used for PM collection. Tape advancement is timed for periods of engine transitions to minimize instrument down-time. The typical instrument duty cycle is greater than 95% during an engine test.

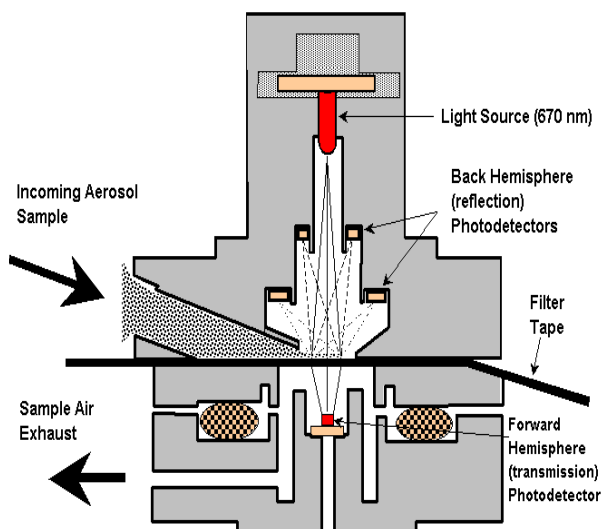


Figure 2.4 Schematic drawing of the MAAP sample chamber.

Gas Species and Smoke Number: The measurement of the conventional gas species (CO_2 , CO , NO , NO_x , total hydrocarbons (THC) and smoke number (SN)) provides data for calculation of

local combustion efficiency and comparison to engine manufacturer's legacy emissions database to confirm normal performance behavior for this engine type. The analyzer types for these species are shown in Table 2.1. These measurements are performed on an undiluted probe and sampling line system.

Table 2.1 Instruments for conventional gas species and smoke number measurements.

Analyzer Type	Species Detected
Non-dispersive Infrared	CO ₂
Non-dispersive Infrared	CO
Chemiluminescence	NO
Chemiluminescence	NO _x
Flame Ionization Detector	Total Unburned Hydrocarbons
MultiGas TM Analyzer (MGA)	CO, CO ₂ , NO, NO ₂ , H ₂ O
SAE Smoke Meter	Smoke Number

A suite of instruments useful for assessing the quality of exhaust sampling for measurements of non-volatile PM is shown in Table 2.2. These measurement techniques can be used to measure levels of trace gas species, some of which are condensable in the diluted sample line. The CO₂ measurements are used to determine the level of dilution gas.

Table 2.2 Trace gas instruments for assessing the quality of exhaust sampling for PM.

Instrument	Species Detected	Detection Limit^a	Time Resolution
Licor 6262 Licor 820	CO ₂ CO ₂ (high range)	300 ppb 2 ppm	1 sec
NO _x Chemiluminescence Analyzer ThermoElectron (model 42C)	NO NO _x ^b	0.5 ppb 0.5 ppb	1 sec/20 sec 20 sec
QC-TILDAS ^{c,d}	NO ₂	0.5 ppb	1 sec
	C ₂ H ₄	2 ppb	1 sec
	CO	2 ppb	1 sec
	HCHO	1 ppb	1 sec
	HONO	2 ppb	1 sec
PTR-MS ^e	acetaldehyde, propene, benzene, toluene, styrene, C ₂ -benzene ^f , phenol, naphthalene, methylnaphthalene, dimethylnaphthalene	2-5 ppb	8 sec

^a Detection limits are quoted as 2 times instrument noise level.

^b The measurement of NO_x using catalytic reduction of NO₂ to NO (most chemiluminescence analyzers) also measures higher nitrogen oxides such as HNO₃, HONO, and organic nitrates.

^c quantum-cascade tunable infrared laser differential absorption spectrometer (Aerodyne Research, Inc.).

^d tunable infrared laser absorption spectrometer (Aerodyne Research, Inc.).

^e proton-transfer reaction mass spectrometer.

^f C₂-benzene includes *o*-xylene, *m*-xylene, *p*-xylene, and ethylbenzene.

2.6.2 Volatile particle measurement instrumentation

The Aerosol Mass Spectrometer (AMS) is a unique instrument recommended for measuring the amount of volatile gas condensation on non-volatile particles versus particle size. This is an excellent instrument for real-time assessment of the quality of the exhaust sampling system. The lower particle size detection is limited, but detection of volatile coatings on larger non-volatile particles indicates new particle formation in the sample line.

2.7 EMISSIONS TESTING

Various aspects of PM emissions testing important to planning and the execution of the test program are discussed in the IPMTM document (Appendix A) and are not repeated here. Emissions measurements should be representative of the engine. This is usually accomplished by spatial mapping of emissions at selected engine power conditions from idle to take-off power. The engine power levels are usually associated with the landing-takeoff cycle and idle. The definition and approval of engine power settings and acceptable spatial emissions detail that meet “representativeness” can be engine-type specific. These decisions are a joint responsibility of the JSF Program environmental office, the engine manufacturer and the Environmental Protection Agency and will be determined during development of the test plan for the specific engine and engine test facility.

3.0 METHODOLOGY DEVELOPMENT TEST

The technical approach for the IPMTM was based on the methodology applied during the series of experimental gas turbine engine PM characterization studies led by NASA (APEX [Wey, et al., 2006], JETS-APEX2 [Lobo, et al., 2007] and APEX3 [Anderson, to be published]). The sampling methodology evolved throughout the series of tests, but several sampling and PM instrument issues were identified and reported to the SAE E-31 Committee. The focus of PM measurements performed during the Methodology Development Test was unresolved issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine data representativeness. Appendix B gives a detailed report of the Methodology Development Test.

3.1 TEST CONFIGURATION AND MEASUREMENTS

3.1.1 Test configuration

The Methodology Development Test was conducted on a military F100-220 engine at Tinker Air Force Base in Oklahoma City, OK. The photographs in Figure 3.1 show the relative placement of the probe-rake system installed on a traverse stand between the engine and an exhaust diffuser duct. The sampled exhaust entered particle probes, mixed with a dilution gas (nitrogen) and was transmitted through sample lines to a valve box for remote selection of the probe, or probes, to be sampled. Diluted sample traveled through the long sample lines from the valve box, through ports in the machine room wall, down the hallway and into the Missouri S&T trailer; an overall length of approximate 29 m. In the Missouri S&T trailer, the sample was distributed to PM analyzer instruments located in their trailer and other trailers and vans.

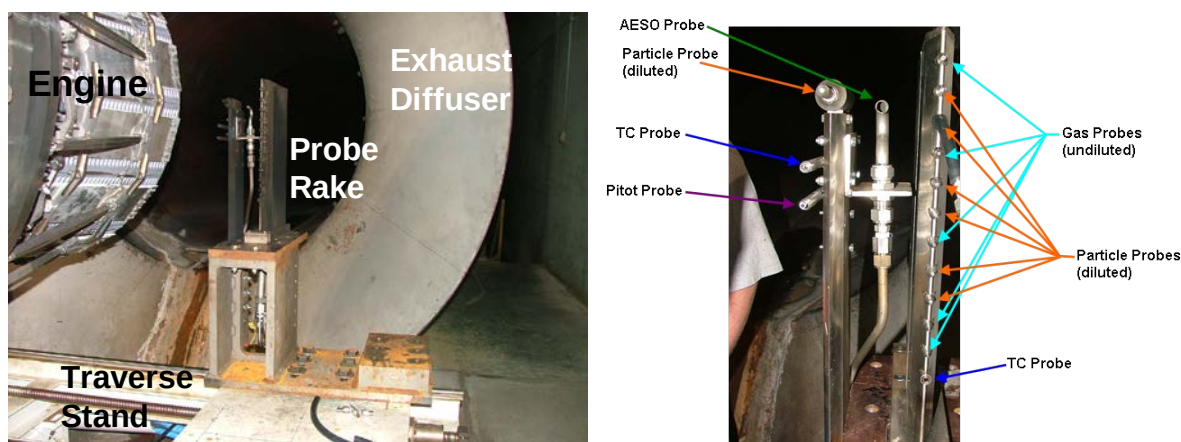


Figure 3.1 Photographs of the probe-rake system mounted behind the F100-220 engine.

Spatial PM mapping measurements were performed by moving the probe-rake horizontally to fixed locations across the exit plane and sampling the particle probes located at vertical positions along the rake.

3.1.2 Diagnostic measurement systems

The Missouri University of Science and Technology (Missouri S&T) deployed their Mobile Aerosol Sampling System (MASS) and a Cambustion DMS500 analytical system. MASS employs state-of-the-art differential mobility analysis and condensation nucleus counting to measure particle number, surface area and volumetric size distributions in jet engine exhaust flows. The volumetric size distributions and total particle concentrations were combined with an appropriate mass density to produce size-dependent mass-based particulate emission factors. The Cambustion DMS500 fast particulate spectrometer instrument provided fast response measurement capability (approximately 200 ms) for the size and number concentration of engine exhaust PM over the full particle size spectrum ranging from 5 nm to 1000 nm.

Aerodyne Research, Inc. (ARI) provided real-time instrumentation for measuring particle size and composition-resolved distributions of aerosol particles (aerosol mass spectrometer (AMS)). ARI also provided a tunable infrared laser differential absorption spectrometer (TILDAS) for measuring gas-phase exhaust constituents. A proton transfer reaction mass spectrometer (PTR-MS) was also used on the diluted sample to measure hydrocarbon constituents in the exhaust including those that can coat the non-volatile particulate phase and form volatile PM.

AEDC provided real-time instrumentation for measuring gaseous species concentrations and the standard filter-extraction based instrument for smoke number measurements. AEDC provided the probe-rake system and rake traverse system, and thermocouple and pressure transducer data acquisition systems. The gaseous concentrations measurements were performed using Fourier transform infrared (FTIR) spectrometer based MKS instruments Model 2030 MultiGasTM Analyzers (MGA) capable of measuring a large number of infrared-active gas species (CO, CO₂, H₂O, NO, NO₂, SO₂, and lighter hydrocarbons from CH₄ to C₄H₁₀). Total hydrocarbon (THC) measurements were performed using a Model 300 Heated Flame Ionization Detector (HFID) analyzer made by California Analytical Instruments.

The United States EPA's National Risk Management Research Laboratory (NRMRL) provided a Teflon[®] filter sampling system and gravimetric analyses to measure the PM mass emissions using a direct gravimetric method in lieu of on-line instruments.

3.1.3 Example data

Measurements were performed at steady-state engine power level settings ranging from idle to maximum (non-afterburning). The chosen metric for setting the engine power was fuel flow rate. During the checkout run, the fuel flow rate was recorded for engine power settings of interest. For reporting, the fuel flow rate was normalized to the maximum fuel flow measured. A normalized fuel flow (NFF) rate greater than 1.0 indicated the repeated engine setting deviated from the intended maximum fuel flow rate set point. Normalized fuel flow rates, not absolute values, are reported in this document.

Example plots of data acquired during the Validation Test are shown in Figure 3.2 to Figure 3.4. On the plots, the engine power levels are given in NFF where the lowest power represents engine idle and the highest represents engine takeoff (non-afterburning). The reader should review Appendix B for more comprehensive data and detailed explanations that support the results presented Section 3.2. Figure 3.2 shows measurements of number-based EI (a) and mass-based EI (b) measurements as a function of NFF. The mass-based non-volatile PM EI (Elm-nvPM) result from measurements using the MAAP instrument.

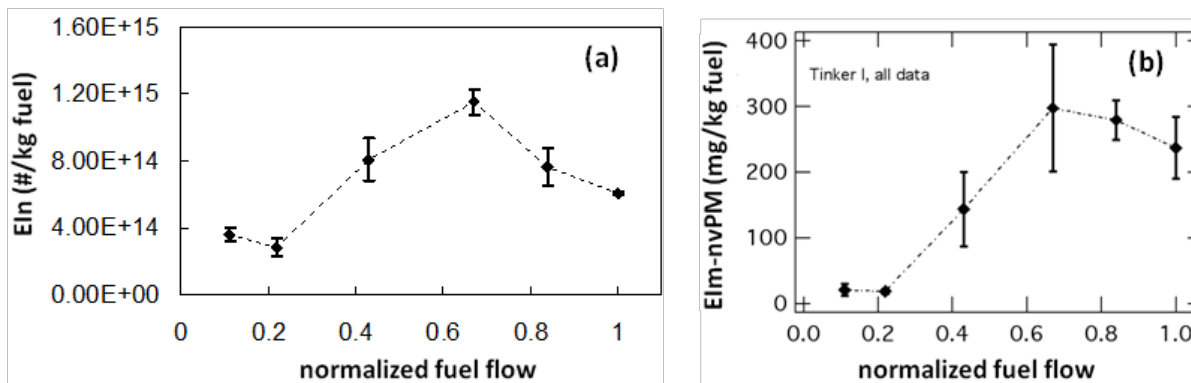


Figure 3.2 (a) Number-based EI and (b) mass-based EI measurements as a function of NFF.

Figure 3.3 (a) contrasts DMA-measured non-volatile PM size distributions for idle and take-off engine power levels while Figure 3.3 (b) contrasts DMA particle size distributions for heated and unheated sample lines for two NFF settings.

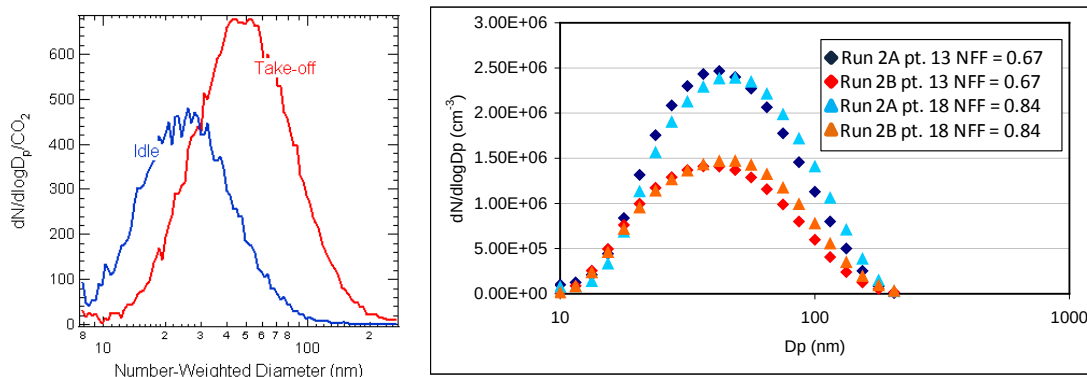


Figure 3.3 Non-volatile size distributions for (a) idle and takeoff and (b) heated (red/orange) and unheated (blue) sample lines at 0.67 and 0.84 NFF.

AMS (aerosol mass spectrometer) data provide the most direct measurement of the volatile coatings acquired by the non-volatile PM during sample transport from the engine to the instrument. Figure 3.4 shows measured AMS organic PM size distributions corrected for sample dilution. The organic mass loadings divided by CO_2 are plotted versus the vacuum aerodynamic diameter. Because this measurement is in mass space, these diameters should only be compared to the volume mode characteristics from a DMA measurement. The red lines indicate data acquired using heated sample lines and the blue lines data acquired using unheated sample lines. These AMS particle size data conclusively show that organic materials are detected as a coating on non-volatile particles for these measurements. The four panels represent different NFF settings.

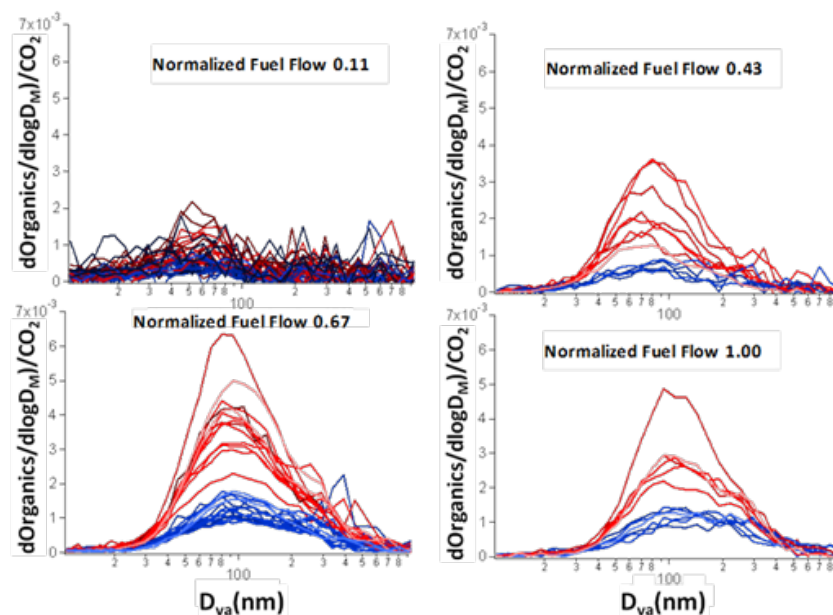


Figure 3.4 Dilution-accounted AMS organic PM size distribution measurements.

Keep in mind that measured data are intended to represent the non-volatile PM in the engine exhaust flow. However, as explained in Section 2.1, volatile gas species in the exhaust flow can, and do, form new particles and condense on non-volatile PM during the sampling process. An objective of the Methodology Validation Test was to acquire a comprehensive set of data with a

set of complimentary diagnostic tools while systematically varying sample-system parameters. Distilling these data gives a better understanding of sample-system sensitivities on new particle formation and condensation to help define a measurement method to mitigate these processes during non-volatile PM measurements.

3.2 SUMMARY OF OBJECTIVES AND RESULTING RECOMMENDATIONS FOR THE IPMTM

The purpose of the Methodology Development Test was to experimentally investigate unresolved issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine data representativeness. This section explains each specific issue and motivation for the research, and summarizes the recommendations for the IPMTM resulting from analysis of the Methodology Development Test data.

3.2.1 Objective 1: Determine the minimum acceptable probe-tip dilution

Dilution is introduced to the probe tip to minimize particle-particle and particle-wall interactions and suppress gas-to-particle conversion within the sampling system. In the case of unheated sample lines, probe-tip dilution also prevents water condensation. With a fixed probe inlet area, the sample flow into the probe increases with engine power due to increased exhaust ram pressure. To maintain a fixed dilution ratio, the dilution flow must be increased significantly at high engine power. This may be difficult to achieve. Too little dilution can allow condensation of water and/or volatile gases. Too much dilution can decrease the PM concentrations to below detectable limits or greatly decrease the signal-to-noise ratio for instruments used to characterize PM and chemical speciation. The objective is to determine an acceptable range of sample dilution.

Recommendation 1

During the engine test, the sample line dilution was varied from 4:1 to 15:1 at individual sample locations and the measured particle data assessed to determine the minimum dilution ratio suitable for the range of sampling and engine operating conditions encountered. A dilution ratio $\geq 10:1$ was sufficient to adequately suppress new particle production and growth due to condensation of condensable gaseous species and maintain an acceptable signal-to-noise ratio for the measurements.

3.2.2 Objective 2: Assessment of probe-tip versus downstream dilution

Probe and sampling systems used for conventional gas sampling do not typically incorporate sample dilution. The sampling lines for conventional gas sampling are heated to 160 °C to prevent water condensation. Researchers prefer probe tip dilution for preserving the state of particles during sampling. This obviates the need for sample line heating to prevent water condensation. To minimize particle-particle and particle-wall interactions, researchers prefer the sample be diluted at the probe tip. Probe-tip dilution requires specialized probes and is complicated by the process of delivery of the diluent to the probe tip. Adding the diluent downstream of the probe tip greatly simplifies the sampling system design. Limited data acquired during the APEX tests suggests that dilution downstream of the probe tip fosters condensation of gas phase species. Assessment of probe-tip dilution versus downstream dilution is desired for potential simplification and flexibility in sample system design.

Recommendation 2

During this engine test, data were acquired using particle probes with probe-tip dilution and a conventional gas probe with the dilution introduced to the sample line at the base of the rake, a couple meters from the probe tip. For unheated sample line experiments, care was taken to add the downstream dilution at a location before the sample temperature had dropped sufficiently to allow water condensation. Comparison of these data indicates little difference in the PM measurements acquired using probe-tip dilution or dilution added just outside the exhaust flow. However, since these results are not considered conclusive and since the introduction of diluent at a downstream location where the line temperature criterion cannot be guaranteed for all testing configurations, probe-tip dilution is recommended for the IPMTM.

3.2.3 Objective 3: Assessment of sample line velocity

The linear sample velocity influences sample residence time and thus particle diffusion and inertial loss mechanisms. High linear velocities tend to suppress diffusion losses but can contribute to inertial loss. Understanding the sensitivity of the PM sample to sample velocity is important to the design and operation of the sample system.

Recommendation 3

The sample line velocity is not an independent variable in the sample line operation. During this engine test, data were acquired at fixed spatial points with varied dilution flow and varied exhaust ram pressure (engine power) while maintaining an approximate ambient pressure at the instrument end of the sample line. The sample velocity ranged from 280 to 1350 cm/s over the range of dilution flows and engine power level settings. These data were assessed to determine sample velocities that minimize both diffusion and inertial loss mechanisms. No PM parameter dependence on line velocity was observed. It appears that with sufficient dilution, the sampling system proposed for the interim PM test IPMTM method is insensitive to sample velocity. However, it is recommended that, when feasible, sample velocity should be maintained within the range of 280 to 1350 cm/s for the IPMTM.

3.2.4 Objective 4: Sample line temperature (active heating on and off)

The E-31 Committee suggested heating the PM sample lines to a constant temperature above any foreseen maximum ambient temperature to eliminate sample line temperature as a variable. Also sample line heating was planned for the dilution study (Objective 1) to prevent water condensation at low dilution levels. Unheated PM sample lines were used in the APEX, JETS-APEX2 and APEX3 campaigns. Although no effect was expected, it was deemed important to verify that that unheated and heated lines produce the same PM measurement results.

Recommendation 4

The engine test measurements were performed with and without the PM sample lines actively heated. PM data acquired using unheated sample lines followed expected trends predicted by theoretical and empirical models and experimental penetration studies. However, heated sample lines produced unexpected effects on measured PM parameters and chemical speciation. Detailed analyses of full data sets acquired with and without heated sample lines were explored to better understand the anomalous PM loss/generation mechanisms encountered. However, the data acquired specifically to address the heated line issue are confounded by extreme variations in ambient engine inlet air temperature. Engine emissions characteristics are known to be influenced by variations in the engine inlet temperature, but in the case of PM this is not well

understood by the research community. Since variations in ambient temperature can produce changes in the absolute values of the engine emissions which in turn obscure the effects associated with active sample line temperature control, the issue of heated sample line effects remains unresolved. Until heated line effects are better understood, unheated lines are recommended for the IPMTM.

3.2.5 Objective 5: Impact of engine power level on PM sampling parameters

The temperature and pressure of the exhaust vary as engine operating conditions change, and these variations impact sample system parameters. In the sampling system, the sample temperature and pressure must be brought to within the operating ranges of the measurement instruments. The design of the sampling system must account for the ranges of pressure and temperature which must be accommodated.

Recommendation 5

The sample pressure at the PM probe inlet is controlled by the exhaust ram pressure at the sampling location, which depends on engine power level setting. At high engine power levels, the sampling pressure can exceed 1.5 atmospheres. Most diagnostic instruments require sample pressures near 1 atmosphere. Therefore, the sample pressure must be reduced before delivery to the instruments. Pressure reduction was successfully accomplished by bypassing excess sample to the ambient atmosphere thereby increasing the sample flow rate and achieving a pressure drop across the PM probe inlet orifice. This solution requires a correspondingly large diluent flow rate to maintain the recommended dilution ratio (i.e., a factor of 10 greater than the sample flow rate). The sample temperature is naturally reduced by its passage through a cooled probe and long unheated sampling line. Sample pressure and temperature measurements are recommended at the inlet of each instrument to assure proper operational parameters during measurements.

3.2.6 Objective 6: Assessment of volatile PM formation during sampling

Researchers believe that volatile particles have not formed at the engine exit plane due to the high temperature of the exhaust. Therefore, volatile particles at the instruments are artifacts of the sampling process caused by gas phase condensation. Gas phase condensation can form new particles and coat non-volatile particles during transit through the sample system. The sampling process should be designed to mitigate these processes. The objective is assessment of sample system conditions that might allow volatile PM formation for understanding and subsequent mitigation during JSF engine testing.

Recommendation 6

There are sample system conditions that can result in volatile particle formation within the sample line through the condensation of volatile gases. During the Methodology Development Test, the dilution ratio was varied to assess its sensitivity on volatile particle formation. The data indicate that condensable gas phase species may have impacted the non-volatile particle measurement results at some engine power level conditions. Measurements of condensable gas phase species were reviewed to quantify microphysical processing through the sampling system, the effects on non-volatile particle measurements and to determine how the effects might be minimized through proper dilution and sample handling. The measured mass-based emission index EIm-nvPM followed a general trend anticipated from previous studies; EIm-nvPM is greater at the engine take-off power than at idle. And as expected, the sample dilution level had little effect on the measurements of EIm-nvPM.

Although new particle formation was observed and believed to be attributed to condensation processes in the sample line (not in the exit plane exhaust), there were negligible effects on integrated mass and volume measurements as a function of dilution level and engine power setting. Comparison of DMA and CPC measurements suggest that the emission index of total particle number (EIn-total) is not affected by new particle formation, but CPC measurements of EIn-total exhibit a surprising dependence on dilution level at the 0.67 normalized fuel flow rate. Gas condensation causes non-volatile particles to acquire coatings during their transit through the sample line. Of the small coating amount, organic materials dominate the mass by a factor of about 10:1 over sulfate material. The organic material contained negligible lubrication oil (<10%). Counter-intuitively, the mass of the organic coating observed at idle conditions increased with increased dilution rate. The trend between EIm-organic and dilution level may be due to deposition of organic materials on the walls of the sample line under low dilution conditions and on the particles at high dilution conditions.

Since these studies support Recommendation 1, from the perspective of volatile particle formation, the recommendation is a dilution ratio of 10:1 or more, especially for low engine power.

3.2.7 Objective 7: Define a field method for sample line penetration, PM instrument calibration and system performance checks.

During each of the former APEX campaigns, there were attempts to perform sample line penetration measurements during field measurements. But often the sample lines were carried back to the laboratory for penetration characterization. A test method needs field-ready processes for sample line penetration, PM instrument comparisons, and calibrations and system performance checks that can be applied intermittently throughout multiple days of testing.

Recommendation 7

A field-ready, transportable system was developed to provide known distributions of particles for sample line penetration, instrument comparisons, and system performance checks. The system was employed and successfully demonstrated during the Methodology Development Test. Improvements were identified that were incorporated before the Validation Test for this project.

3.2.8 Objective 8: Engine Data Representativeness

Emissions from gas turbine engines cannot be assumed azimuthally symmetric. Spatially resolved measurements across the engine exit plane are necessary at several steady-state engine power level settings to represent the emissions from the engine. Highly resolved spatial measurements at each engine power level setting can be costly due to the engine run time required, but are not always necessary. A process should be developed for quickly assessing spatially resolved PM data at predetermined engine power level settings and recommending a reduced set of spatial locations for subsequent engine power settings. The final data set must represent the PM emissions for the engine (engine data representativeness).

Recommendation 8

A method was defined for area-weighted spatial averaging of PM emission factors for each engine power level setting separately and then for all engine power settings combined. If it is necessary (or desired) to reduce the engine run time requirements, it is recommended that a spatial mapping of exhaust emissions parameters be performed at a minimum of two nominal engine power level settings, mid-low and mid-high. The engine manufacturer should be

consulted for selection of proper engine power level settings. The spatially detailed data can be used to define a reduced set of spatial measurements for other engine power levels that should provide comparable averages to high spatial resolution measurements.

4.0 VALIDATION TEST STUDY

The primary objectives of the Validation Test were to (1) demonstrate the IPMTM for PM measurements at the exhaust nozzle exit of a military gas turbine engine in preparation for applications to the Joint Strike Fighter engine, and (2) use the demonstration testing opportunity to address sampling issues that were identified as research issues by the SAE E31 committee. A detailed report of the Validation Test is given in Appendix C.

4.1 TEST CONFIGURATION AND MEASUREMENTS

4.1.1 Test configuration

The Validation Test was conducted on an F100-220 engine at Tinker Air Force Base in Oklahoma City, OK. The test cell layout and test configuration are essentially the same as for the Methodology Development Test described in Section 3.0 and are not repeated here. The differences in the sample system details are discussed in Appendix C. The most notable difference is the probe-rake system hardware. The Validation Test used the AEDC probe-rake system developed specifically for the JSF Program. The probe-rake system is shown installed behind the F100-220 engine in Figure 4.1 (right most structure) along with a schematic showing the configuration of particle sampling probes (“P”), gas sampling probes (“G”) and dummy probes (“X”) for this test.

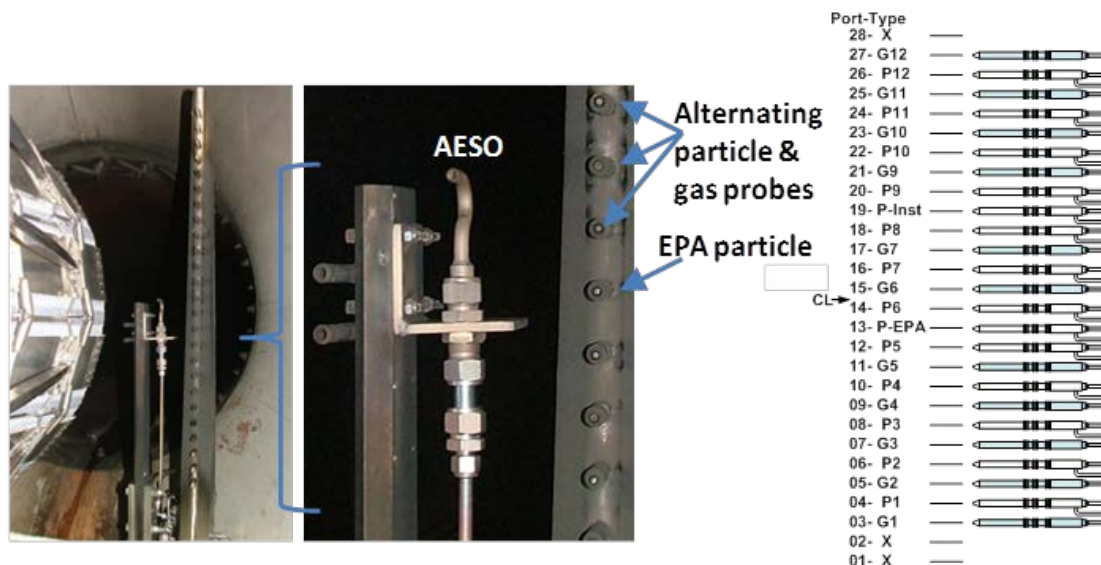


Figure 4.1 Photograph of the rake and probes, looking downstream, and a schematic configuration for the AEDC probe-rake used during the Validation Test.

The AEDC rake has 28 probe ports spaced at 3.81 cm (1.5 in) intervals along the rake structure. Probe ports 1, 2 and 28 were not used for sampling on this test. These ports contained “dummy” probes that filled the port and allowed cooling water to flow properly through the rake. The rake was configured with alternating particle and gas probes except for a particle probe in port 13

dedicated solely to EPA and a particle probe in port 19 that was instrumented with thermocouples. The particle probes have the capability to add dilution gas to the sample near the probe tip as illustrated in Figure 2.2. The gas sampling probes do not have dilution capability and were used primarily for conventional gas species concentration and smoke number measurements.

The sampling parameters were purposely varied in the Methodology Development Test to discern the best practices for mitigation of adverse effects throughout the sampling process on measurements of non-volatile PM. For the Validation Test, the sample system was operated according to the recommendations of the IPMTM and the data analyzed to determine the effectiveness of the sampling procedures. During designated test runs, sampling parameters were varied to acquire data that might further the understanding of issues unresolved during the Methodology Development Test or identified by the E-31 Committee.

4.1.2 Diagnostic measurement systems

The diagnostic measurement systems were essentially the same as for the Methodology Development Test described in Section 3.0 and are not repeated here, except to remark that EPA gravimetric measurements are not reported.

4.1.3 Example data

Example plots of data acquired during the Validation Test are shown in Figure 4.2 through Figure 4.6. The reader must review Appendix C for more comprehensive data and detailed explanations that support the results presented in the next section. As a reminder, the engine power levels are given in NFF where the lowest represents engine idle and the highest represents engine takeoff (non-afterburning). Figure 4.2 shows size dependent sample line particle penetration curves measured at the test facility.

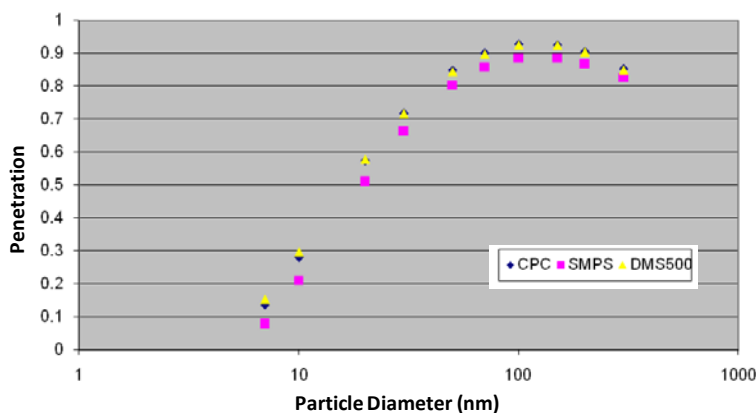


Figure 4.2 Sample train penetration as a function of particle diameter from the probe to the instrument.

Figure 4.3 shows EIn (a) and EIm (b) measured versus sampling rake position during the test. Since the error bars overlap, the measured values between sampling locations is not statistically significant in the core region of exhaust flow (-10 to +10 inches). The points at ± 15 inches appear to be predominantly bypass air as evidenced by their statistically lower values.

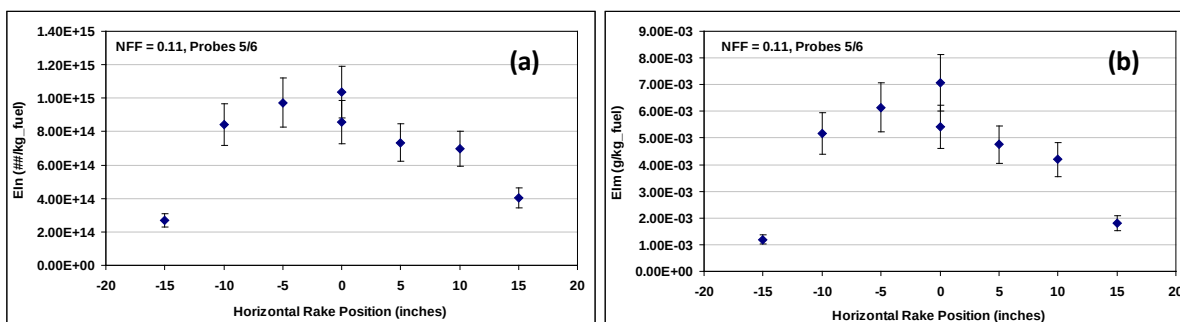


Figure 4.3 EIn (a) and EIm (b) measured versus sampling rake position 2009 Validation Test.

The PM size distributions are determined using differential mobility analysis (DMA) coupled with condensation particle counters. Assuming that the particles are spherical, this technique provides not only number density distribution of the engine PM emissions but also surface area and volume distributions. In agreement with our anticipated observations, the non-volatile particle mode dominates the particle size distribution with respect to number density and volume for all test conditions (Figure 4.4)

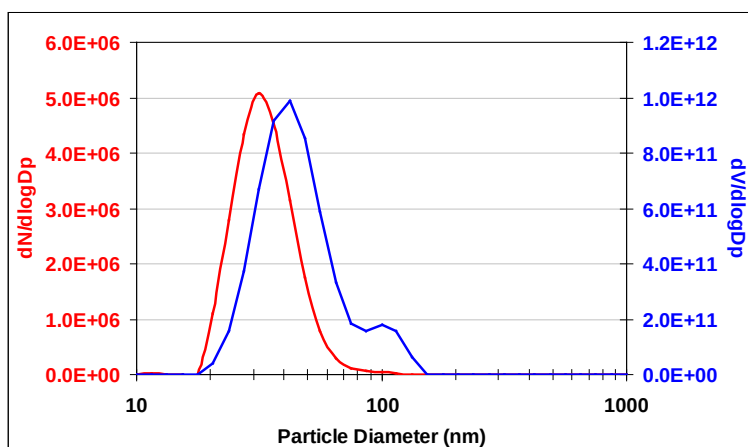


Figure 4.4 Number and volume size distributions for NFF = 0.11.

Measurements of emission indices for formaldehyde (HCHO) and ethene (C₂H₄) at NFF=0.11 as a function of vertical particle probe location at the centerline-rake position are shown in Figure 4.5 for both heated and unheated sample lines. These data indicate that the volatile organic compound (VOC) emission indices do not vary significantly with radial position of the sampling probe.

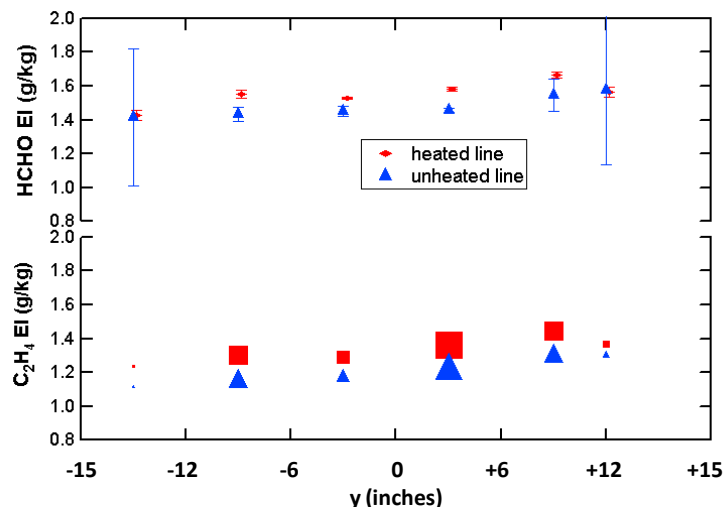


Figure 4.5 HCHO and C₂H₄ EI's versus radial position along the vertical axis at engine centerline.

Assuming the particles are spherical, DMA measurements directly yield information on volume per particle. The mass per particle can be determined from these volumes by assuming a particle mass density (e.g., 1 g cm^{-3}) for non-volatile particles. As shown in Figure 4.6, mass per particle measured from jet engine exhaust increases monotonically with increasing fuel flow rate.

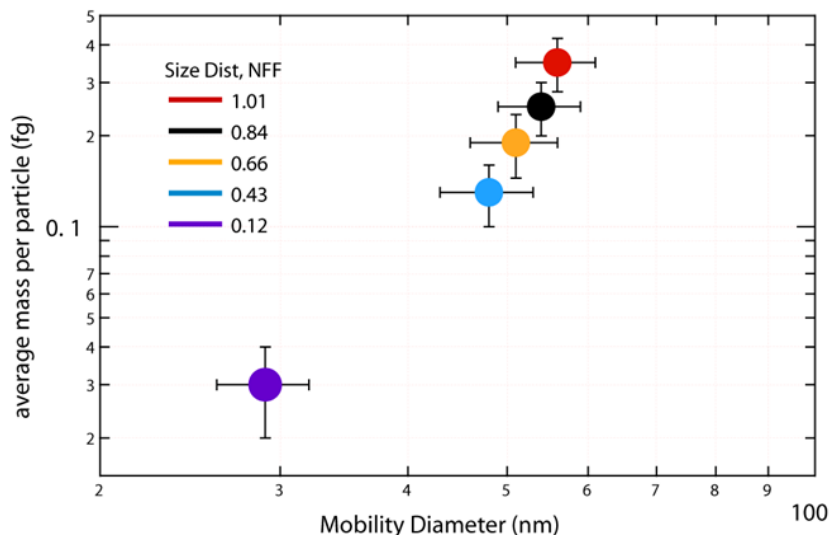


Figure 4.6 Average mass per particle versus mobility diameter with respect to NFF, where average mass per particle is calculated assuming a particle mass density = 1 g cm^{-3} .

Again, these are sample data from the test and the reader is referred to Appendix C for detailed explanation of the results presented in the next section.

4.2 SUMMARY OF THE VALIDATION TEST

- The Validation Test campaign demonstrated that emissions measurements following the prescribed IPMTM gave results comparable to the detailed measurements of the Methodology Development Test.

- EIm-nvPM follows a general trend that is reported in the previous Methodology Development Test; EIm-nvPM reached a maximum at NFF = 0.6-0.8.
- The number and mass based emission indices of the organic component of volatile PM (EIn-vPM_{Organic} and EIm-vPM_{Organic}) are less sensitive to engine power condition than EIm-nvPM.
- Mass density of non-volatile PM, derived from two different methods of measurements, remains independent of normalized fuel flow rate. These measurements give rise to the average mass density of $1.26 \pm 0.49 \text{ g/cm}^3$.
- The particle number emission index (EIn) is maximum at the center of the engine exit plane and remains statistically unchanged throughout the core region. Outside the core flow EIn is statistically lower.
- Highly volatile gaseous species such as HCHO and C₂H₄ are insensitive to radial location within the core flow.
- The semi-volatile naphthalene increases with radial position.

5.0 SUMMARY AND CONCLUSIONS

A test methodology has been developed for the Joint Strike Fighter Program to characterize non-volatile particulate matter (PM) emissions from gas turbine engines using state-of-the-science measurement instrumentation as an alternative approach to the current reference EPA Test Method 5. The IPMTM improves the accuracy of PM emissions reporting, reduces the cost and time required for testing, and includes additional PM properties that are important for human effect studies. The IPMTM is applied at the engine exit plane in a manner similar to current regulatory measurements of gas species and smoke number on commercial engines. This makes it possible to be applied in open air test stands and, although not as desirable, on the wing of aircraft; as opposed to requiring an exhaust duct.

Sampling issues were investigated and the results incorporated into the IPMTM sample system design and operation. PM analyzers were evaluated; a condensation nuclei counter (CNC) is recommended for measurements of particle number density, a differential mobility analyzer (DMA) coupled to a CNC for particle size distribution, and a multi-angle absorption photometer (MAAP) for non-volatile PM mass. These PM analyzers allow real-time data monitoring to better assure quality data for post-test analysis and sample line size-dependent penetration corrections.

The IPMTM was successfully demonstrated during the Validation Test on another military F100-220 engine using the diagnostics and the probe-rake and sampling system hardware developed for future JSF applications. The IPMTM will be applied to the JSF Program for reporting PM emissions and will be available for use on other military engines as necessary to meet PM reporting requirements.

Throughout this project, research findings were reported regularly to the SAE E-31 Committee responsible for developing long-term accepted recommended practices for commercial engine certification using a similar technical approach. Many of the experimental research activities conducted (outside of this project) in hopes of simplifying the sampling system approach also

use measurements conducted according to the IPMTM method as the referee for quality. This is testimony for the success of this project.

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APPENDIX A INTERIM PARTICULATE MATTER TEST METHOD FOR THE DETERMINATION OF PARTICULATE MATTER FROM GAS TURBINE ENGINES

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June 27, 2011

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Defense through the Strategic Environmental Research and Development Program (SERDP) and the Office of the Chief of Naval Operations (N45). It is a pleasure to acknowledge Mr. Bruce Sartwell, Dr. Jeffrey Marqusee, Mr. Charles Pellerin and Mr. Jeff Houff for their leadership and enthusiastic support of this project. We are also thankful to the advisory council for their oversight and advice.

We appreciate the efforts of Mr. William Voorhees, Director of Science and Technology, Propulsion and Power Engineering Department of Naval Air Systems Command, for initiating this effort and Mr. Steven Hartle and Mr. Curtis Kimbel, Naval Air Systems Command, for their administration during the initial phases of this project.

And there are several organizations and individuals with valuable contributions who provided support with planning or technical collaboration. We gladly acknowledge:

Dr. Stephen O. Andersen - US EPA, Director of Strategic Climate Projects, Office of Air and Radiation

Mr. John Kinsey – US EPA Office of Research and Development National Risk Management Research Laboratory; Technical Liaison to the Project, SAE E31

Mr. Triet Nguyen - Navy Aircraft Environmental Support Office (AESO), SAE E31

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LIST OF ACRONYMS

AEDC	Arnold Engineering Development Center
AESO	Aircraft Environmental Support Office (Navy)
AFB	Air Force Base
APEX	Aircraft Particle Emissions eXperiment
ARI	Aerodyne Research Inc.
ATA	Aerospace Testing Alliance
CAA	Clean Air Act
CPC	Condensation Particle Counters
DMA	Differential Mobility Analyzer
DMS	Differential Mobility Spectrometer
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
IPMTM	Interim Particulate Matter Test Method
JSF	Joint Strike Fighter
MAAP	Multi-Angle Absorption Photometer
MASS	Mobile Aerosol Sampling System
Missouri S&T	Missouri University of Science and Technology

NASA	National Aeronautics and Space Administration
PEN	Penetration
PM	Particulate Matter
PTR-MS	Proton-Transfer Reaction Mass Spectrometer
PTFE	Polytetrafluoroethylene
QAPP	Quality Assurance Project Plan
QC-TILDAS	Quantum-Cascade Tunable Infrared Laser Differential Absorption Spectrometer
SAE	Society of Automotive Engineers
SAE E-31	SAE E-31 Aircraft Exhaust Emissions Measurement Committee
SERDP	Strategic Environmental Research and Development Program
TILDAS	Tunable Infrared Laser Differential Absorption Spectrometer

LIST OF TERMS AND SYMBOLS

D_{geomM}	Mass-based Geometric Mean Diameter
D_{geomN}	Number-based Geometric Mean Diameter
D_{va}	Aerodynamic Particle Diameter
E_{Im}	Mass-based Emission Index [g/kg-fuel]
E_{In}	Number-based Emission Index [number/kg-fuel]
LPM	Liters per Minute
M	(Total) particle mass concentration (derived from integral of number size distribution)
$M(N_0)$	Mass of Aerosol per Unit Volume of Exhaust Sample
$M(X)$	Mass of a Substance X per Unit Volume of Exhaust Sample
n	(Logarithmic) differential number concentration
N	(Total) number concentration of the particle size distribution
NFF	Normalized Fuel Flow
Q	Gas flow rate
Δ	Width of the size cut

A-1.0 INTRODUCTION

Changes to the United States Clean Air Act (CAA) require accurate reporting of particulate matter (PM) less than 2.5 micrometers in diameter (PM 2.5) emitted from military aircraft. The EPA provided clear guidance on developing an Interim Particulate Matter Test Method (IPMTM) for the Joint Strike Fighter (JSF) that is more accurate, provides more PM information and is less expensive to implement (reduced engine run time) than the current EPA Method 5. This document describes the interim methodology recommended for measuring and reporting the JSF engine PM emissions while accepted recommended practices are under development by the Society of Automotive Engineers (SAE) Aircraft Exhaust Emissions Measurement Committee (E31).

A-1.1 PRINCIPLE

Particles emitted at the exhaust nozzle exit plane of aircraft are small, typically less than a few tenths of a micron, and result from the combustion of hydrocarbon fuels. These particles are classified as non-volatile PM. Non-volatile particles are comprised primarily of carbonaceous particles (optically black carbon), and metal particles from engine erosion and trace metals in the fuel. The objective of the IPMTM is to provide an accurate measure of the non-volatile particle size, number and mass concentrations in non-afterburning plumes within one half of an exit nozzle diameter. To this end, exhaust products are extracted from the plume through sampling probes specially designed to preserve sampled-particle integrity by affording sample dilution at the probe tip. Dilution of the sample at the point of extraction suppresses modification of the PM through gas to particle conversion, agglomeration and condensation of volatile gases, and reduces sample system particle losses. The diluted exhaust sample is transported through sample lines to a suite of diagnostic instruments located at a safe distance from the test engine. An on-line, near real-time mass measurement system, multi-angle absorption photometer (MAAP), is recommended for measurement of non-volatile particle mass concentration. A differential mobility analyzer (DMA) in combination with a condensation particle counter (CPC) is recommended for measurement of particle size and number, and a secondary indirect measure of mass concentration. A sample dilution gas (dry, clean nitrogen) will help preserve the PM sample integrity, but unfortunately not eliminate particle losses through sample extraction and transport. The sample system throughput losses will be measured as a function of particle size and the particle test data corrected accordingly. For selected power conditions from idle to maximum non-afterburning, spatially resolved data will be acquired across the nozzle exit plane for reporting PM emissions for the engine.

A-1.2 APPLICABILITY

The IPMTM is based on research conducted by the DoD, NASA, EPA, FAA and their contractors. The development of the test method was undertaken with coordination of the SAE E31 Committee. The E31 Committee is actively developing measurement and sampling procedures for PM emissions from aircraft engines for adoption by the United Nations International Civil Aviation Organization as standards and recommended practices to be contained in Annex 16 to the Convention on International Civil Aviation. The new PM test method will be more accurate, provide more particle information and less expensive to implement (through reduced engine run time) than the EPA Method 5, the current reference

method for reporting PM from of military engine emissions. Application of the IPMTM will afford prompt basing of the JSF, save the DOD engine run time and money, and further the science of PM testing. It is anticipated that an EPA approved PM test methodology developed for the JSF will be applied to other emerging military aircraft programs.

A-1.3 ENGINE TEST VENUE

The IPMTM can be applied to engines in test cells (i.e., sea level static test cells, and for limited engine run conditions, in simulated altitude test chambers) as illustrated in a, and, if necessary, on engines mounted to the airframe as illustrated in Figure A-1.1b. The static test cell configuration is preferred because the engine mounting is rigid and engine operating parameters are usually better controlled and more accurately monitored.



Figure A-1.1 Engine test configurations; (a) static test cell, (b) on-airframe.

A-2.0 APPARATUS

A-2.1 OVERVIEW

Emissions measurements for reporting purposes are typically conducted in sea-level static test stands with ducted exhaust as shown in Figure A-1.1a. The discussions in this document will be limited to static test stand configurations. The exhaust duct (diffuser) is typically within a few feet of the engine exit plane and allows access for installation of a sampling probe rake system near the nozzle exit region. The recommended sampling concept for the IPMTM includes a probe-rake, rake-traverse, particle sampling probes, gas sampling probes and the sample line delivery system. Figure A-2.1 shows more detailed photographs of the water-cooled probe-rake system (Figure A-1.1a) and the particle and gas sampling probes that meet recommendations for the PM test method. The blank-off (dummy) probes are used to seal probe ports that are not needed for gas or particle probes for a particular test configuration. This probe-rake system was developed by AEDC to meet JSF F135 and F136 PM measurement requirements.



Figure A-2.1 Water-cooled probe-rake system and sampling probes developed by AEDC for JSF PM measurement requirements.

The Missouri University of Science and Technology (Missouri S&T) in collaboration with AEDC developed the particle sampling system control hardware and software. The sampling components are represented schematically in Figure A-2.2. The linear rake contains 28 sampling ports on 3.8 cm (1.5 in) centers and is attached to a horizontal-mounted, linear traversable table. The probe configuration as shown has alternating particle and gas sampling probes, but gas and particle probes are interchangeable at either probe location. Conventional gas measurements are not required for the characterization of PM, but are recommended to verify proper engine combustion performance during the PM measurements. The rake-sampling probes vertically span the diameter of the nozzle exit plane. Detailed measurements across the nozzle exit plane are obtained by stepping the rake to fixed horizontal locations across the nozzle. At each fixed position, measurements are performed at vertical probe positions along the rake.

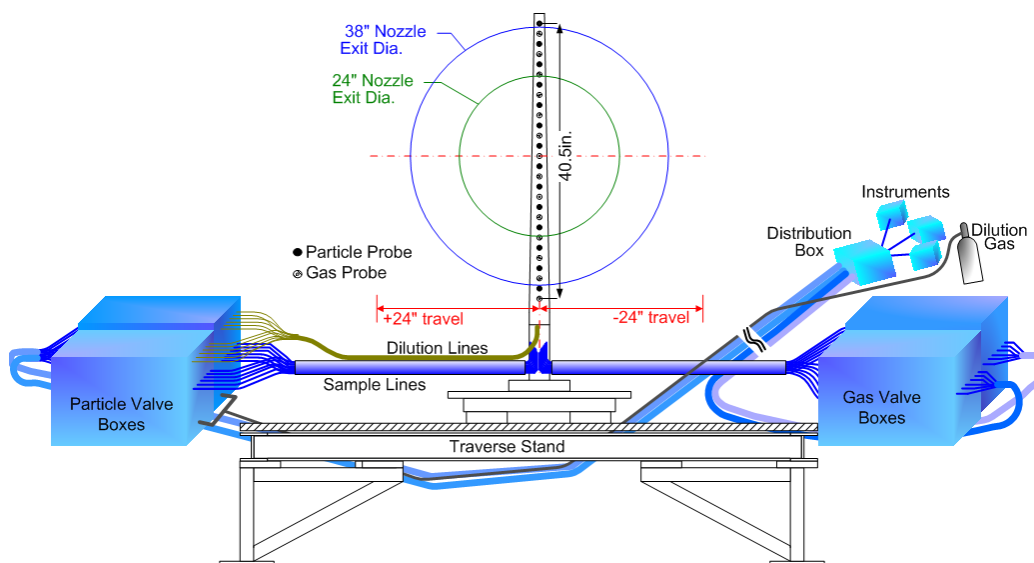


Figure A-2.2 The AEDC and Missouri S&T sampling components.

Alternatively, detailed mapping of the nozzle exit plane could be achieved by using a single probe mounted to a 2-dimensional traverse mechanism. A disadvantage could be the inability to group (or gang) two or more probes to achieve a higher sample flow rate, if needed, or to

measure a spatial average for selected power conditions and to reduce overall engine run time. On previous test programs, it has never been necessary to gang more than two particle probes to achieve adequate flow, and only at the lowest engine power level.

For the sampling configuration illustrated in Figure A-2.2, the exhaust gas upon entering a particle probe mixes with a diluent gas (particle-free, dry N₂) and continues through a sample line to a probe selection box (valve box). Each valve box has multiple input lines, but only one output line, referred to as the main trunk line. The valve boxes allow remote selection of one or more probes to be sampled at a given time. Locating the valve boxes near the rake greatly decreases the number of long sample lines required to reach the instruments that might be up to 30 meters away. The sample exhaust from each probe not selected is directed to a vent pump and vented to the atmosphere; or, the vent pump is replaced by a nitrogen gas supply and the lines are back purged to prevent exhaust from entering at the probe tip. If one or more probes are selected for sampling, the diluted exhaust samples mix and travel via the main trunk line to a distribution box near the instruments. If more than one valve box is used, valves in the inlet of the distribution box are remotely actuated to select the main trunk line to be sampled. The distribution box is also used to distribute the sample to multiple instruments. A separate dilution controller box contains mass flow controllers for controlling the dilution flow to the probes.

A-2.2 SAMPLING TRAIN

A-2.2.1 Probes

A-2.2.1.1 PM Probes

The goal of the sampling system is to provide a continuous sample of exhaust gas to analyzer instrumentation while preserving the integrity of the sampled gas. There seems to be a general consensus among the scientific community that diluting the sampled gas with a particle-free gas minimizes particle-to-particle interactions, gas-to-particle conversion, chemical reactions and particle diffusion losses to the wall (AIR6037). It is therefore advantageous to introduce the diluent to the sampled gas as close to the probe tip as possible. Several additional factors were considered in the particle probe design and recommendations herein. Consideration was given to the mixing of the particle-laden extracted stream with the diluent gas to minimize particle loss to the internal surfaces of the probe by turbulent mixing of the two streams. Also the mixing region within the probe was designed to enhance the sample pumping action toward the sensing instrumentation while inhibiting the tendency for diluent gas to be discharged out of the probe tip. Isokinetic sampling, obtained when the velocity of the sample stream into the probe tip is equal to the exhaust free-stream velocity, was considered and can be achieved only over a small range of engine operating conditions; and only if proper pressures and flow rates are maintained operationally. For a fixed geometry probe, isokinetic sampling is not practical: (1) over the full range of engine thrust settings from idle to full power, (2) over the varied range of diluent requirements and (3) due to the potential need for ganging multiple probes. Since gas turbine exhaust particles are typically less than 200 nm in diameter, they tend to follow flow streams, and thus isokinetic sampling is not considered necessary (AIR6037).

The effects of probe temperature on the sampled gas have not been quantified to date due to experimental difficulty. Laboratory studies cannot simulate the inlet temperature and pressures of turbine engine exhaust, and turbine engine exhaust studies make it almost impossible to distinguish effects of the probe temperature versus effects due to sample line or other sampling

parameters. The probe-rake system used in APEX, JETS-APEX2 and Delta Atlanta Hartsfield studies employed active water cooling to the rake and probes (Lobo et al., 2007a, b; 2008). The probe-rake system for APEX3 was not actively cooled and the investigators noted anomalies in the measurements of chemical species and PM data that might be attributable to the uncooled rake and probes. However, it should be noted that the overall sampling system design for APEX3 resulted in the rake structure, probes and several feet of sampling line being elevated to temperatures approximately equivalent to the total exhaust flow temperature ($> 600\text{ }^{\circ}\text{C}$), not just over the short 15 to 25 mm probe length as in other test programs. The anomalies in the APEX3 data and subsequent issues arising from heated line particle transport during the April 2007 Methodology Development Test (Appendix B) have led the investigators to recommend water cooled probes for this IPMTM when applied to the high temperature exhaust of the JSF F135 engine.

AEDC developed a particle sampling probe, Figure A-2.3, designed to address PM sampling issues. This probe design has been used in numerous scientific turbine exhaust characterization studies conducted at or by AEDC, NASA, Missouri S&T, Aerodyne Research, Air Force Research Laboratory, EPA, Pratt & Whitney, and General Electric. The probe concept is considered state-of-the-art based on current understanding and experience in turbine exhaust sampling, and is recommended for the IPMTM. The cross-sectional view in Figure A-2.3 illustrates the conceptual design. The sampled exhaust gas enters the 0.1 mm (0.040") diameter tube at the probe tip, travels 38 mm (1.5") through the length of the tube and enters the 6.4 mm (0.25") i.d. main sampling tube. The diluent gas enters from the rear of the probe, travels to the probe tip, and turns as it enters the main sampling tube. The diluent gas travels along the sample inlet tube allowing the flow to straighten before "gently" mixing with the sample flow in the main sampling tube.

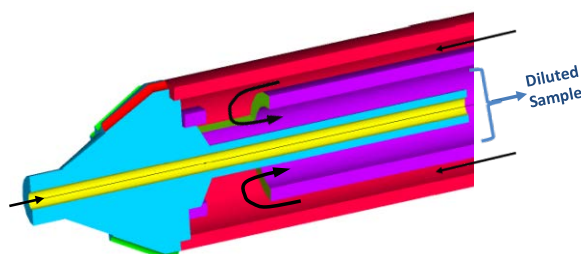


Figure A-2.3 Cross-section view of the particle probe sampling concept.

Not illustrated in the figure, the outer sheath has a series of water channels along the length of the probe for cooling to maintain structural integrity in harsh environments. Except for the tip of the probe, the sample tube is not in direct contact with the water cooled sheath.

A-2.2.1.2 Other probes

Figure A-2.1 shows conventional gas sampling probes used for measurements of gas species concentrations and smoke number following the measurement protocol set forth in ICAO ANNEX16. The gas probes are water cooled but do not have sample dilution capability. Blank-off (dummy) probes are used to occupy ports not needed for gas or particle sampling probes.

A-2.2.2 Sample Probe-Rake System

The rake is the structure used to hold sampling probes in the exhaust flow field. The IPMTM requires no special rake design criteria other than extending spatially across the exhaust plane

and sufficient structural integrity for the expected flow-field properties as defined by the exhaust temperature, pressure, gas velocity, and radial extent of the plume. Water cooling of the rake structure is optional, as long as the probes are cooled and the rake is structurally sound for engine exhaust conditions. The AEDC probe-rake system (Figure A-2.1) has water supplied to the rake and probes. The rear cover plates, used to protect the sample lines from the harsh turbine exhaust, are also water cooled. Care must be taken to assure that the exhaust sample temperature in the rear rake section does not drop below water condensation temperature. Typically, AEDC heats the gas sampling lines in this section of the rake. Diluting the sample in the particle probes prevent water condensation in the particle sample lines.

The AEDC probe-rake system shown in Figure A-1.1 (a) was designed to span the nozzle exit diameters of large military engines. The rake has 28 sampling ports spaced at 38 mm (1.5 in) with the first probe port located 30.5 cm (12 in) above the rake base plate. Twelve particle probes on 7.62 cm (3 in) centers alternated with 12 gas probes on 7.62 cm (3 in) centers will span the engines of interest to the military with both probe types. The rake body is made from stainless steel and has water cooling channels over the entire front and side surfaces just below a nickel-plated skin. Two large channels run the length of the rake for supplying cooling water to the probes and returning the water to a dump line. The large water passages are sealed at the probe ports by o-rings on the probes as shown in Figure A-2.1. The system design allows either probe type (gas, particle or blank-off) to be installed at either probe port location.

A-2.2.3 Rake Traverse Stand

The traverse system, illustrated in Figure A-2.2, has a slide table attached to a linear worm drive turned by a computer controlled stepper motor that allows remote positioning of the rake at discrete locations across the nozzle exit plane. The traverse system allows 1.22 meter (4 feet) horizontal travel and is capable of traversing the rake across the exit plane, and out of the exhaust flow stream during engine startup. The traverse table and stand are designed to carry the weight of the probe-rake system and withstand the load produced by the exhaust onto the probe-rake system hardware. The computer control positioning accuracy of the rake is ± 0.25 mm.

A-2.2.4 Particle Probe Operation

There is no hard requirement for the method of controlling the particle probes. If a multi-probe rake is employed, there must be a method to select individual probes for sampling. Care should be taken to prevent fuel-rich contamination of the sampling system during engine startup. Also, stagnation of exhaust sample in the sampling line should be avoided. The probe operation sampling methodology used for the field-test studies during the development of the IPMTM is described in this section meet these criteria.

The sample control system developed to complement the AEDC probe-rake system accommodates 12 particle and 12 gas sampling probes using 2 valve boxes for each type to keep the box weight and size manageable. There are separate valve boxes for gas and particle probe sampling lines due to different sample line requirements. Individual probes are selected for sampling using individual, remotely actuated, three-way valves. Sample from a selected probe is directed to the main trunk line while sample from the remaining probes is either directed to a vent pump and dumped to atmosphere, or prevented from entering the sampling system by purging a gas back through the sample line and out the probe tip.

Since the particle probes require a dilution gas, separate valves in the particle valve boxes are activated to connect the primary dilution line to the selected particle probe. A dilution gas controller, located near the instruments, is used to set the amount of diluent flow to the individual particle probes. The diluent flow rate to the selected probe is adjusted for each sampling condition (probe location and engine power) to achieve the recommended sample dilution ratio.

A-2.2.5 Probe Ganging

Probe ganging refers to sampling from two or more probes simultaneously. Probes are ganged for two reasons: (1) low engine power settings may not provide sufficient ram pressure to get the required sample flow rate from a single probe, and (2) ganged probe samples at prescribed power settings can reduce the engine run time and thus the expense of the test program. When ganging particle probes, it is necessary to maintain the nominal dilution ratio for each particle probe individually; otherwise water condensation and volatile PM formation can occur, especially for unheated particle sampling lines. A preferred method for ganging particle probes is the use of separate mass flow controllers for the dilution line to each particle probe to be ganged, and monitoring the individual dilution flow rates as well as the total sample flow reaching the instruments.

A more expedient but less certain method for ganging the probes is the use of a single mass flow controller on the dilution gas supply to multiple particle probes simultaneously. In the latter method, it would be necessary to validate pretest that dilution flow rates are the same for each probe over the range of dilution supply pressures and probe tip exhaust gas pressures that are expected during the test. Since detailed procedures have not been formulated and this method validated, it is not recommended for the IPMTM.

Ganging probes by any method requires attention to the fact that spatial variations in exhaust ram pressure will alter the dilution ratio from tip to tip. Therefore, to avoid this issue for the IPMTM, it is recommended that ganged sampling be used only if there is insufficient flow rate from a single probe; and thus ganging only closely-spaced adjacent particle probes with nearly equivalent exhaust ram pressures.

A-2.2.6 Sample Lines

A-2.2.6.1 Design Characteristics

Sample line heating experiments conducted during the Methodology Development and Validation Tests (Appendix B and Appendix C) produced unexplained results. The penetration of particles decreased when the sample lines were heated to 150 °C as compared to unheated lines at ambient temperatures around 25 °C. The measured penetration of unheated lines follows trends expected by physics models that are accepted by the particle measurement community. Until research studies are conducted to understand the “actively heated” sample line data, active sample line heating is not recommended for the IPMTM as long as the ambient temperature is 25 ± 15 °C during measurements.

Sample lines are specified in four segments, but with overall stipulations that follow:

- Segment 1: Probe exit to the base of the rake
 - Length ≤ 2 m
 - Stainless steel
 - Internal diameter ≥ 3.8 mm (0.15 in)

- Segment 2: Base of the rake to the particle valve box
 - Length ≤ 4 m
 - Stainless steel preferred; but optional flexible conductive PTFE to allow traversing
 - Internal diameter ≥ 7.6 mm (0.30 in)
- Segment 3: Particle valve box to the distribution box (main trunk line)
 - Length ≤ 30 m with a residence time ≤ 6 sec (calculated time for plug flow)
 - Stainless steel preferred; but optional flexible conductive PTFE to allow traversing
 - Internal diameter ≥ 12.7 mm (0.50 in)
- Segment 4: Distribution box to the instruments
 - Length ≤ 3 m
 - Stainless steel
 - Internal diameter ≥ 7.6 mm (0.30 in)
- Overall: The total sample line length from probe tip to the instruments should be as short as possible but not exceed 35 m and a sample residence time of less than 8 sec (calculated time for plug flow). All stainless steel lines should be seamless and have a minimum number of bends, fittings and valves. All valves should be full-bore (i.e., the internal diameter of the valve matches as much as possible the internal diameter of the tubing). All bends should have radius of curvature greater than 10 sample line diameters.

A-2.2.6.2 Sample System Operation

Trade-offs must be considered in sample system operation to balance sufficient dilution to mitigate new particle formation and condensation of volatile gases within the sample system, but maintain a sufficient concentration within the detectable range of the PM analyzers. Following are sample system recommendations:

- The valve box should be located near the rake with remotely actuated valves to select the probe(s) to sample.
- A mass flow controller on the dilution line allows faster and more accurate control of the dilution level.
- Sample line segments for probes not sampled should be back purged with nitrogen gas,
- The extracted exhaust sample should be diluted with dry, particle-free (HEPA-filtered) nitrogen near the probe tip,
- Sample lines must be leak checked from the probe tip to the instrument and demonstrated to yield less than 5 particles/cc measured with a CPC when drawing ambient air through a HEPA filter at the probe tip.
- Sample line penetration as a function of size should be measured and must be greater than 80% for particle sizes greater than 80 nm. Full penetration should be performed pre- and post test.
- Sample line integrity with respect to leaks and penetration should be checked at least on a daily basis
- The CO₂ concentration on the diluted and undiluted sample lines should be measured and monitored for real-time assessment and recording the dilution ratio.
- Dilution ratios from 10 to 20 are recommended; the higher dilution ratios (approaching 20:1) are preferred and usually achievable at low engine power (idle) and help maintain a smaller

sample residence time; lower dilution ratios are acceptable at high engine power conditions where precursors are minimal. Overall, recognize the tradeoff in sample system operation to balance sufficient dilution to mitigate new particle formation and condensation of volatile gases within the sample system, but maintain a sufficient concentration within the detectable range of the PM analyzers. The dilution ratio should never be allowed to drop below a level that would allow condensation of water in the sample line; typically in the range of 4 to 6.

- Through dilution, the particle concentration should be kept to below $5 \times 10^6 \text{ cm}^{-3}$ to avoid particle coagulation effects in the sample line.
- If multiple probe tips are sampled simultaneously (ganged), the specified dilution ratio must be maintained per probe tip.
- Sample line pressure at the instrument end of the sample line should be maintained between about 0.85 and 1.02 atm; venting excess flow at the instrument end of the sampling system.
- Active heating of the sample lines is not recommended as long as the ambient temperature during measurements is $25 \pm 15 \text{ }^\circ\text{C}$.

A-2.3 DILUTION SYSTEM

A-2.3.1 Diluent Gas (N₂)

Although dry air is considered acceptable for diluting the sampled exhaust, N₂ has been used for most of the research efforts conducted to-date and is recommended for the IPMTM. The N₂ can be provided from gas bottles or evaporated liquid N₂, but must be dry and particle free.

A-2.3.2 Dilution Lines

The dilution lines are used to transmit particle-free N₂ diluent gas to the particle probes to mix with the sampled exhaust and must not introduce particles. Stainless steel and Teflon® materials are recommended for the IPMTM, but must be clean. The length and diameter must be sized to transmit the required flow.

A-2.3.3 Pump for Dilution System

The N₂ based dilution system does not require pumps or pressure gauges. The gas bottles and liquid evaporation systems provide ample head pressures to drive delivery of the N₂.

A-2.3.4 Dilution Ratio Adjustment System

There are no hard requirements for the method of controlling the dilution ratio. For the diluent control system developed during the Methodology Development Test (Appendix B), the diluent flow adjustment is handled by an open loop electronic flow controller, which receives control signals from a computer. An operator initially sets a desired diluent flow rate and adjusts this rate for a given engine condition until the diluted CO₂, particle concentrations, and other gas species concentrations are within desired ranges. This generally brings the dilution ratio (undiluted CO₂ concentration / diluted CO₂ concentration) to a value around 10 to 1. Typical N₂ delivery systems with a flow rate of about 120 LPM will provide ~ 20 to 1 dilution ratios at low engine power conditions (non-afterburning) for JSF type engines. The probe experiences high ram pressures at high power conditions which drive increased sample flow through the probe tip orifice. Hence the maximum diluent flow rates (not ratios) are required at high engine power. The stability of the dilution system can be quantified by the ratio of the standard deviation of the diluted CO₂ to its average, for each engine condition. For JSF type engines, this ratio is expected to have average and maximum values ~ 0.0074 and 0.047, respectively.

A-2.4 INSTRUMENTATION

A-2.4.1 Particulate Matter Species

The Condensation Particle Counter (CPC) and Differential Mobility Analyzer (DMA) instruments are recommended for PM size and number characterization. These instruments have been deployed previously during gas turbine engine field tests and have been proven to provide accurate and reliable data. (Hagen et al., 1994, 1995, 1997; Whitefield et al., 2002; Wey et al., 2006). The Multi-angle Absorption Photometer (MAAP) [Petzold and Schonlinner, 2004; Petzold et al., 2005] is recommended for PM mass characterization.

CPC: Saturator-condenser type Condensation Particle Counters (CPCs) are generally used for concentration measurements. Typical models are TSI 3022A and 3025A (Section A-5.1).

DMA: Commercial Differential Mobility Analyzers (DMAs) are available from several vendors, e.g. TSI (St. Paul, MN), Hauk (Vienna), and Grimm (Douglasville, GA – US office). Typical models are TSI 3071 or 3081 (Long), TSI (short), TSI 3085 (nano), used in the scanning mode (Section A-5.2).

MAAP: Black Carbon (BC) PM mass was measured using a Thermo Electron Multi-Angle Absorption Photometer (MAAP) [Petzold and Schonlinner, 2004; Petzold et al., 2005]. The MAAP measures particulate black carbon by collecting aerosol onto a 2 cm² quartz fiber filter tape. The transmission and scattering of 630 nm wavelength LED light are monitored by multiple photodetectors. A two-stream radiative transfer calculation separates the scattering from the absorption component for the total particle loading on the filter tape. The instantaneous loading is computed by the derivative of the total.

A-2.4.2 Conventional Gas and Smoke Number Measurement Instrumentation

Non-volatile particle characterization measurements are the primary purpose for the development on the IPMTM. However, a local measurement of the conventional gas species (CO₂, CO, NO, NO_x, total hydrocarbons (THC) and smoke number (SN)) provides local combustion efficiency and allows comparison to the engine manufacturer's emissions database to confirm normal performance behavior for this particular engine. These measurements are performed on an undiluted probe and sampling line system. The CO₂ concentration measurement in the undiluted sample here will be compared to a measure of CO₂ in a neighboring particle (dilution) probe to quantify the dilution ratio in the particle sampling line.

Table A-2.1 lists the typical measurement techniques sanctioned by SAE E31 for commercial engine certification measurements. The MultiGasTM Analyzer (MGA) is listed in the table as an acceptable alternative for the purpose of these measurements, but has not yet been accepted by SAE E31 as an accepted practice for commercial engine certification measurements. The MGA instrument uses Fourier transform infrared (FTIR) spectroscopy through a multi-pass absorption cell and is under consideration by the SAE E31. Smoke number measurements are made using a standard filter-based technique and procedures defined in the SAE Aerospace Recommended Practices (ARP) 1179 and ICAO ANNEX16.

Table A-2.1 Instruments for conventional gas species and smoke number measurements.

Analyzer Type	Species Detected
Non-dispersive Infrared	CO ₂
Non-dispersive Infrared	CO
Chemiluminescence	NO
Chemiluminescence	NO _x
Flame Ionization Detector	Total Unburned Hydrocarbons
MultiGas TM Analyzer (MGA)	CO, CO ₂ , NO, NO ₂ , H ₂ O
SAE Smoke Meter	Smoke Number

A-2.4.3 Trace Gas and Volatile Particle Measurement Instrumentation

As stated in the previous section, non-volatile particle measurement is the primary purpose for development of the IPMTM. But measurements of trace gas and volatile particle properties provide a check that the engine, exhaust gas extraction probe, and sample delivery system are all operating properly. These measurements are performed on the diluted particle line, are usually fast (1 Hz or faster update rate), and can provide real-time feedback for quick determination of engine and sample line stability thereby improving data quality and mission economy. These data identify periods of unstable operation or sampling that can justify removal of PM data during posttest data processing.

Table A-2.2 lists the instruments typically deployed during emissions testing of gas turbine engines. Concentrations of gas phase species are measured using several non-dispersive infrared sensor (Li-Cor) for CO₂, a chemiluminescence analyzer (for NO/NO_x, where NO_x is defined as the sum of NO and NO₂), a proton transfer reaction mass spectrometer (Knighton, 2007) (PTR-MS, e.g., benzene, alkylated benzenes, styrene, and naphthalene), and two quantum cascade tunable infrared laser differential absorption spectrometers (Nelson, 2002) (QC-TILDAS for HCHO, NO₂, C₂H₄, CO). All of the trace gas instruments have been deployed previously during gas turbine engine field tests and have been proven to provide accurate and reliable data (Herndon et al., 2004; Herndon et al., 2006; Knighton et al., 2007; Timko et al., 2008; Wood et al., 2008; Wormhoudt et al., 2007; Yelvington et al., 2007).

Table A-2.2 Trace Gas Instruments Deployed during the F100-220 Engine Tests.

Instrument	Species Detected	Detection Limit^a	Time Resolution
Licor 6262 Licor 820	CO ₂ CO ₂ (high range)	300 ppb 2 ppm	1 sec
NO _x Chemiluminescence Analyzer ThermoElectron (model 42C)	NO NO _x ^b	0.5 ppb 0.5 ppb	1 sec/20 sec 20 sec
QC-TILDAS ^{c,d}	NO ₂ C ₂ H ₄ CO HCHO HONO	0.5 ppb 2 ppb 2 ppb 1 ppb 2 ppb	1 sec 1 sec 1 sec 1 sec 1 sec
PTR-MS ^e	acetaldehyde, propene, benzene, toluene, styrene, C ₂ -benzene ^f , phenol, naphthalene, methylnaphthalene, dimethylnaphthalene	2-5 ppb	8 sec

^a Detection limits are quoted as 2 times instrument noise level.

^b The measurement of NO_x using catalytic reduction of NO₂ to NO (most chemiluminescence analyzers) also measures higher nitrogen oxides such as HNO₃, HONO, and organic nitrates.

^c quantum-cascade tunable infrared laser differential absorption spectrometer (Aerodyne Research, Inc.).

^d tunable infrared laser absorption spectrometer (Aerodyne Research, Inc.).

^e proton-transfer reaction mass spectrometer.

^f C₂-benzene includes *o*-xylene, *m*-xylene, *p*-xylene, and ethylbenzene.

A-2.4.4 Ancillary Instruments

The necessary ancillary equipment and are given in Table A-2.3.

Table A-2.3 List of ancillary equipment.

Item #	Name	Description	Manufacturer	Model Number
1	Ice Bath	Removes excess water vapor from the sheath air flow to the DMA	Various manufacturers	
2	HEPA Filter	Removes particles before instrument	www.whatman.com	6700-7501
3	Mass Flow Controller	Controls sample and diluent flow	www.mksinstruments.com	1179 and 247D
4	Vaisala RH	Measures Relative Humidity	www.vaisala.com	HMP235 or HMP247
5	Calibration gases	Calibration gas for CO ₂ detectors	www.mathesontrigas.com	
6	Pressure Gauge	Pressure Gauge & Transmitter	www.Cecomp-usa.com	F4L100PSIA
7	Intercom	Communication between operators	www.sigtronics.com	

A-2.4.5 Volatile Particle Measurement Instrumentation

The objective of the IPMTM is to accurately measure the non-volatile particulate matter from the exit plane of gas turbine engines. Volatile particles do not exist at the exit plane (AIR6037), but are observed at the end of the sampling line, indicating that these are artifacts of the sampling system. Volatile particles introduce error for instruments that detect, but do not distinguish, volatile and non-volatile particles. The approach in the IPMTM is using sampling methodology that mitigates volatile particle formation and condensation of volatile gases during sample transport. Therefore it is recommended to have a measure of volatile particulate matter as an indicator that the sampling system operation keeps volatile particle formation to acceptable levels throughout the non-volatile PM characterization. The recommended instrument for this is the Aerosol Mass Spectrometer (AMS).

A-2.4.6 Aerosol Generation System

An aerosol generation system that produces a size selectable, monodisperse source of aerosol is necessary for particle sample line penetration characterization measurements. A description of the aerosol generation system for sample line penetration testing is given in Section A-5.3.

A-2.5 REAL-TIME DATA QUALITY ASSURANCE

When possible, measurement data should be recorded and displayed in real time to assure data are acquired during stable engine and sample system operation. Fast response particle size instruments (e.g., Cambustion DMS500) display size distribution in real time. Monitoring measured PM properties and size distributions permits instrument operators to select optimal dilution conditions, minimize particle-to-gas conversion in the sampling line. To further improve

data quality control, data streams from the various instruments should be merged and displayed simultaneously on the same monitor. Side-by-side comparison permits rapid visual confirmation of data quality.

A-3.0 TEST MEASUREMENT PROCEDURE

A-3.1 INTRODUCTION

This section describes the procedure for non-volatile PM measurements in the exit plane of the exhaust nozzle of a military gas turbine engine, mounted in a test cell, in conjunction with existing protocol for combustion gas sampling for the JSF F135 engine. The procedure depends on the sample extraction system and diagnostic suites described in Section A-2.0. These measurements will provide a spatial measure of the non-volatile PM emissions near the exit plane for a range of engine operating conditions.

A-3.2 PRE-TEST ACTIVITIES

A-3.2.1 Leak checking / sample line integrity

Two experimental tests are recommended to verify sample train integrity prior to testing. (1) Seal the front and rear ends of the sample system and evacuate to approximately 8 psia using a vacuum pump. Close the pump valve and monitor the pressure in the sample system. A pressure increase of ≤ 0.5 psi/min is acceptable. (2) Operate the sample system and analyzers pulling ambient air through an absolute particle filter mounted at the probe tip. Dilute the sample with particle free dry nitrogen at a ratio of 8 to 1 and set the flow rate through the sample line to that anticipated for the test campaign. Measure the particle concentration at the normal CPC instrument location. A particle concentration of $\leq 100 / \text{cm}^3$ is acceptable. Passing these tests indicates the system is leak-free and not emitting particles from the sample line wall. If the sample train shows evidence of leaks, the line can be pressurized and checked for leaks in the normal way. If the line is emitting particles from the internal wall, the line must be cleaned or replaced.

A-3.2.2 Diagnostic Instrument Calibration

A-3.2.2.1 Condensation Particle Counter

Calibration of the CPC involves three facets of experimental activity relating to performance:

(1) Validation of the smallest particle size that the instrument can measure: The CPC condenses fluid on small particles to grow them to a sufficiently large size so that they can be seen optically and counted. The counting efficiency of a CPC falls off at the small diameter end of the particle size spectrum. The point at which the counting efficiency falls off to 50% is reported as the small size cut-off for the instrument. Experimental determination of the lower limit cut-off diameter to the initial sized particle that can be sufficiently grown by condensation is described in Section A-5.4.

(2) Validation of the particle counting performance over the main (fundamental) part of the concentration measurement range: Over the fundamental range of concentration (total particle concentration $< 10,000$ p/cc), the CPC operates in single counting mode (SPC). The CPC can be calibrated using an electrometer as the reference as described in Section A-5.4.

(3) Validation of the upper particle concentration measurement range: When the total particle concentration to the CPC exceeds $\sim 10,000$ p/cc, CPC switches from SPC to photometric mode and must be calibrated in that regime as described in Section A-5.4.

A-3.2.2.2 DMA

The DMA (Differential Mobility Analyzer) is an instrument that measures particle size distributions (particle concentration versus size) using electrical mobility. The DMA must be calibrated for (1) static operation in which the instrument is held at fixed particle size and size is the sole issue, and (2) dynamic operation in which the instrument temporally sweeps through the range of particle size and yields concentration versus size information. The static mode of operation is of concern when the instrument is used to provide a monodispersed size distribution for the calibration of other instruments, or for line penetration measurements. It does not come into play when the instrument is used for its primary task of measuring size distributions. Details of DMA calibration methods are given in Section A-5.4.

A-3.2.3 Dilution System

The dilution system should be tested for leaks by sealing a particle probe tip, closing the corresponding sample line, and pressurizing the system to approximately 20 psia for that probe. After closing the gas source valve, a pressure change rate of ≤ 0.5 psi / min is acceptable. At ambient pressure with the probe-tip open, the dilution system should be validated to have the ability to deliver 120 LPM of diluent to the sample train.

A-3.2.4 Line loss estimations

The long sample lines used in jet engine emissions testing invariably suffer significant aerosol line loss that should be taken into account. Experimental determination of the size dependent penetration function for the sample line (probability that a particle entering the front of the sample line is able to pass through the line and exit from the line's end) is recommended. For a given particle size, the penetration is determined by measuring the concentration of particles exiting the sample line for a known (measured) monodispersed size aerosol delivered to the front of the line. The ratio (concentration entering/ concentration exiting) per size gives the size dependent penetration function. The detailed method is discussed in Section A-5.5. The sample line penetration function should be experimentally measured before the engine emissions test and then spot checked at least daily.

A-3.2.5 Quality control

A document called the Quality Assurance Project Plan (QAPP), Appendix D, has been generated as a guide for quality control during implementation of the IPMTM described in this document.

A-3.2.6 Sample train operation

A-3.2.6.1 Sample Line Pressure and Control

Most analyzer instruments are designed to work at ambient atmospheric pressure. The sample handling system must deliver particle laden gas to the instruments at near atmospheric pressure. Further, changes in particle microphysical processing (e.g., particle wall loss, coagulation, condensation/evaporation, new particle formation) may result if the sample pressures deviate too much from atmospheric pressure, thus reinforcing the need for a standard measurement pressure. For most measurement situations, sample line pressure at the instrument end of the sample line

should be maintained between about 0.85 and 1.02 atm. Instrument operational procedures are typically followed to adjust the measurement for variations within this range of pressure.

Also, the dilution gas flow can be varied to partially offset changes in sample line pressure. Control of sample line pressure is complicated by the fact that total (static + dynamic) pressure in the exhaust gas varies significantly from low power (idle) conditions to full power (take off) engine operation. For a fixed probe orifice size, the sample stream flow rate entering the probe can increase by 100% or more over this engine power range. Typically, at higher engine powers, excess flow is vented to stabilize the pressure at the inlet of the instrument. But, since the exhaust gas sample flow rate into the probe determines the amount of dilution gas required for a constant dilution factor (nominally 10 to 1), there can be tradeoffs. Fortunately, some variation in dilution factor is desirable; typically more dilution is preferred at low power where higher exhaust gas concentrations of condensable species tend to form unwanted volatile particles. During development of the IPMTM, it was not unusual to achieve greater than 15 to 1 dilution at the idle power setting. This helped stabilize the sample pressure at the inlet of the instrument and aided in mitigating unwanted volatile particle formation in the sample line.

A-3.2.6.2 Sample Line Temperature and Control

For certification measurements of conventional gas species and smoke number, ANNEX16 specifies that sampling lines are heated to 160 °C to prevent water condensation. For particle sampling, there is an additional concern for condensation of other low-vapor pressure gaseous species that can form undesirable volatile particles during sample transport. The addition of a diluent gas for particle sampling reduces the requirement for elevated line temperature by preventing supersaturation as the sample cools to a lower temperature. However, even with a 10:1 dilution, very cold temperatures could cause supersaturation in the sampling line. Unfortunately, sample lines heated to a temperature of 160 °C have been shown to enhance particle loss (Appendix B and Appendix C). Until the reasons for the enhanced loss are understood and mitigated, it is recommended that PM measurements be conducted using a dilution ratio greater than 8:1 and the sample lines maintained at a constant temperature 25 ± 15 °C. This will avoid supersaturation of water while minimizing particle wall loss.

For much of the research prior and during development of the IPMTM, exhaust sample extraction probes were typically water cooled. Some experimental evidence (Timko et al., 2008) suggests that failure to cool the exhaust gas extraction probes may result in inter-conversion of NO and NO₂. To minimize potential chemical reactions, it is recommended for the IPMTM that the gas and particle extraction probes be cooled. No studies have been performed to determine the optimum probe-tip temperature for particle measurements. Therefore, it is recommended that probes for the IPMTM be cooled using a 25 ± 20 °C water temperature, similar to that of recent research studies.

A-3.2.6.3 Dilution Settings

Operationally, several constraints limit the range of dilution that is practical during an engine test. Since the exhaust contains a few percent of water vapor as a combustion product, significant dilution (~6:1) is required to prevent water condensation for room temperature sample lines. Condensation of other low vapor-pressure species, like hydrocarbons and sulfuric acid, is also reduced by diluting the exhaust sample, and dilution with dry gas (nitrogen or air) is essential for controlling the condensation appropriately. Improved theoretical understanding (Wong et al., 2008) may permit refined dilution setting recommendations in the future.

While maximizing dilution would minimize condensation effects, high dilution levels limit the concentrations detectable by measurement instruments. Dilution ratios of 10-20 have typically been a good compromise between sufficient amounts of dilution to suppress unwanted condensation, yet allowing a high enough concentration of emissions for accurate measurements. Significant volatile PM nucleation and growth sometimes occur at dilution ratios below ~4. Engine operation at low power or during conditions of low ambient temperature and combustion of high sulfur fuels can promote particle-gas-conversion at dilution ratios less than ~10. Higher dilution ratios reduce instrument signal-to-noise and reduce data quality. Within the acceptable range of dilution, higher dilution ratios (approaching 20) are preferred at low engine power for which more HC species are available to condense. Low dilution ratios (approaching 10) at high engine power allow sample line pressure to be maintained near atmospheric levels, while providing sufficient dilution to suppress gas-to-particle conversion. Therefore, dilution ratios ranging from 10 to 20 are recommended for the IPMTM. Real-time feedback from the instrument operators and communication with the researcher controlling the dilution flow is crucial for maintaining the optimum dilution ratio over the range of test conditions.

A-3.2.7 Engine test facility shakedown and test matrix optimization

After pretest sampling system checkout, instrumentation calibrations, and line penetration measurements, the system should be operated under engine loads to verify functionality of all aspects of the system. The engine manufacturer and test facilities have a prescribed set of engine operation guidelines to assure proper engine warm up and engine stability. It is recommended that those procedures be followed when implementing the IPMTM.

Prior to engine start, the sampling system should be back-purged with dilution gas to prevent pre-ignition unburned fuel from fouling the sampling system during engine start. Small amounts of residual fuel present in the sampling line can take several minutes to clear the system, and during this time gas-to-particle conversion may be artificially enhanced. Lines saturated with unburned fuel may have to be cleaned or replaced. As a safety precaution, sampling system operation and stability should be confirmed at low engine powers. After sampling system structural integrity has been confirmed, engine power should be slowly increased while carefully monitoring the sampling system support structure and sampling probes, as well as cables, lines, and attachments that may loosen due to vibration.

After noting and correcting all potential problems with the test facility and diagnostic equipment, the engine should be operated at discrete power settings from idle to military power and data acquired at a few discrete points as the traverse is exercised. These data will provide emission parameter ranges and permit accurate estimation of test point sampling duration times and optimum dilutions as a function of engine operating condition. This information will allow optimization of the test matrix for the subsequent emissions characterization measurements.

A-3.3 EMISSIONS TESTING

Emissions measurements reported for environmental purposes should be representative of the engine. This is usually accomplished by spatial mapping of emissions at selected engine power conditions from idle to take-off power, usually associated with the landing-takeoff cycle and idle. The definition and approval of engine power settings and acceptable spatial emissions detail is a joint responsibility of the JSF Program environmental office, the engine manufacturer and

EPA. This section discusses the experience gained through development of the IPMTM that might guide decisions in the development of a PM characterization test plan for the JSF Program.

A-3.3.1 Spatial mapping versus engine power

Emissions from gas turbine engines should not be assumed azimuthally symmetric, in which case spatially resolved measurements across the engine exit plane are necessary at several steady state power settings to represent overall emissions from the engine. Highly resolved spatial measurements at each power setting can be costly due to the engine run time, but not always necessary. Historical data for the F100-220 and JSF F135 military engines indicate that spatial profiles of emission index are fairly constant (Appendix B and Appendix C for the F100-220 data, and unpublished Quick-Look data for the JSF F135). To reduce engine run time, it is recommended that spatial mapping measurements of exhaust emissions parameters be performed at two nominal engine power settings (mid-low and mid-high); actual power settings to be determined as most appropriate by the engine manufacturer. These data can be used to define a reduced set of spatial measurements for other engine powers that should provide comparable averages to high spatial resolution measurements. The process and criteria to select a reduced set of spatial point measurements over the full range of engine power settings is described Section A-5.7.

A-3.3.2 Definition of the test matrix and quality of the PM emission measurements

The test matrix prescribes the schedule for a set of replicate engine operating conditions and sampling durations for the required emissions characterization measurements, i.e. non-volatile PM number, size distribution and mass. Figure A-3.1 depicts a typical engine power cycle matrix used in research studies. Measurements acquired when the engine power is returned to idle is useful for a reference point for reproducibility and to check for engine stabilization and sampling system replication. Spatial measurement can be performed at each power setting. Previous experimental studies indicate that the characteristics of engine exhaust can be relatively sensitive to small changes in engine conditions near idle thrust. If at idle, CO and unburned hydrocarbons are at or below detectable limits, an off-idle condition is recommended to produce measurable quantities for assurance that instruments are working properly. It is not necessary to report emissions for the off-idle conditions. It is recommended that the engine manufacturer be consulted in defining the test matrix.

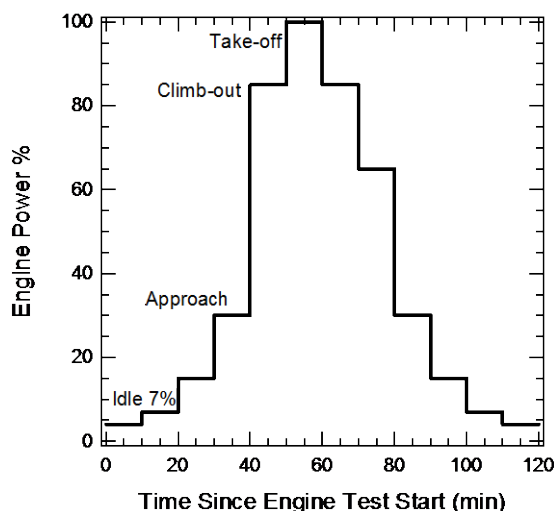


Figure A-3.1 Engine operating conditions frequently employed during engine emissions research testing.

A-3.3.3 Data acquisition and data back-up

It is recommended that raw data be stored in parallel to real-time display. Real-time display is important to allow instrument operators to confirm data quality and storage during the engine test. Engine operation should be temporarily suspended – or experimental conditions re-visited – if an operator identifies a problem in the data storage system. Typically, raw data is simultaneously stored on the individual computers dedicated to instrument operation and a central computer dedicated to data display. At the end of every a run period, raw data should be backed up on an external hard drive which is stored off-site. The external hard drive should be packaged and shipped separately from the instrument computers to provide redundant data sources in the event of mishap during shipping.

A-4.0 DATA REDUCTION AND PREPARATION OF MASTER SPREADSHEET

The raw data from the suite of diagnostic instruments must be processed before the final parameters can be reported. The following list describes each of these processes.

A-4.1 REDUCTION OF RAW DATA TO FINAL FORMAT

A-4.1.1 Data Synchronization

Transport times of the exhaust sample from the probe tip to the instrument can vary with instrument location along the sample train. Furthermore, each piece of diagnostic equipment can have its own sampling frequency. During post-test data processing, these instrument specific data must be synchronized in time. Since all PM diagnostic instruments recommended for the IPMTM record the time at which the data is acquired, the data synchronization process is straightforward. To accomplish this, the data from several instruments are plotted together as a function of time and their time lags with respect to a standard time are determined. These time lags are either subtracted or added to the instrument measurement time to bring it in line with the standard time. Figure A-4.1 (a) and (b) present time series plots of data before and after synchronization to illustrate the data synchronization process.

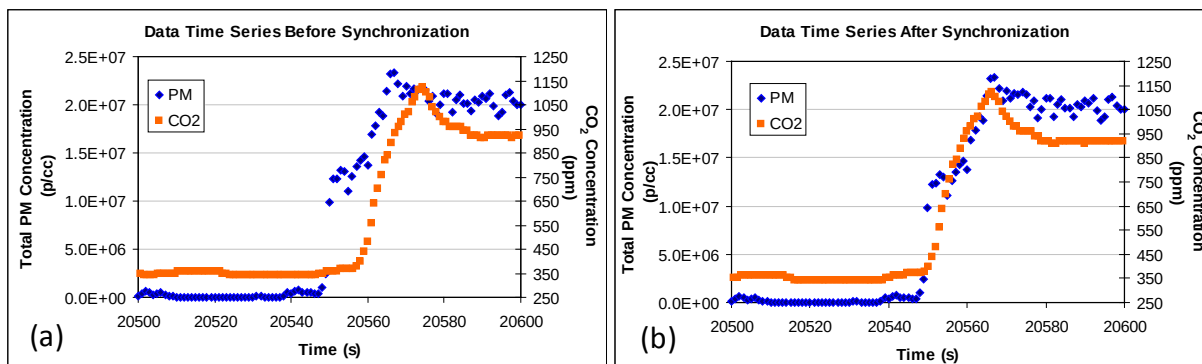


Figure A-4.1 Time series plots of data before (a) and after (b) synchronization to illustrate the data synchronization process.

A-4.1.2 Application of Instrument Calibration Corrections

Instrument calibrations should be conducted as recommended by the manufacturers. These calibrations provide correction functions that must be applied to the synchronized raw data for respective instruments. These calibrations correct for instrument variations, but not sample line effects on the measured data.

A-4.1.3 Application of line loss corrections

The measured line loss correction functions discussed in Section A-3.2.4 need to be applied to the data after instrument calibrations have been applied. For size distribution data, the measured differential concentrations in each size bin are divided by the size dependent penetration functions for the appropriate sample train.

A-4.1.4 Test Point Averages and Standard Deviations

The measured size distribution data from the corrected synchronized data set are examined to define a time after which the emissions have reached equilibrium. A subsequent time interval is then selected over which a test point average and standard deviation can be computed for each bin in the size distribution. This time interval must be larger than the time smear associated with the sample train.

A-4.1.5 Uncertainty Estimates

Experimental uncertainty stems from two primary sources: (1) the instruments themselves and (2) the statistical fluctuation in the sample. Instrument uncertainty is specified by the instrument manufacturer. The sample statistical fluctuation is determined by analysis of replicate measurements. Standard statistical methods are employed to combine these factors thus providing experimental uncertainty estimates.

A-4.1.6 Calculation of Derived Parameters

The characterization of the exhaust aerosol is accomplished using the following parameter set.

(1) The size distribution is described by a differential concentration function $N(D_p)$, dependent on particle diameter (D_p), which specifies the concentration of particles, dn , having the logarithm of their diameters between $\log D_p$ and $\log D_p + d\log D_p$ to be $N \cdot d\log D_p$. The logarithmic scale is used since aerosol diameter covers such a large size range.

$$dn = N * d \log D_p \quad (\text{Eq. A-4.1})$$

(2) Number-based geometric mean diameter (D_{geomN}), defined by the equation

$$\log D_{\text{geomN}} = \frac{1}{n_0} \int_0^{\infty} \log D_p * dn = \frac{1}{n_0} \int_0^{\infty} \log D_p * N * d \log D_p \quad (\text{Eq. A-4.2})$$

where n_0 denotes the total particle concentration,

$$n_0 = \int_0^{\infty} N * d \log D_p \quad (\text{Eq. A-4.3})$$

(3) Geometric standard deviation (σ_g), defined by

$$\log \sigma_g = \left(\frac{\int_0^{\infty} \left(\log \left(\frac{D_p}{D_{\text{geomN}}} \right) \right)^2 N d \log D_p}{n_0 - 1} \right)^{1/2} \quad (\text{Eq. A-4.4})$$

(4) Mass-based geometric mean diameter (D_{geomM}), defined by

$$\log D_{\text{geomM}} = \frac{1}{\int_0^{\infty} D_p^3 * N * d \log D_p} \int_0^{\infty} \log D_p * D_p^3 * N * d \log D_p \quad (\text{Eq. A-4.5})$$

(5) Number based emission index (EIn), the number of particles per kilogram fuel burned can be calculated by

$$EIn = EI_{CO_2} \frac{N_0}{M(CO_2)} \quad (\text{Eq. A-4.6})$$

where EI_{CO_2} denotes the mass emission index of CO_2 (for aircraft engines $EI_{CO_2} = 3160$ g/kg; (Schulte and Schlager (1996)). $M(CO_2)$, the mass of CO_2 per volume exhaust sample, is calculated by multiplying measured CO_2 mixing ratios with $(44/29)\rho_{\text{air}}$, where ρ_{air} is the air density and 44/29 is the molar mass ratio of CO_2 and air. Strictly speaking, in Eq. A-4.6 both N_0 and $M(CO_2)$ have to be values above ambient, i.e., enhancements over the background signal. However, for measurements close to the engine exit plane of gas turbine engines, the background signals are negligibly small.

(6) Mass-based emission index (EIm) is the mass of particles per kilogram fuel burned and its calculation is analogous to that for EIn and is given by

$$EI_m = EI_{CO_2} \frac{M(N_0)}{M(CO_2)} \quad (\text{Eq. A-4.7})$$

where $M(N_0)$ is the mass of aerosol per unit volume of exhaust sample.

These derived parameters are to be extracted from the corrected and synchronized size distributions.

A-4.2 FINAL DATA FORMAT – THE MASTER SPREADSHEET

The primary data product from the application of the methodology is a master spreadsheet which contains gas phase and PM engine emission parameters, ambient conditions, engine operating conditions and associated uncertainty estimates. These data are recorded for each test point defined in the test matrix. An example of a typical master spreadsheet can be found in Section A-5.8.

A-5.0 SUPPLEMENTAL INFORMATION

A-5.1 CPC MANUAL (TSI)

“Model 3022A Condensation Particle Counter Instruction Manual”, TSI Corp. Revision I, August 2002

“Model 3025A Ultrafine Condensation Particle Counter Instruction Manual”, TSI Corp. Revision I, July 2002.

A-5.2 DMA MANUAL (TSI)

“Model 3071 Electrostatic Classifier Instruction Manual”, TSI Corp. Revision B, September 1990.

A-5.3 CALIBRATION AEROSOL GENERATION SYSTEM

The aerosol generation system (Figure A-5.1) provides challenge aerosols used to determine the detection efficiency of the condensation particle counters, the sizing accuracy of the various instruments, and the penetration of particles through the long sample delivery lines. The aerosol generation system can provide aerosols either from a nebulizer (spherical polystyrene latex (PSL), cubical NaCl particles, or spherical $(NH_4)_2SO_4$ particles) or a furnace (spherical NaCl particles or spherical Ag particles). If PSL is to be used, approximately 4 drops of the solution is added to 300 cc of distilled water and placed in the nebulizer. If NaCl or $(NH_4)_2SO_4$ is used, approximately 0.2 gram of either NaCl or $(NH_4)_2SO_4$ is added to 300 cc of distilled water and placed in the nebulizer. Compressed air at 30 psig drives the nebulizer while 15 L/m of filtered, dry dilution air (Q-D1) is added as dilution air to lower the sample relative humidity. An electrically heated region brings the temperature of the aerosol to approximately 80 °C, causing the aerosol to attain a state of very low relative humidity. This assures that the aerosol particles are completely dry and not small solution droplets. (It should be noted that even though the Q-D1 brings the relative humidity to approximately 40%, unless NaCl solution droplets which exit the nebulizer attain a relative humidity of less than approximately 32%, they will not become completely dry particles.) The resulting aerosol is then fed to a differential mobility analyzer

(DMA) which cuts the rather broad aerosol size distribution into a very narrow slice with respect to particle diameter. For PSL, diameters of 60 nm to 250 nm and concentrations of a few 100 p/cc can be produced. For the NaCl and $(\text{NH}_4)_2\text{SO}_4$, challenge aerosols with diameters between 20 nm and 150 nm and concentrations of $\sim 10,000$ p/cc can be produced.

The aerosol generation system also contains a tube furnace for generating small NaCl (or Ag) particles. A few grams of NaCl (or Ag) are placed in a ceramic boat and inserted into the 1.25" OD mullite tube. 1.5 L/m of filtered air (Q-F) flows through the furnace and 10 L/m of dilution air (Q-D2) is required to suppress coagulation. The tube furnace temperature is brought to approximately 650 °C, at which point a vapor of NaCl (or Ag) is produced. The vapor exiting the tube furnace condenses and forms a large number of particles with diameters in the 10 nm size range. This aerosol is then fed to a differential mobility analyzer (DMA), which cuts the aerosol size distribution into a very narrow slice with respect to particle diameter. Challenge aerosols with diameters between 7 nm and 50 nm and concentrations of $\sim 30,000$ p/cc can be produced using the furnace.

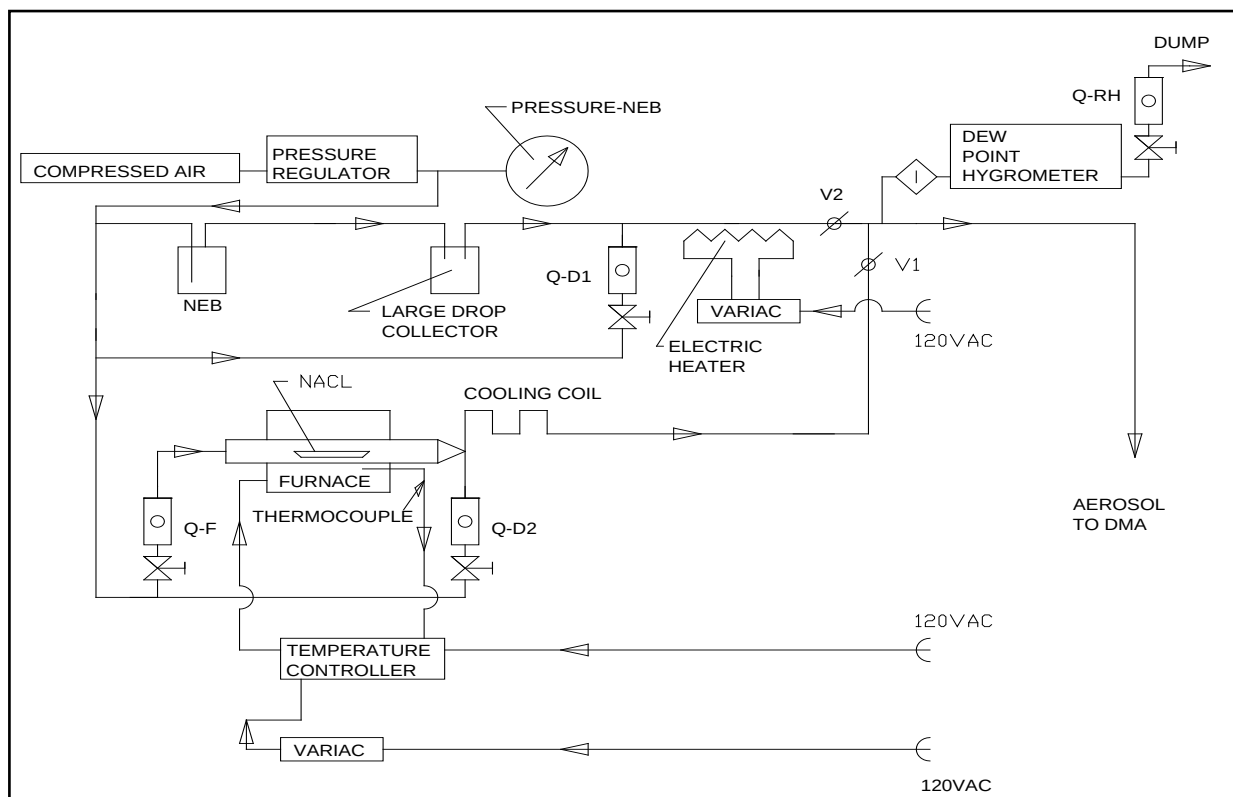


Figure A-5.1 Calibration Aerosol Generation System

A-5.4 CPC AND DMA CALIBRATION

A-5.4.1 Calibrating the CPC detection efficiency with respect to size

The counting efficiency of a CPC falls off at the small diameter end of the particle size spectrum. The point at which the counting efficiency falls off to 50% is determined and this is reported as the small size cut-off for the instrument. This can be determined experimentally using an alternating gradient thermal diffusion chamber with optical particle counter as the reference for

size specific concentration (Alofs et al., 1995; Hagen et al., 1993). In this section the concentration as measured by the CPC (TCN-cpc) is compared to that reported by the alternating gradient thermal diffusion chamber (TCN-algr). The alternating gradient uses a stack of 25 rings that have a water soaked cloth on the inside surface of the $\frac{1}{2}$ inch diameter passing down through them. The rings alternate in temperature between a low temperature and a higher temperature (typically 5 °C and 30 °C), providing a supersaturation of approximately 25%. A monodispersed challenge aerosol is split and sent to both counters using short lines between the split and counters. The efficiency of the CPS is defined as the ratio of TCN-cpc to TCN-algr. The goal of this calibration is to determine the particle diameter at which the detection efficiency of the CPC falls to 50%. An example of this calibration, for a commercial saturator-condenser type CPC using 1-butanol, is shown in Figure A-5.2.

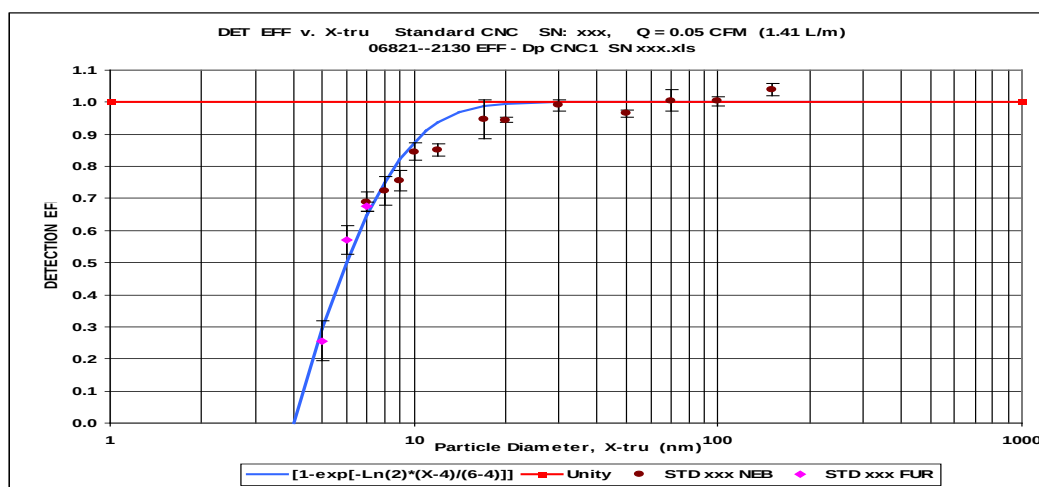


Figure A-5.2 Representative plot of efficiency versus particle diameter for the CPC used as the standard.

A-5.4.2 Calibrating the CPC concentration with an electrometer

The CPC can be calibrated using an electrometer as the reference. A test aerosol is generated with a known size distribution (see Section A-5.3) and delivered to a DMA. The DMA is used to cut the aerosol at a particular size on the right hand side of its distribution (large size end) such that the concentration of doubly charged particles is greatly reduced. This aerosol cut becomes the challenge aerosol. It will be primarily singly charged. This source aerosol sample is split into two streams and supplied to both the CPC and the electrometer. The current from the electrometer can be used to determine the aerosol concentration using fundamental physical principles. The CPC concentration reading can be referenced to the electrometer based concentration.

The correlation between electrometer current and particle concentration can be developed as follows:

Let:

x_1 denote the particle diameter selected for the size cut,

Δ the width of the size cut,

sn_1 the differential concentration at diameter x_1 ,

N_1 the probability that a particle at diameter x_1 picks up one charge in the charger,

x_j the diameter for which a particle holding j charges has the same electric mobility as diameter x_1 with one charge.

sn_j the differential concentration at diameter x_j ,

N_j the probability that a particle at diameter x_j picks up j charges in the charger,

$r_j = sn_j/sn_1$,

$R_j = N_j/N_1$,

Q the air flow rate into the electrometer,

and e the elementary charge = $1.6E-19$ Coulombs.

Then the number of charged particles in the flow downstream of the DMA is given by

$$N_c = \Delta sn_1 N_1 + \Delta sn_2 N_2 + \Delta sn_3 N_3 + \dots = \Delta sn_1 N_1 \sum_{j=1}^J r_j R_j \quad (\text{Eq. A-5.1})$$

where $j = 1, 2, 3, \dots, J$ (J represents the maximum number of charges on a particle)

$$\Delta sn_1 N_1 = N_c / \sum_{j=1}^J r_j R_j \quad (\text{Eq. A-5.2})$$

The current in the electrometer is given by

$$\begin{aligned} I &= \Delta sn_1 N_1 Q e + \Delta sn_2 N_2 Q 2e + \dots = \Delta sn_1 N_1 Q e \sum_{j=1}^J j^* r_j R_j \\ &= N_c Q e \sum_{j=1}^J j^* r_j R_j / (\sum_{j=1}^J r_j R_j) \end{aligned} \quad (\text{Eq. A-5.3})$$

$$N_c = (I/Qe) (\sum_{j=1}^J r_j R_j) / (\sum_{j=1}^J j^* r_j R_j) \quad (\text{Eq. A-5.4})$$

This is the concentration of the test aerosol delivered to both the electrometer and the CPC being calibrated.

$$\text{For } J = 2, \quad N_c = (I/Qe)(1+r_2 R_2) / (1+2r_2 R_2) \quad (\text{Eq. A-5.5})$$

$$\text{and for } r_2 R_2 \ll 1, \quad N_c = (I/Qe)(1-r_2 R_2) \quad (\text{Eq. A-5.6})$$

The electrometer used in this calibration experiment is a Keithley MN 617 (Keithley Instruments, 28775 Aurora Rd, Cleveland, OH 44139). This particular electrometer has a minimum detectable current of 2×10^{-15} A and a maximum allowable current of 1×10^{-10} A. Inserting these values into Eq. A-5.4 gives the minimum and maximum allowable concentrations for proper operation of the electrometer ($C_{\min} = 102$ p/cc and $C_{\max} = 1.3 \times 10^7$ p/cc). The uncertainty in the flow measurement is approximately 2.2% of full scale (2% from the MFM and 1% from the Gilibrator that calibrates the MFM). The uncertainty in the current measurement is approximately 2% of full scale. Thus the total uncertainty in the concentration measurement is approximately 2.8%.

A-5.4.3 Calibration of the CPC in the high concentration regime

The CPC must be calibrated to relate its registered concentration to the true concentration, when it is operating in the high concentration regime in its photometric mode.

The CPC concentration should make a smooth transition when passing from the photometric or attenuation (ATT) mode (total particle concentration $> 10,000$ p/cc) to the single particle

counting (SPC) mode (total particle concentration < 10,000 p/cc), however small discontinuities are often encountered.

Instrumentation is setup as shown in Figure A-5.3. Adjust the nebulizer to give an aerosol with a peak concentration around 30 nm. Confirm the sizing with the DMA. Then route the aerosol around the DMA. The concentration should be adjusted to achieve values around 1E6. Valve V1 is closed and valve V2 is opened. The flow through the tank is 7 L/m, and 5.5 L/m of the output is dumped. The concentration exiting the tank (TK) is monitored. When the concentration has settled to within 10% of the asymptote, V1 is opened and V2 is closed. The concentration is monitored until it reaches a value ~10 p/cc.

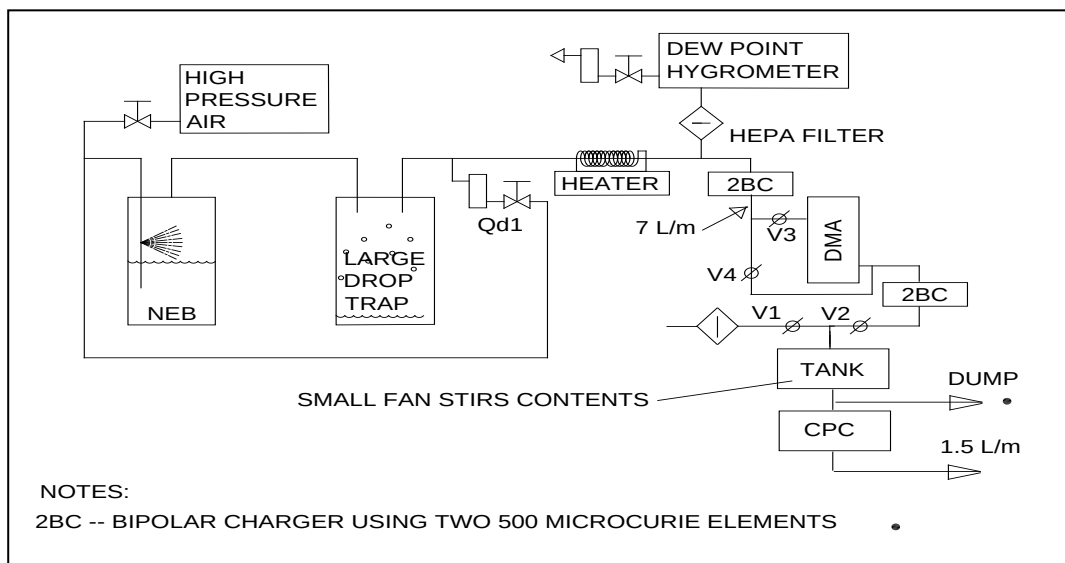


Figure A-5.3 Schematic of setup for checking the calibration of the CPC with a stirred tank.

Let C_0 be the original concentration at the asymptote and T be the characteristic time constant. (Ideally, this time constant T should be the quotient of the volume of the tank and the flow rate being drawn through it.) The concentration should decay exponentially with time t given by

$$C(t) = C_0 * \exp(-t/T)$$

$$\ln(C(t)) = (-t/T) + \ln(C_0)$$

Thus a plot of $\ln(C(t))$ versus t should have a slope of $(-1/T)$ and an intercept of $\ln(C_0)$. Furthermore, the transition between modes (ATT and SPC) should be smooth and continuous. Sample data from such an experiment is shown in Figure A-5.4. Note the linearity of the plot and also the very slight discontinuity at the point where the counter changes from the photometric mode to the single particle counting mode ($\ln(C(t)) = 9.21$). Figure A-5.5 shows the same data, but for only a narrow window around the transition point. Note how closely the slopes agree. Figure A-5.6 shows the high concentration ATT mode plus an extrapolation of the SPC mode data back in time to the high concentration regime. This extrapolated data represents the true concentration data. Note that the extrapolated data is of lower magnitude than the actual reported data. The ratio of these two sets of data becomes the calibration correction factor function. This result is shown in Figure A-5.7.

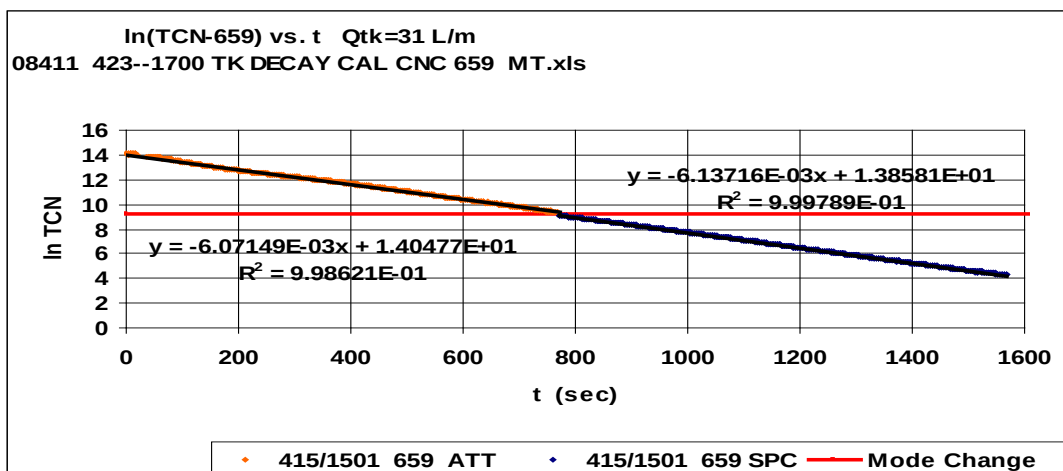


Figure A-5.4 Plot of $\ln(C(t))$ versus time (t) for sampling from a stirred tank.

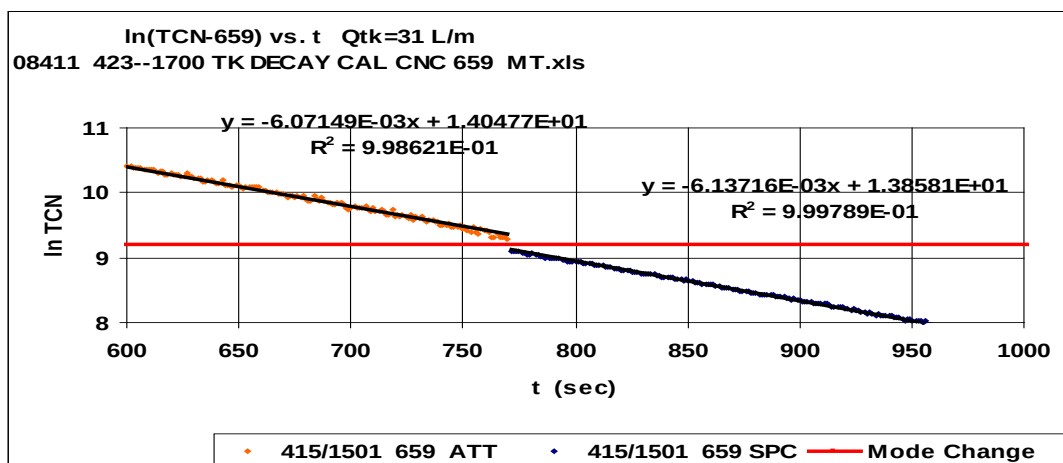


Figure A-5.5 Plot of $\ln(C(t))$ versus time (t) for a narrow window where the discontinuity at the mode change is more easily noticed.

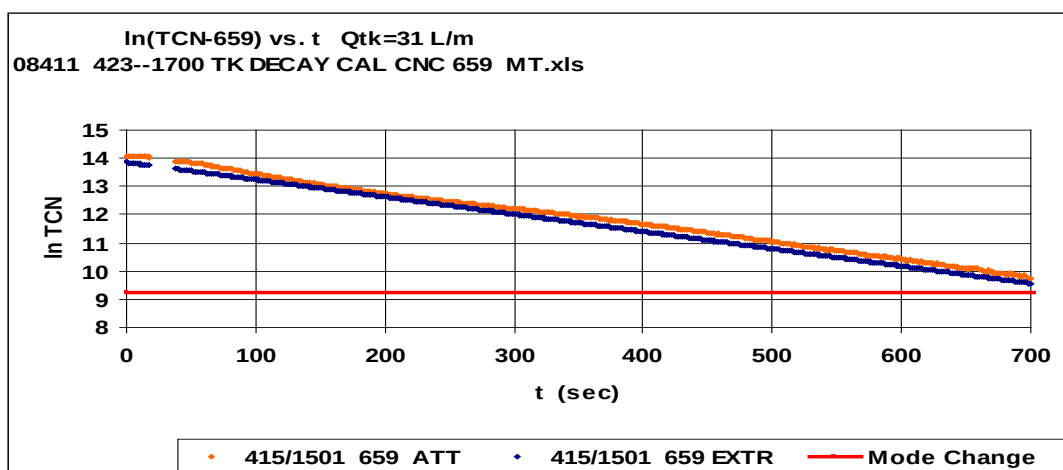


Figure A-5.6 Plot of $\ln(C(t))$ versus time (t) during which the concentration was greater than 10,000 p/cc.

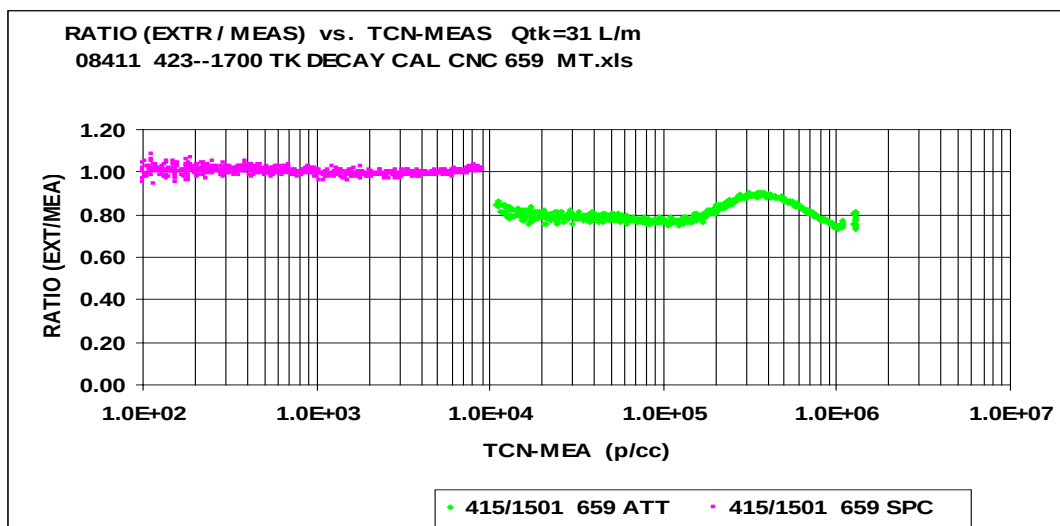


Figure A-5.7 Plot of the Ratio (EXTR / MEAS) versus TCN-MEAS that constitutes the calibration correction factor versus reported concentration for the TCN.

In this experiment the aerosol was withdrawn from the tank at 31 L/m. Similar results were observed when the aerosol was withdrawn at only 3 L/m and 14 L/m. Thus one concludes that the fraction of aerosol being lost to the walls and the stirring fan was inconsequential.

A-5.5 LINE LOSS ESTIMATION

A schematic of the set up to determining the penetration of particles through the sampling line as a function of size is shown in Figure A-5.8. The nebulizer feeds aerosol to the two ZDMAs (high flow rate DMAs), which are both set to pass particles of a given diameter (D_p). Two DMAs are used to give sufficient amounts of test aerosol. A junction box is placed in the line to allow the aerosol to pass to either the sample train or the line L1 without making a 90 degree turn at a high flow velocity. The two lines marked L1 are carefully cut to the same length (approximately 30 m) of soft 3/8" OD copper tubing. The overall flowrate through the trunk line should be approximately equal to what is used for the jet engine testing. In this example, the total flowrate in the sample train is ~ 55 L/m. With valve V1 closed and valve V2 open, the concentration upstream is determined (Cup). Then valve V1 is opened and valve V2 is closed and the concentration downstream is determined (Cdn). The penetration (PEN) of particles of diameter D_p is computed as

$$\text{PEN}(D_p) = (C_{dn} * 14.7 / P_{1dn}) / (C_{up} * 14.7 / P_{1up}) \quad (\text{Eq. A-5.7})$$

$$\text{PEN}(D_p) = (C_{dn} / P_{1dn}) / (C_{up} / P_{1up}) \quad (\text{Eq. A-5.8})$$

where, P_{1up} is the line pressure when the sample is drawn from the junction box and, P_{1dn} is the line pressure when the sample is drawn through the sample train.

The result of such a calibration performed on a typical sample train (~40 m L, ~0.75 inch ID, and flow of ~55 L/m) is shown in Figure A-5.9. The PEN ranges from $\text{PEN}(10 \text{ nm}) \sim 0.65$ to $\text{PEN}(240 \text{ nm}) \sim 1$. It should be noted that PEN may take on other values for other configurations, e.g., at other trunk line flow rates, for other trunk line IDs, etc.

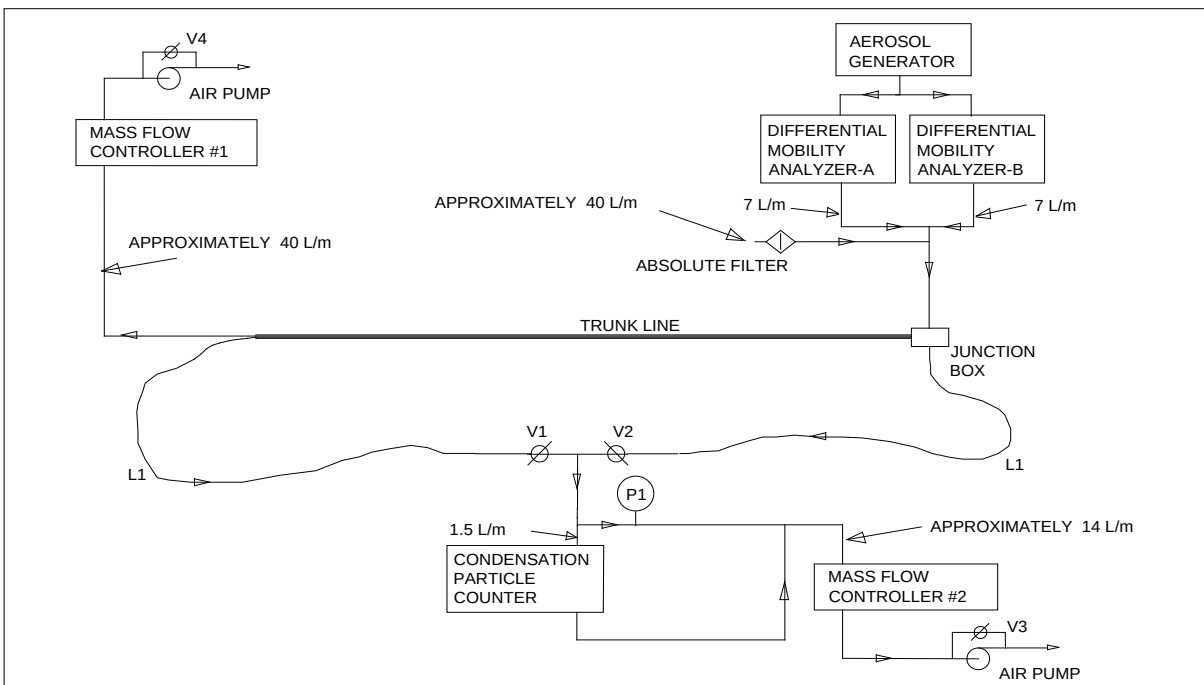


Figure A-5.8 Apparatus for determining the penetration as a function of size of the particles through the sample train.

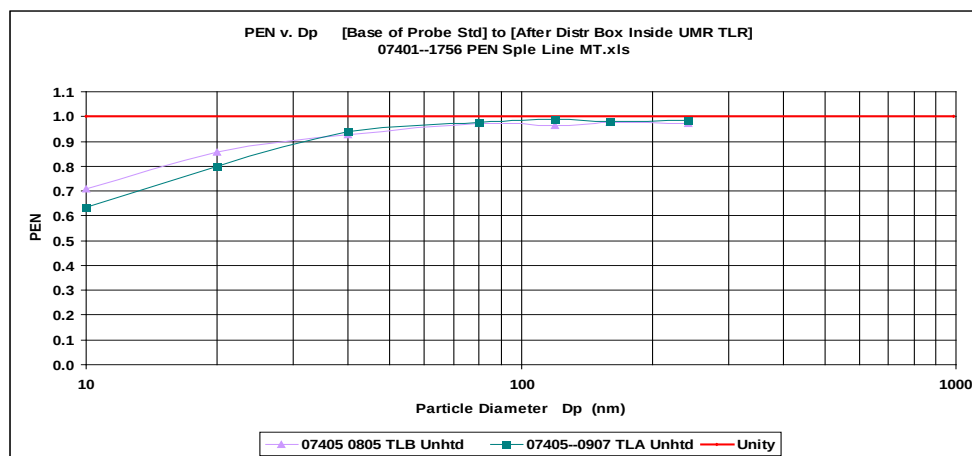


Figure A-5.9 Sample plots of the penetration PEN as a function of particle diameter for a typical sample train employed in JSF-type engine testing.

A-5.6 DETERMINE THE OPTIMUM SAMPLING LOCATION(S) VIA MAPPING TESTS AT TWO POWERS

Generally, it should not be assumed that the characteristics of the PM exhaust emissions are spatially non-uniform over the engine exit plane. However, if data exists that indicate that the emission index is spatially uniform, or just azimuthally symmetric, engine run time could be reduced by performing high spatial resolution mapping measurements at two engine power settings and a lower density of measurement points at other power level conditions. The engine power levels should represent medium-low and medium-high powers, respectively, consulting the engine manufacturer to help define most appropriate power settings. Assume that

the engine exhaust velocity vector is horizontal. Let c denote the vertical spacing between particle sampling probes, and R denote the engine exit plane radius. Consider a set of (x,y) coordinates (x – horizontal, y – vertical) given by:

$J = [R/c]$ [] denotes the greatest integer function.

$$y_j = c_j \quad j = -J, -J+1, \dots, -1, 0, 1, 2, \dots, J$$

$$x_i = c_i \quad i = -J, -J+1, \dots, -1, 0, 1, 2, \dots, J$$

Some of these points will be within the exit plane, some will be outside.

Let $r_{ij} = \sqrt{c^2 i^2 + c^2 j^2} = c \sqrt{i^2 + j^2}$. For a given j , find I_j , the max value of i for this j , with $r_{ij} \leq R$.

$$r_{I_j, j} = \sqrt{c^2 I_j^2 + c^2 j^2} < R$$

$$c^2 I_j^2 + c^2 j^2 < R^2$$

$$I_j = [\sqrt{(R^2 - c^2 j^2) / c^2}] = [\sqrt{R^2 / c^2 - j^2}].$$

A set of sampling locations within the exit plane is given by:

$$y_j = c_j \quad j = -J, -J+1, \dots, -1, 0, 1, 2, \dots, J.$$

$$x_i = c_i \quad i = -I_j, -I_j+1, \dots, I_j$$

$$I_j = [\sqrt{R^2 / c^2 - j^2}]$$

Separate these points into internal and external (surface) points. Internal points have neighbors on all 4 sides. External points have less than 4 neighbors because of their location adjacent to the nozzle perimeter. The area associated with each internal point is given by $AA_{int,ij} = c^2$. Let N_{int} denote the number of internal points. The total area associated with internal points is given by $TA_{int} = N_{int} * c^2$. The total area associated with external points is given by $TA_{ext} = \pi R^2 - TA_{int}$. External points with radii closer to R represent less area than do external points with larger $R - r_{ij}$.

Let $AA_{ext, ij} = TA_{ext} * (R - r_{ext,ij}) / (\sum_{ext} (R - r_{ext,ij}))$. Then the area associated with sampling location ij is given by:

$$AA_{ij} = AA_{int,ij} \text{ for internal points}$$

$$= AA_{ext, ij} \text{ for external points.}$$

A normalized area for sampling location ij is given by:

$$A_{ij} = AA_{ij} / (\sum AA_{ij}).$$

Run the engine at two power settings ($k = 1, 2$) and measure exhaust aerosol PM characteristics at each of the above sampling locations in the exhaust plane. Take the resulting measurement

data and compute the parameters $R_{ij,k}$ and $\sigma_{k,var}$. The calculation methodology is given below (see section Calculation Methodology).

R_{ijk} is the Probe location rating; it's a metric for measuring the "badness" of a probe location; you want R_{ijk} to be small.

$\sigma_{k,var}$ denotes the variability (standard deviation) of emissions across the engine exit plane at the given engine power condition

i^*j^* is the point that gives the minimum R_{ijk} .

σR_k denotes the standard deviation in $\{R_{ijk}\}$

If $i(1)^*, j(1)^* = i(2)^*, j(2)^*$, then $i(1)^*, j(1)^*$ is the prime location for all powers.

If $i(1)^*, j(1)^* \neq i(2)^*, j(2)^*$, then find the i^*j^* which minimizes

$$RR = R_{i^*j^*} - (R_{ij,1})_{\min} + R_{i^*j^*} - (R_{ij,2})_{\min} = R_{i^*j^*} - R_{i(1)^*j(1)^*,1} + R_{i^*j^*} - R_{i(2)^*j(2)^*,2}$$

and satisfies

$$R_{i^*j^*} - (R_{ij,1})_{\min} < 0.1 * \sigma R_1$$

$$R_{i^*j^*} - (R_{ij,2})_{\min} < 0.1 * \sigma R_2$$

(Notes: $R_{i^*j^*} - (R_{ij,1})_{\min}$ quantifies how far the point i^*j^* is from optimum for power 1. Same for 2.

The cut-point parameter 0.1 can be a topic of discussion. If it's set too small then a satisfactory solution may not be available).

If no satisfactory i^*j^* can be found, then a full mapping has to be done at each power condition to be studied.

A-5.7 CALCULATION METHODOLOGY

Here the data reduction methodology is given to compute the parameters $R_{ij,k}$, σR_k and $\sigma_{k,var}$ from the data collected from the engine mapping runs at two powers. The measurement data set is represented by $\{ap_{mij}, \delta ap_{mij}, A_{ij}, dap_{mij}\}$.

ap_m denotes an aerosol parameter of type m.

ap_1 = number-based geometric mean diameter,

ap_2 = mass-based geometric mean diameter,

i denotes sampling tip, i.e. vertical position,

j is a horizontal position index,

A_{ij} denotes the fractional area associated with each probe location; $\sum_{ij} A_{ij} = 1$.

dap_{mij} = RMS distance (in ap_m -space) to nearest neighbors ($i'j'$) = $\sqrt{\sum_{nbr} (ap_{mi'j'} - ap_{mij})^2 / \text{NumberOfNeighbors}}$

The summation runs over the group of nearest neighbors.

If this is limited to only two nearest neighbors, this becomes

$$dap_{mij} = \text{Average distance (in } ap_m\text{-space) to nearest (two) neighbors (' for 1^{st} \text{ nbr, " for 2^{nd} \text{ nbr})} \\ = [\text{abs}(ap_{mi'j'} - ap_{mij}) + \text{abs}(ap_{mi''j''} - ap_{mij})] / 2.$$

An area and uncertainty weighted average value is calculated for ap_m . This is our best estimate for what the whole engine will produce regarding parameter m.

$$ap_m = (\sum_{ij} ap_{mij} A_{ij} / \delta ap_{mij}^2) / (\sum_{ij} A_{ij} / \delta ap_{mij}^2)$$

Compute a normalized (fractional) value for this parameter

$$bp_{mij} = ap_{mij} / ap_m$$

Now consider a weighted average normalized global aerosol parameter to represent the collection of aerosol parameters.

Weight functions: $w_{mij} = w_m A_{ij} (ap_m / \delta ap_{mij})^2$

w_m = weight function for ap type m; chosen by user

e.g., $w_1(Dgn)=1$, $w_2(Dgm)=1$, $w_3(\sigma)=1$, $w_4(EIn)=2$, $w_5(EIm)=2$.

$$bp = (\sum_{mij} w_{mij} bp_{mij}) / (\sum_{mij} w_{mij}) = 1$$

We are not interested in bp itself, but rather its variance. The unbiased variance in bp is given by

$$\text{Variance} = (\sum_{mij} w'_{mij} (bp_{mij} - bp)^2) / (1 - \sum_{mij} w'_{mij})$$

$$w'_{mij} = w_{mij} / \sum_{mij} w_{mij} \text{ (normalized weight function)}$$

$$= [(\sum_{mij} w_{mij})(\sum_{mij} w_{mij} bp_{mij}^2) - (\sum_{mij} w_{mij} bp_{mij})^2] / [(\sum_{mij} w_{mij})^2 - (\sum_{mij} w_{mij}^2)]$$

$$\sigma_{var} = (\text{variance})^{1/2}$$

σ_{var} represents the variability (standard deviation) of PM emissions across the engine exit plane at the given engine power condition. This metric is one of our objectives.

$$\sigma_{var} = \{[(\sum_{mij} w_{mij})(\sum_{mij} w_{mij} bp_{mij}^2) - (\sum_{mij} w_{mij} bp_{mij})^2] / [(\sum_{mij} w_{mij})^2 - (\sum_{mij} w_{mij}^2)]\}^{1/2}$$

The fractional deviation of aerosol parameter Δap_m from the average is given by

$$\Delta ap_{mij} = \text{abs}(ap_{mij}/ap_m - 1) = \text{abs}(bp_{mij} - 1).$$

A probe location rating metric, R_{ij} , can now be defined. User defined weight functions (u_k , $k = 1,2,3$) are employed in the calculations. u_1 controls the weight used to force the optimum sampling location to reflect the emissions from the entire engine; u_2 pushes the location choice to a region where the measurement uncertainty is low, and u_3 pushes the location choice towards a point where the aerosol parameters are varying relatively slowly.

$$\begin{aligned} R_{ij} &= u_1 \sum_m w_m \Delta ap_{mij} + u_2 \sum_m w_m \delta ap_{mij} / ap_m + u_3 \sum_m w_m d ap_{mij} / ap_m \\ &= \sum_m w_m (u_1 \Delta ap_{mij} + u_2 \delta ap_{mij} / ap_m + u_3 d ap_{mij} / ap_m) \end{aligned}$$

Better locations are indicated by smaller values of R_{ij} . R_{ij} is a measure of the “badness” of the probe location.

A-5.8 SAMPLE DATA MASTER SPREADSHEET

ENGINE OPERATING CONDITIONS					SAMPLE INFORMATION AMBIENT CONDITIONS					UMR TOTAL AEROSOL PARAMETERS *									
Power_% ¹	N1_%	N2_%	EGT_(K)	Fuel_Flow_Rat e_(kg/sec)	Sample_Rake	[CO ₂] (ppm)	T (K)	P (Pa)	Dew Point (K)	Uncertainty GMD (nm) in GMD (nm)		Sigma	Uncertainty in Sigma	El Number (part/kg fuel)	Uncertainty in El Number (part/kg fuel)	El Mass (g/kg fuel)	Uncertainty in El Mass (g/kg fuel)		
4	210	55	794		30	731	301	93876	268	14.08	0.23	137	0.02	1.33E+16	9.80E+14	4.01E-02	1.38E-03		
4	215	60	798	0.0983	30	685	305	94016	268	14.13	0.39	135	0.02	1.10E+16	2.42E+15	3.63E-02	2.95E-03		
4	210	60	798	0.0945	30	399	307	93987	268										
4	210	60	798	0.0945	35	10	307	93982	268	15.56	0.26	152	0.02	1.23E+15	1.91E+14	1.61E-02	8.16E-04		
4	210	60	795	0.0983	1-P-3	1303	306	93905	268	16.97	0.24	153	0.02	7.03E+14	6.79E+13	5.19E-03	3.10E-04		
4	210	60	795	0.0983	1-P-3	2183	306	93922	268										
4	210	60	792	0.0983	30	733	306	93924	268	14.44	0.33	136	0.01	8.39E+15	1.78E+15	2.49E-02	1.98E-03		
4	210	60	805	0.0958	30	702	306	93924	268	14.37	0.19	136	0.01	9.63E+15	1.33E+15	2.79E-02	1.12E-03		
4	210	60	797	0.0995	10	1349	308	93889	264	15.24	0.38	148	0.03	1.63E+15	5.51E+14	8.52E-03	2.53E-04		
4	210	60	797	0.0995	30	331	308	93913	264										
4	210	58	752	0.0970	10	618	289	93876	269	14.81	0.12	155	0.01	9.21E+15	4.65E+14	8.01E-02	4.38E-03		
4	205	59	767	0.0907	10	915	290	93916	269	14.31	0.07	149	0.01	4.77E+15	2.59E+14	4.19E-02	5.89E-04		
4	205	59	767	0.0907	1-P-3	915	290	93902	270	16.78	0.09	164	0.01	1.99E+15	1.17E+14	5.09E-02	6.91E-05		
4	210	59	795	0.0932	1-P-3	2125	292	93907	270	16.66	0.07	154	0.02	1.23E+15	1.06E+14	1.16E-02	6.43E-04		
4	205	59	771	0.0932	1-P-3	1998	294	93931	271	16.55	0.08	154	0.01	1.47E+15	6.21E+13	1.27E-02	1.61E-04		
4	205	59	771	0.0932	10	1158	294	93888	271	14.28	0.06	149	0.01	4.23E+15	2.32E+14	2.63E-02	5.67E-04		
4	205	59	777	0.0932	10	1001	295	93902	272	14.39	0.18	151	0.01	3.79E+15	2.78E+14	2.89E-02	2.30E-04		
4	205	59	777	0.0932	30	542	295	93902	272	13.43	0.06	129	0.00	2.09E+16	2.39E+15	5.44E-02	1.68E-03		
4	205	59	779	0.0920	30	577	297	93886	272	13.24	0.07	129	0.00	1.95E+16	1.22E+15	4.87E-02	1.02E-03		
4	210	60	813	0.0959	30	380	306	93079	265										
4	210	60	813	0.0959	30	595	306	93079	265										
4	215	62	795	0.0970	30	585	306	93496	265	13.66	0.14	128	0.00	1.90E+16	2.18E+15	4.06E-02	1.95E-03		
4	215	62	795	0.0970	10	2046	306	93406	265	15.17	0.18	151	0.01	1.39E+15	9.34E+13	8.25E-03	6.91E-05		
4	210	60	782	0.0946	10	1927	305	93321	265	15.18	0.28	151	0.01	1.24E+15	1.55E+14	7.54E-03	1.55E-04		
4	210	60	782	0.0946	1-P-3	1430	305	93321	265	16.77	0.16	155	0.01	6.41E+14	4.37E+13	5.04E-03	9.49E-05		
4	213	61	796	0.0982	1-P-3	2083	305	93314	265	17.40	0.25	155	0.01	6.97E+14	5.42E+13	5.94E-03	1.58E-04		
4	213	61	796	0.0982	1-P-3	1506	305	93314	265	17.76	0.13	160	0.01	1.98E+15	1.38E+14	2.39E-02	4.03E-04		
4	215	60	766	0.0946	1-P-3	286	1630	92895	265	16.02	0.08	150	0.00	6.39E+14	9.65E+13	3.47E-03	8.42E-05		
4	215	60	766	0.0946	10	1186	298	92897	265	13.10	0.14	140	0.01	2.54E+15	2.37E+14	7.14E-03	1.10E-04		
4	215	60	773	0.0966	10	1195	298	92892	265	13.66	0.16	144	0.01	2.30E+15	1.63E+14	8.25E-03	6.86E-05		
4	215	60	785	0.0966	30	520	298	92863	265	13.22	0.10	125	0.00	4.46E+16	1.37E+15	7.42E-02	7.93E-04		
4	215	60	782	0.0970	30	499	299	92817	266	13.08	0.12	125	0.00	4.29E+16	2.18E+15	7.12E-02	1.15E-03		
4	205	58	808	0.0949	30	475	302	92597	269	12.33	0.09	129	0.00	2.94E+16	2.36E+15	6.72E-02	1.21E-03		
4	215	61	781	0.0964	30	452	302	92569	270	12.27	0.06	126	0.01	1.82E+16	2.38E+15	3.92E-02	1.34E-03		
4	215	61	781	0.0964	10	1511	302	92575	271	15.89	0.28	152	0.01	8.84E+14	2.76E+14	6.39E-03	2.95E-04		
4	210	60	773	0.0945	10	1571	302	92595	271	15.51	0.16	149	0.01	1.19E+15	2.11E+14	6.85E-03	1.76E-04		

UMR PARTICLE SIZE DISTRIBUTIONS FOR TOTAL AEROSOL - d(Eln)/dlogDp

10 nm	11.5 nm	13.3 nm	15.4 nm	17.8 nm	20.5 nm	23.7 nm	27.4 nm	31.6 nm	36.5 nm	42.2 nm	48.7 nm	56.2 nm	64.9 nm	75 nm	86.6 nm	100 nm	115 nm	133 nm	154 nm	178 nm	205 nm	237 nm
4.00E+16	4.80E+16	4.22E+16	3.20E+16	2.08E+16	1.18E+16	6.49E+15	4.02E+15	2.67E+15	1.87E+15	1.29E+15	7.90E+14	4.10E+14	1.68E+14	4.47E+13	7.21E+12	7.88E+11	6.55E+10	1.65E+09	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.14E+16	3.78E+16	3.50E+16	2.80E+16	1.90E+16	1.12E+16	6.10E+15	3.37E+15	1.85E+15	1.05E+15	6.08E+14	3.35E+14	1.70E+14	8.12E+13	4.03E+13	2.33E+13	1.55E+13	1.10E+13	8.10E+12	6.49E+12	5.51E+12	4.79E+12	4.16E+12
3.40E+15	3.68E+15	3.26E+15	2.60E+15	1.90E+15	1.35E+15	1.03E+15	9.11E+14	5.86E+14	3.89E+14	2.49E+14	1.39E+14	7.14E+13	4.63E+13	3.97E+13	3.55E+13	2.66E+13	1.60E+13	8.46E+12	5.93E+12	6.11E+12	6.76E+12	6.73E+12
1.48E+15	1.85E+15	1.53E+15	1.33E+15	1.13E+15	9.57E+14	8.25E+14	7.03E+14	5.52E+14	3.93E+14	2.52E+14	1.40E+14	6.80E+13	2.42E+13	5.64E+12	7.27E+11	1.93E+11	3.08E+11	4.94E+11	5.56E+11	4.68E+11	3.37E+11	2.62E+11
2.24E+16	2.78E+16	2.57E+16	2.10E+16	1.51E+16	9.63E+15	5.73E+15	3.34E+15	1.87E+15	1.01E+15	5.34E+14	2.63E+14	1.25E+14	5.93E+13	2.92E+13	1.39E+13	5.18E+12	1.21E+12	1.74E+11	5.13E+10	2.57E+10	3.73E+09	1.79E+07
2.63E+16	3.19E+16	2.95E+16	2.40E+16	1.71E+16	1.09E+16	6.50E+15	3.75E+15	2.06E+15	1.08E+15	5.36E+14	2.40E+14	1.00E+14	4.73E+13	3.07E+13	2.24E+13	1.27E+13	4.28E+12	4.83E+11	4.24E+09	0.00E+00	8.60E+09	1.06E+10
4.78E+15	5.50E+15	3.90E+15	3.11E+15	2.43E+15	1.83E+15	1.39E+15	1.06E+15	7.75E+14	5.23E+14	3.37E+14	1.93E+14	9.75E+13	4.69E+13	2.40E+13	1.32E+13	6.07E+12	1.52E+12	8.70E+10	0.00E+00	3.39E+10	6.12E+10	5.96E+10
4.25E+16	2.77E+16	1.94E+16	1.39E+16	1.07E+16	8.31E+15	6.72E+15	5.51E+15	4.34E+15	3.27E+15	2.32E+15	1.52E+15	9.23E+14	5.96E+14	2.69E+14	1.36E+14	7.21E+13	4.59E+13	3.41E+13	2.69E+13	2.12E+13	1.68E+13	1.42E+13
1.77E+16	2.09E+16	1.09E+16	7.32E+15	5.25E+15	3.89E+15	2.96E+15	2.30E+15	1.78E+15	1.27E+15	9.68E+14	5.51E+14	3.20E+14	1.72E+14	9.02E+13	5.12E+13	3.50E+13	2.89E+13	2.53E+13	2.20E+13	1.83E+13	1.45E+13	1.18E+13
5.25E+15	5.71E+15	4.05E+15	3.33E+15	2.78E+15	2.32E+15	1.95E+15	1.62E+15	1.28E+15	9.53E+14	6.85E+14	4.32E+14	2.61E+14	1.53E+14	9.49E+13	6.79E+13	4.93E+13	4.32E+13	3.71E+13	3.11E+13	2.59E+13	2.22E+13	
2.43E+16	3.99E+15	2.70E+15	2.24E+15	1.90E+15	1.59E+15	1.33E+15	1.09E+15	8.56E+14	6.19E+14	4.12E+14	2.48E+14	1.30E+14	5.82E+13	2.29E+13	9.22E+12	5.05E+12	4.10E+12	3.04E+12	3.57E+12	2.99E+12	2.34E+12	1.90E+12
3.23E+16	4.62E+15	3.20E+15	2.67E+15	2.25E+15	1.87E+15	1.55E+15	1.28E+15	9.98E+14	7.21E+14	4.84E+14	2.95E+14	1.60E+14	7.78E+13	3.47E+13	1.52E+13	6.83E+12	3.33E+12	2.04E+12	1.87E+12	1.95E+12	1.85E+12	1.71E+12
1.82E+16	1.63E+16	9.01E+15	6.23E+15	4.59E+15	3.49E+15	2.74E+15	2.19E+15	1.68E+15	1.22E+15	8.27E+14	5.16E+14	2.93E+14	1.56E+14	8.03E+13	4.24E+13	2.31E+13	1.30E+13	7.82E+12	5.69E+12	4.75E+12	3.96E+12	3.30E+12
1.71E+16	1.38E+16	7.84E+15	5.54E+15	4.15E+15	3.20E+15	2.56E+15	2.07E+15	1.59E+15	1.19E+15	7.77E+14	4.83E+14	2.78E+14	1.54E+14	8.71E+13	5.22E+13	3.18E+13	1.91E+13	1.17E+13	8.35E+12	7.11E+12	6.35E+12	5.63E+12
6.37E+16	7.80E+16	7.00E+16	5.27E+16	3.18E+16	1.46E+16	5.30E+15	2.02E+15	9.87E+14	7.89E+14	7.65E+14	5.77E+14	3.26E+14	1.40E+14	4.82E+13	2.23E+13	2.19E+13	2.33E+13	2.03E+13	1.54E+13	1.11E+13	8.16E+12	6.48E+12
6.66E+16	7.94E+16	6.76E+16	4.91E+16	2.87E+16	1.27E+16	4.35E+15	1.62E+15	8.16E+14	7.31E+14	7.27E+14	5.39E+14	2.93E+14										

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APPENDIX B

METHODOLOGY DEVELOPMENT TEST

SERDP Project WP-1538

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June 24, 2011

ABSTRACT

A measurement test method using modern PM measurement techniques is under development to replace EPA Method 5 for reporting PM emissions of gas turbine engines for the Joint Strike Fighter Program. This test method is to be applied at the engine exit plane in a manner similar to regulatory measurements of gas species on commercial engines. A ground-level engine test campaign on a military turbine engine was conducted to experimentally address unresolved PM measurement issues identified during prior NASA PM characterization studies on gas turbine engines. These issues include sampling, instrument comparisons, instrument calibrations, sample line penetration and engine representativeness. This report documents the Methodology Development Test, experimental results and recommendations for the new PM measurement test method.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Defense through the Strategic Environmental Research and Development Program (SERDP) and the Office of the Chief of Naval Operations (N45). It is a pleasure to acknowledge Mr. Bruce Sartwell, Dr. Jeffrey Marqusee, Mr. Charles Pellerin and Mr. Jeff Houff for their leadership and enthusiastic support of this project. We are thankful to the advisory council for their oversight and advice.

We appreciate the efforts of Mr. William Voorhees, Director of Science and Technology, Propulsion and Power Engineering Department of Naval Air Systems Command, for initiating this effort and Mr. Steven Hartle and Mr. Curtis Kimbel, Naval Air Systems Command, for their administration during the initial phases of this project.

We appreciate the efforts of the Air Force Management at Tinker AFB for making available piggy-back test opportunities for the Methodology Development Test; in particular Mr. David P. Hughes and Mr. Jeffrey L. Copeland and the staff who directly supported the research group.

And there are several organizations and individuals with valuable contributions that supported the planning, provided measurements or technical collaboration. We gladly acknowledge:

Dr. Stephen O. Andersen - US EPA, Director of Strategic Climate Projects, Office of Air and Radiation

Mr. Triet Nguyen - Navy Aircraft Environmental Support Office (AESO), SAE E31

Dr. Xu Li-Jones - CTR FRC-SW, 08212, AESO, SAE E31

Mr. Keith Skaggs and Dana Yenawine - AESO

Ms. Jean Hawkins - Joint Program Office, JSF, Environmental, Safety and Health Manager

Dr. Anuj Bhargava - Pratt & Whitney (JSF PM Measurement Requirements), SAE E31

Dr. David Liscinsky – United Technologies Research Center, SAE E31

Dr. Chowen Wey - Army Research Lab, SAE E31

Dr. Bruce Anderson, Dr. Edward Winstead, Mr. Charles Hudgins and Mr. James Plant - NASA Langley Research Center

Mr. Richard Shores – EPA-Research Triangle Park

Dr. W. Berk Knightington and Mr. Edward Fortner – Montana State University

Dr. Wayne Miller - University of California-Riverside

Dr. Dave Gemmill - Quality Assurance Consulting, LLC

Mr. Roy Carroll, Mr. Gary Storey and Mr. Brad Besheres – ATA/AEDC, Arnold AFB

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Dr. Ezra Wood, Mr. Ryan McGovern, Mr. Robert Prescott, Ms. Eva Wong and Dr. John Jayne - ARI

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LIST OF ACRONYMS

AEDC	Arnold Engineering Development Center
AESO	Aircraft Environmental Support Office
AFB	Air Force Base
AMS	Aerosol Mass Spectrometer
APEX	Aircraft Particle Emissions eXperiment
ARI	Aerodyne Research Inc.
ATA	Aerospace Testing Alliance
CPC	Condensation Particle Counters
DQI	Data Quality Indicator
DMA	Differential Mobility Analyzer
DMS	Differential Mobility Spectrometer
DoD	Department of Defense
EC	Elemental Carbon
EPA	Environmental Protection Agency
FID	Flame Ionization Detector
FPCL	Fine Particle Characterization Laboratory
FTIR	Fourier Transform Infrared
HFID	Heated Flame Ionization Detector
HITRAN	High Resolution Transmission Molecular Absorption Database
IPMTM	Interim PM Test Method
JSF	Joint Strike Fighter
MAAP	Multi-Angle Absorption Photometer
MASS	Mobile Aerosol Sampling System
MGA	MultiGas TM Analyzer
Missouri S&T	Missouri University of Science and Technology
NASA	National Aeronautics and Space Administration
NRMRL	National Risk Management Research Laboratory
PLA	Power Lever Angle

PM	Particulate Matter
PTR-MS	Proton-Transfer Reaction Mass Spectrometer
PTFE	Polytetrafluoroethylene
QAPP	Quality Assurance Project Plan
QC	Quality Control
SAE E-31	SAE E-31 Aircraft Exhaust Emissions Measurement Committee
SERDP	Strategic Environmental Research and Development Program
SMPS	Scanning Mobility Particle Sizer™
SOA	State-of-the-Art
SS	Stainless Steel
TC	Thermocouple
THC	Total Hydrocarbons
TILDAS	Tunable Infrared Laser Differential Absorption Spectrometer

LIST OF TERMS AND SYMBOLS

EI	Emission Index
EIm	Mass-based emission index [g/kg-fuel]
EIm-area	Mass-based emission index of particle surface area [cm ² /kg-fuel]
EIm-nvPM	Mass-based emission index [g/kg-fuel] of non-volatile Particulate Matter
EIm-x	Mass-based emission index for species “x” [g/kg-fuel]
EIn	Number-based Emission Index [number/kg-fuel]
EIn-nvPM	Number-based emission index [number/kg-fuel] of non-volatile Particulate Matter
EIn-x	Number-based emission index for species “x” [number/kg-fuel]
M	(Total) particle mass concentration (derived from integral of number size distribution)
M(N ₀)	Mass of Aerosol per Unit Volume of Exhaust Sample
M(X)	Mass of a Substance X per Unit Volume of Exhaust Sample
n	(Logarithmic) differential number concentration
N	(Total) number concentration of the particle size distribution
NFF	Normalized Fuel Flow
Q	Gas flow rate
SN	Smoke Number

B-1.0 INTRODUCTION

The US Department of Defense is required to measure and report the gaseous and particulate matter (PM) emissions from military turbine engines as a part of federal, state and local environmental reporting requirements. This information is critical for determining the allowable number of aircraft based at military installations. In lieu of EPA Method 5 that has been used for reporting particle emissions from military engines and sea-level test facilities, the DoD is developing a PM test method for the Joint Strike Fighter (JSF) Program that implements modern particle measurement techniques. These techniques are to be applied at the engine exit plane in a manner similar to regulatory measurements of gas species on commercial engines. Modern particle measurement techniques offer improved accuracy in PM reporting, provide additional information such as the particle size distribution, and require shorter engine run times at significantly reduced costs. The overall program objective is development of an Interim PM Test Method (IPMTM) to replace EPA Method 5 for use in reporting PM emissions for the JSF Program.

The IPMTM plan calls for two ground-level engine test campaigns on military turbine engines. The first is the Methodology Development Test designed to experimentally address unresolved measurement issues identified during prior NASA PM characterization studies. The second test campaign will evaluate the interim method using the diagnostic probe-rake and sampling system hardware developed for the JSF F135 particle characterization measurements. The results of the validation test program will be used to finalize the interim method document.

The Methodology Development Test was conducted to address unresolved issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine representativeness. Investigators from the Arnold Engineering Development Center (AEDC), Missouri University of Science and Technology (Missouri S&T) and Aerodyne Research, Incorporated (ARI) planned and conducted the test campaign. These investigators are responsible for the development of the interim PM test method. The measurements were conducted in collaboration with investigators from the U.S. EPA, NASA and the Navy Aircraft Environmental Support Office (AESO) who also performed PM characterization measurements. EPA measurements were conducted as a part of the Methodology Development Test and are reported. Results from the NASA and AESO measurements were incorporated into the recommendations for the interim test method through collaboration and technical workshops. However, the explicit measurements and data are not reported here.

This report describes the Methodology Development Test and recommendations for the IPMTM derived from the results of the experimental studies. The test was conducted on an F100-220 engine in an engine test facility at the Tinker Air Force Base, OK during the last week of March and first week of April 2007. Preliminary results were used in drafting the IPMTM document. Due to a delay in funding, analysis of the data was not completed until late 2009. Updated recommendations accounting for final analysis results were incorporated into the IPMTM document, as appropriate.

B-1.1 TEST OBJECTIVES

The Methodology Development Test was designed to focus on unresolved issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine data

representativeness. The objectives addressing specific issues, in no order of priority, are listed here:

- Experimental assessment of sample dilution at the probe tip for determination of a minimum acceptable sample dilution ratio;
- Experimental assessment of sample dilution at the probe tip versus a downstream sample line location;
- Experimental assessment of sample line flow velocity;
- Experimental assessment of sample line temperature (active heating on and off);
- Experimental assessment of engine power level on PM sampling parameters focused on mitigation of sampling issues due to changes in sample-line flow pressure, temperature, and velocity;
- Experimental assessment of the ratio of particles formed from condensable species (volatile particles) within the sample system to non-volatile particles, evaluated as a function of engine power level;
- Demonstration of field methods for sample system penetration measurements and PM instrument calibration/performance checks;
- Assessment of data for reporting engine representativeness.

B-1.2 TEST CONFIGURATION

The Methodology Development Test was conducted on an F100-220 engine in Building 3703 at Tinker Air Force Base in Oklahoma City, OK. The control room was located adjacent to the test cell as shown in Figure B-1.1. An F100-220 engine was mounted on a test stand in the Test Cell 3 sea-level engine test facility as shown in Figure B-1.1 and Figure B-1.2. The engine exhaust was vented through the diffuser duct, or augmentor tube, and after several meters was turned vertically and vented through the roof of the facility.

The sampling probes were mounted between the engine exit and the exhaust diffuser duct as shown in Figure B-1.1 and the photograph in Figure B-1.2. The rake and probes are shown in better detail in Figure B-1.3. Sample lines were routed from the probes in the test cell, through wall feed-through ports into the machine room, and down the hallway to the particle and gas analyzer instruments located in the trailers and vans parked outside the building. Figure B-1.4 shows the outside facility wall just beyond the vertical exhaust stack where the trailers were parked during the test. The Missouri S&T, ARI, AEDC, AESO and NASA trailers and vans were parked along the wall near the Test Cell 3 hallway opening as shown in Figure B-1.1 and photographs in Figure B-1.5. NASA and AESO conducted measurements along with the team dedicated to development of the interim test method. Although their results were used in the assessment and recommendations reported here, their explicit measurements and data are not documented in this report.

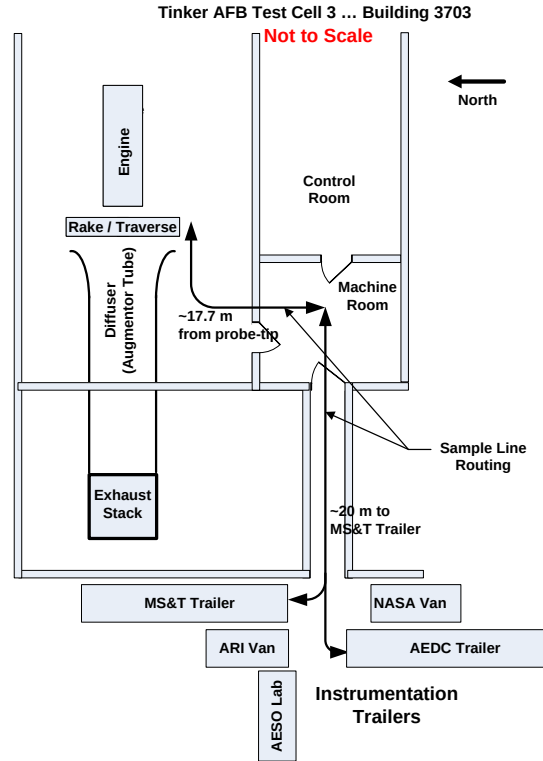


Figure B-1.1 Illustration of the Test Facility and Measurement Layout.

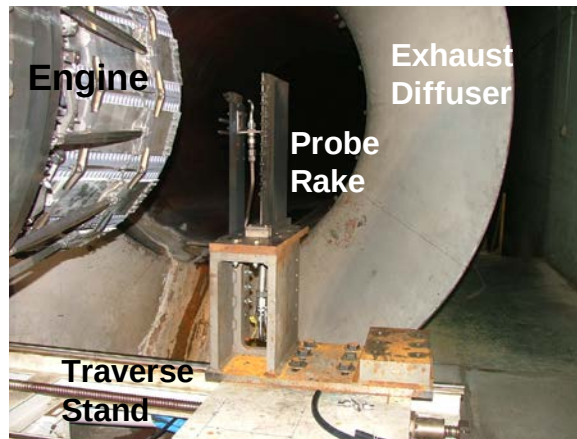


Figure B-1.2 Relative positions of the engine, probe-rake traverse stand and the exhaust diffuser duct.

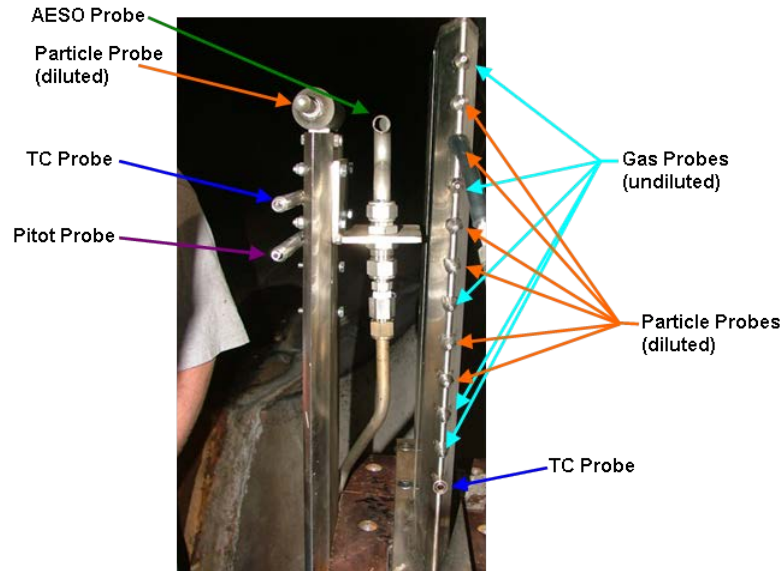


Figure B-1.3 Photograph of the rakes and probes for the Methodology Development Test at Tinker (looking downstream from the engine).



Figure B-1.4 Outside of the Tinker Test Cell 3 before trailers were positioned.



Figure B-1.5 Photographs showing relative trailer placement outside Tinker Test Cell 3.

Measurements were performed at steady-state engine power level settings ranging from idle to maximum (non-afterburning). The chosen metric for setting the engine power was fuel flow

rate. The fuel flow rate was normalized to the maximum fuel flow measured during the check out run. A normalized fuel flow (NFF) rate greater than 1.0 indicated the engine setting deviated from the intended set point. Normalized fuel flow rates, not absolute values, are reported in this document.

B-1.3 SAMPLE RAKE, PROBES AND TRAVERSE SYSTEMS

Probe support structures were attached to a traverse stand mounted between the engine and the exhaust diffuser duct as shown in Figure B-1.1. The probe tips were placed at an axial position within a few inches of the engine nozzle exit plane of the engine. During the test, the probes were traversed to fixed horizontal positions across the nozzle exit plane to perform spatial profile measurements. At horizontal rake positions, measurements were performed at vertical probe positions along the rake.

Figure B-1.3 shows the rakes and probes used during the Methodology Development Test. The skewed appearance of the vertical rake to the right is an artifact of the camera. The right-most rake in Figure B-1.3 was water cooled and contained the primary sampling probes for the test. The rake was developed by AEDC for NASA and has been used in several DoD and NASA research efforts including APEX1 and JETS-APEX2. This rake has 12 probe ports spaced at 3.12 cm (1.25 in) intervals along the rake structure. The rake was configured as shown in Figure B-1.3 (forward-looking-aft) and schematically in Figure B-1.6 (aft-looking-forward) with six water-cooled particle sampling probes, five water-cooled gas sampling probes and one thermocouple (TC) probe. Probes were designed specifically for particle measurements. The particle probes have the capability to add dilution gas to the sample near the probe tip as illustrated in Figure B-1.7. The gas sampling probes do not have dilution capability and were used primarily for conventional gas species concentration and smoke number measurements.

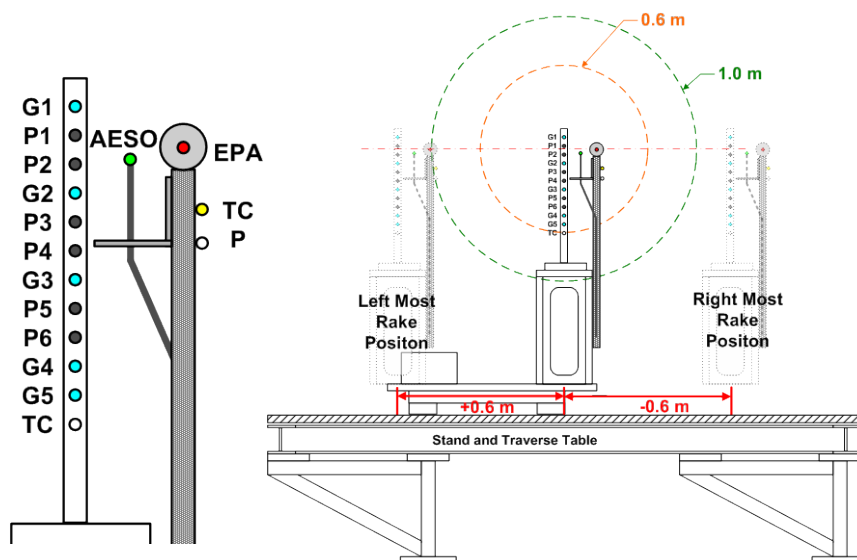


Figure B-1.6 Rake and probes in relation to the nozzle exit (aft-looking-forward).

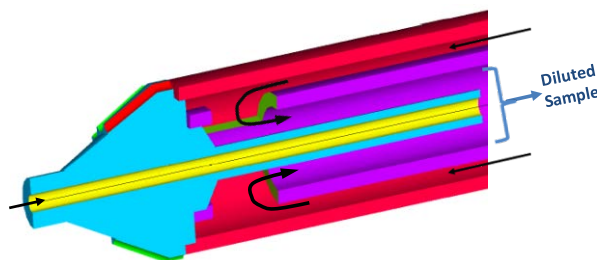


Figure B-1.7 Cross-section view of the particle probe sampling concept.

The left most probe-support structure in Figure B-1.3 supports a single water-cooled particle probe mounted atop a strut that holds the probe approximately 15.2 cm (6 in) from the primary probe-rake. This probe was dedicated to EPA for filtered, gravimetric mass measurements. Two probes were mounted to the left side of the strut; one a thermocouple probe for measuring total exhaust temperature and the other a pitot probe for measuring the exhaust total pressure. The probe in the center belonged to AESO and is referred to as a “button hook” probe. The AESO probe, Figure B-1.3, was mounted to the right side of the strut about mid-way between the EPA probe and the primary probe-rake system. The AESO measurements complemented this effort but were performed independently and are not reported here.

Figure B-1.6 illustrates the rake mounted to the traverse stand behind the engine. The small circles on the primary rake represent the probe locations; “G” designates gas and “P” designates particle probes. The second probe from the top was located approximately 6.3 mm (0.25 in) above the vertical centerline of the engine nozzle. The large inner and outer circles illustrate the smallest (0.6 m) and largest (~1.0 m) nozzle exit diameters for the range of engine power level settings during the test. The nozzle exit diameter was maximum (~1.0 m) at ground idle, decreased to about 0.71 m at flight idle, and further to 0.6 m at the highest power level setting. The probes in the primary rake spanned about half of the nozzle diameter at the horizontal-centerline rake position. The primary rake was traversed during steady-state power level settings (nozzle diameters-fixed) to perform spatial measurements across the lower half of the exhaust plume.

All primary measurement techniques used in the sampling study required in situ exhaust sampling. As discussed earlier, the rake contained dilution probes designed specifically for particle sampling by introducing dilution gas (dry N_2) within the probe tip as shown in Figure B-1.7. The rake also contained undiluted gas sampling probes for measurements of conventional gas species concentration and smoke number. During a traverse operation, probes positioned outside the physical dimensions of the nozzle exit were seldom sampled. The particle probes were operated functionally similar to applications in the APEX1, JETS-APEX2 and APEX3 test programs. Lessons learned in these test programs were incorporated in the Methodology Test operations. A dilution control system was developed to increase the accuracy and provide semi-automated control of the amount of dilution. Carbon dioxide (CO_2) measurements were performed on the diluted particle probe sample and the undiluted gas probe sample to accurately determine the operating dilution ratio in the particle sample line.

B-1.4 SAMPLING SYSTEM

The primary components of the particle sampling system used for the IPMTM development team are illustrated schematically in Figure B-1.8. Exhaust gas entering a particle probe is mixed with

a diluent gas (dry, particle-free N₂) introduced within the tip of the probe and continued through a sample line to a valve box containing three-way valves that allow remote selection of one or more probes to be sampled. The valve box had multiple input lines, but only one sample line out that was referred to as the trunk line. For each non-selected probe, the respective three-way valve directed the sample from the input line to a pump vented to the atmosphere. Diluted exhaust sample from the probe, or probes, selected for sampling, traveled to the Missouri S&T instrument trailer via the trunk line. Within the trailer, the diluted exhaust sample was further distributed to the various instruments using the valve distribution system.

The gas sampling system used to transport exhaust to gas analyzers was similar except that no dilution gas was provided to the sample.

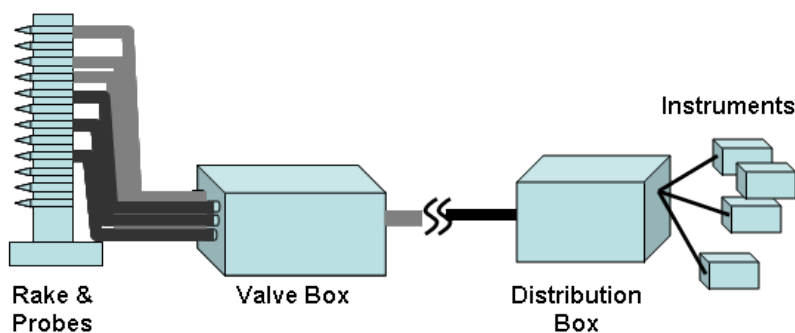


Figure B-1.8 Block diagram of the sample system.

For the primary rake, the sample lines from the particle and gas probes to the base of the rake stand were made of 0.64 cm (0.25 in) diameter stainless steel (SS). These lines averaged approximately 1.5 m in length. Sample lines from the base of the rake to the valve box were about 3 m in length. These lines consisted of 0.95 cm (0.375 in) diameter flexible conductive-Polytetrafluoroethylene (PTFE), commonly called Teflon® tubing, rated for particle measurements. The main trunk lines, from the valve box located near the traverse stand to the distribution box in the Missouri S&T trailer, were made of SS. These lines were 1.9 cm (0.75 in) diameter and approximately 29 m in overall length, made up of 6.1 m (20 ft) sections. All primary lines were wrapped with electrical heater strips and insulated. Particle measurements were performed with the particle sampling lines heated and unheated. The main trunk lines from the valve boxes were routed through wall ports from the test cell to the machine room (see Figure B-1.1). From the machine room, the main trunk lines were routed up and over a hallway door, down the hallway and out of the building through the outside wall opening (see Figure B-1.1) to the Missouri S&T trailer.

The gas probe sampling system was configured and operated in a similar manner, but without adding diluent gas to the sampled exhaust flow. These lines were routed to the AEDC trailer. An exception was experimental measurements using a gas probe for particle measurements. In that case, diluent gas was introduced into the sample line at the base of the rake stand approximately 2 m from the probe tip. Sample lines from the gas probes were always heated to approximately 150 °C to prevent water condensation.

Prior PM measurements conducted on an F135 engine (unpublished) and an F100-229 engine in the 1990's (Howard, et al.) indicated that particle number concentrations were comparatively low for advanced military fighter engines. It was recognized that at idle, low particle number concentrations might rival the detection limits of the particle instruments for desired dilution

levels. Also, the desired sample line flow rates are more difficult to achieve at idle due to low exhaust ram pressure at the probe inlet. Optimized sampling parameters for both particle number detection and sample line flow rate can require simultaneous sampling from two particle probes for lower power level settings. The rake was designed to allow installation of either probe type (gas or particulate) at either probe location prior to testing. For this purpose, the rake was configured with pairs of neighboring particle probes as shown in Figure B-1.3. The particle sample system was designed to control diluent flow individually to one or two simultaneous particle probes as needed.

B-1.5 EXHAUST SAMPLING STUDY MEASUREMENT STRATEGY

The technical approach consisted of utilizing state-of-the-art (SOA) measurement techniques and a particle sampling methodology based on previous measurement campaigns. This approach is believed to have the greatest promise for accurate PM characterization at the harsh nozzle exit plane conditions that are characteristic of military gas turbine engines.

B-1.6 SAMPLING STUDY MEASUREMENT PARAMETERS

In previous measurement studies, priority was given to emissions characterization rather than resolving all sampling issues. However, sampling issues were noted. For our purposes, the sampling study required an engine, ideally with exhaust conditions that are representative of the exhaust flow for the F135 engine. Although not ideal, the F100-220 engine was deemed suitable. An extensive set of data were obtained to resolve protocol sampling issues with a series of experiments focused on:

- Varied source pressure and temperature to cover the range of conditions expected in future test environments (achieved via engine power level settings);
- Varied dilution to the probe tip;
- Compared probe-tip and downstream sample line dilution;
- Measured chemical speciation under such conditions;
- Varied sample line temperature with active heating on and off;
- Varied amounts of condensable species versus non-volatile particles (achieved via engine power level settings and sample dilution ratio);
- Varied sample line velocity (achieved via engine power level settings and sample extraction variables).

B-2.0 DIAGNOSTICS AND INSTRUMENTATION

B-2.1 MISSOURI S&T DIAGNOSTIC MEASUREMENT SYSTEMS

The Missouri University of Science and Technology (Missouri S&T) deployed their Mobile Aerosol Sampling System (MASS) and a Cambustion DMS500 analytical system which has been used on previous field campaigns (Schmid et al., 2004; Lobo et al., 2007). MASS employs state-of-the-art differential mobility analysis and condensation nucleus counting to measure particle number, surface area and volumetric size distributions in jet engine exhaust flows. The volumetric size distributions and total particle concentrations were combined with an appropriate mass density to produce size-dependent mass-based particulate emission factors. The Cambustion DMS500 fast particulate spectrometer instrument provided fast response

measurement capability (approximately 200 ms) for the size and number concentration of engine exhaust PM over the full particle size spectrum ranging from 5 nm to 1000 nm.

The Missouri S&T diagnostic instrument list for the Methodology Development Test included the following:

- Two fast particle size spectrometers (Cambustion DMS 500, 5-1000 nm, 1Hz)
- Thermal denuder set at 300 °C to precede one of the DMS 500 for non-volatile PM monitoring
- TSI CPC's (2 each of model numbers 3022, 3025)
- Tandem DMA system for hydration property analysis (soluble mass fraction)
- Fast CO₂ concentration monitors
- Laser Particle counter
- Relative humidity monitors
- Sample flow distribution and dilution control system
- Weather station

B-2.2 ARI DIAGNOSTIC MEASUREMENT SYSTEMS

Aerodyne Research, Inc. (ARI) provided real-time instrumentation for measuring particle size and composition-resolved distributions of aerosol particles (aerosol mass spectrometer (AMS)). ARI also provided a tunable infrared laser differential absorption spectrometer (TILDAS) for measuring gas-phase exhaust constituents. A proton transfer reaction mass spectrometer (PTR-MS) was also used on the diluted sample to measure hydrocarbon constituents in the exhaust including those that can coat the non-volatile particulate phase and the volatile PM.

The ARI AMS provides quantitative real-time inorganic and organic particulate mass and size-resolved compositional analysis of aerosol particles in the size range from 0.04 to ~1.5 µm diameter. The AMS consists of an aerodynamic lens (Zhang et al., 2002) that focuses sub micron particles (30 nm to 1 µm diameter) into a differentially pumped vacuum chamber (Jayne et al., 2000). Particle velocity, measured via time-of-flight between a mechanical chopper and the detector, determines the aerodynamic diameter of the aerosol particles. The detector consists of a resistively heated vaporizer placed directly in the electron impact ionizer of a quadrupole mass spectrometer. Volatile and semi-volatile components are flash-vaporized and are analyzed (0 - 400 amu mass range) by a mass spectrometer. A distinct advantage of this approach is the separation of particle vaporization and exhaust gas detection, enabling quantification (via straight forward calibrations) of vaporized particulate matter species. Moreover, electron impact ionization generated mass spectra can be directly compared with standard mass spectral libraries. Elemental carbon (EC), including engine non-volatile PM, does not vaporize at the 600-1000 °C temperature of the detector.

The ARI TILDAS instrument provides rapid time response optical measurements of exhaust gas species, such as NO, NO₂, CO, and SO₂, and reactive trace species, such as HONO and formaldehyde. The TILDAS can measure up to four species simultaneously, with a response time that is limited only by the sampling system flow and the optical volume (1/3 liter). The TILDAS system is among the world's best gas phase species detection systems that can be deployed in the field. For sampling at a speed of one Hz, the detection limit for all species measured is less than a few ppb. The instrument works by a direct wavelength sweep in the vicinity of one or more infrared absorption features. The resulting baseline-resolved absorption

profile is curvefit to a Voigt absorption model, which accounts for the known innate linewidth and broadening due to pressure and Doppler effects. The concentrations measured by TILDAS are tied only to known linewidths in a database such as HITRAN. Though no calibration of this system is required once the linewidths are known, at the Methodology Development Test, calibration standards were used for NO, NO₂ and CO measurement accuracy validation.

A key aspect of the ARI measurements is the combination of the AMS and TILDAS data with that of other instruments aboard the Lab. For example, CO₂, which serves as the plume ‘dilution’ tracer, is measured by a commercial LiCOR instrument. Both the AMS and the TILDAS instruments provide data with a time response of seconds, allowing transient behavior and variation in emission performance to be quantitatively tracked in real time.

ARI used the following instruments during the Methodology Development Test:

- Aerosol Mass Spectrometer (AMS)
- Condensation Particle Counter (CPC)
- Scanning Mobility Particle Sizer (SMPS)
- Multi-Angle Absorption Photometer (MAAP)
- Licor CO₂ measurement
- NO by Chemiluminescence (NO_x box)
- Tunable Infrared Laser Differential Absorption Spectrometers (TILDAS) for species such as NO₂, CO, HCHO (formaldehyde), C₂H₄ (ethylene)
- Proton Transfer Reaction Mass Spectrometer (PTR-MS) for species such as acetaldehyde, propene, acrolein, benzene, other aromatic compounds and hydrocarbons up to a molecular weight of ~150 amu

B-2.3 AEDC DIAGNOSTIC MEASUREMENT SYSTEMS

AEDC provided real-time instrumentation for measuring gaseous species concentrations and the standard filter-extraction based instrument for smoke number measurements. These measurements were performed to compliment the PM data and data quality assurance. If there were anomalies in spatial PM data, gas measurements could be used to diagnose the engine combustion efficiency in those regions. Additionally, AEDC provided the probe-rake system and sample system traverse system, and thermocouple and pressure transducer data acquisition systems.

The gaseous concentrations measurements were performed using a Fourier transform infrared (FTIR) spectrometer based MKS Instruments Model 2030 MultiGasTM Analyzers (MGA) capable of measuring a large number of infrared-active gas species (CO, CO₂, H₂O, NO, NO₂, SO₂, and lighter hydrocarbons from CH₄ to C₄H₁₀). Total hydrocarbon (THC) measurements were performed using a Model 300 Heated Flame Ionization Detector (HFID) analyzer made by California Analytical Instruments.

Smoke number (SN) measurements were acquired using procedures defined in the SAE Aerospace Recommended Practices (ARP) 1179.

AEDC used the following instruments and hardware during the Methodology Development Test:

- MultiGasTM Analyzer (MGA)
- Flame Ionization Detector (FID)

- SAE Smoke Meter (SM)
- Thermocouples (TC)
- Pressure Transducers
- Video Cameras
- Probe-Rake System
- Traverse System

B-2.4 EPA DIAGNOSTIC MEASUREMENT SYSTEMS

To support this engine test program, the EPA's National Risk Management Research Laboratory (NRMRL) was requested to conduct Teflon filter sampling and gravimetric analyses to determine the PM mass emissions using a direct gravimetric method in lieu of on-line instruments with their inherent limitations. NRMRL provided an appropriate filter sampling system to conduct these measurements.

B-3.0 DETAILED DATA ANALYSIS

This section discusses on a point-by-point basis, issues addressed during the Methodology Development Test. Section B-3.1 provides an overview of expected and observed trends supporting the discussion and analyses presented in Sections B-3.2 through B-3.9. The data are reported in terms of emission index (EI) defined as the "quantity" of emissions of a given constituent per thousand mass units (kg) of fuel burned. The mass emission index of PM (EIm) is the mass of PM per thousand grams of fuel burned. The number emission index of PM (EIn) is the number of particles per kg of fuel burned.

B-3.1 OBSERVED TRENDS WITH RESPECT TO ENGINE POWER LEVEL CONDITION

The formation of non-volatile particles and condensable gas species (organic materials and sulfate), products of the combustion process, varies with engine power level. Strategies to eliminate particle microphysics in the sample line must be effective over the entire range of power conditions. The changes in non-volatile particle and condensable species production can be summarized as follows:

- Based on previous measurements acquired on military and commercial engines, measured PM parameters versus engine power are qualitatively similar but their absolute measurement trends differ for engines of different types.
- As the engine power level increases, measured number-based non-volatile PM emission index (EIn-nvPM) increases reaching a maximum at normalized fuel flow rate (NFF) > 0.6. Figure B-3.1 depicts the correlation of measured EIn-nvPM and NFF for the applicable data acquired during the Methodology Development Test.

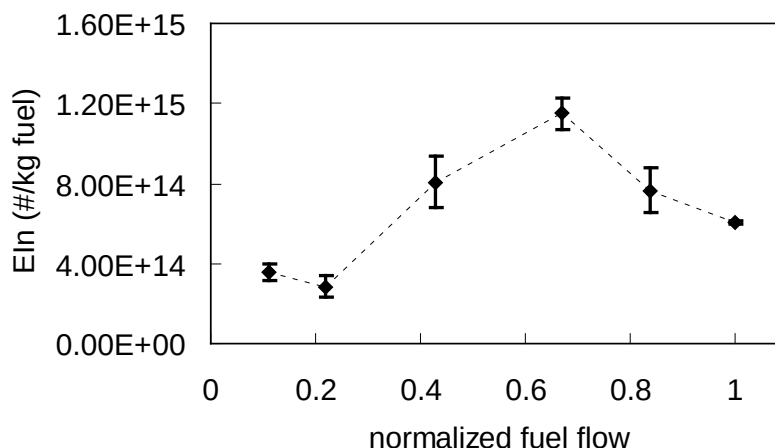


Figure B-3.1 Number-based emission index as a function of NFF.

- As the engine power level increases, the measured mass-based non-volatile PM emission index (EIm-nvPM) increases, reaching a maximum at NFF > 0.6. The EIm-nvPM is depicted in Figure B-3.2 for non-volatile PM data measured by the MAAP during the Methodology Development Test. Although the measurement is essentially based on absorption of light, the response is proportional to emitted mass. No information about particle size is provided by the MAAP black carbon measurement.

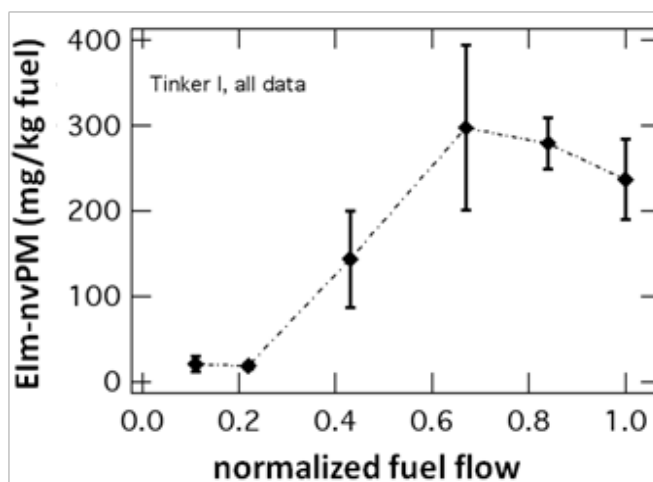


Figure B-3.2 Non-volatile PM emission index as a function of NFF.

- Particle size increases with increasing fuel flow rate. Figure B-3.3 depicts measured particle size distributions normalized to ppmv of CO₂ for two normalized fuel flow rate conditions, NFF=0.11 for idle and NFF=1.0 for take-off. Note that, despite the relatively small increase in apparent integrated area between idle and take-off, there is a greater relative increase in mass as seen in Figure B-3.3. This is attributed to the cubic dependence of particle mass on diameter. A similar result is observed for particle surface area due to its quadratic dependence on particle diameter.

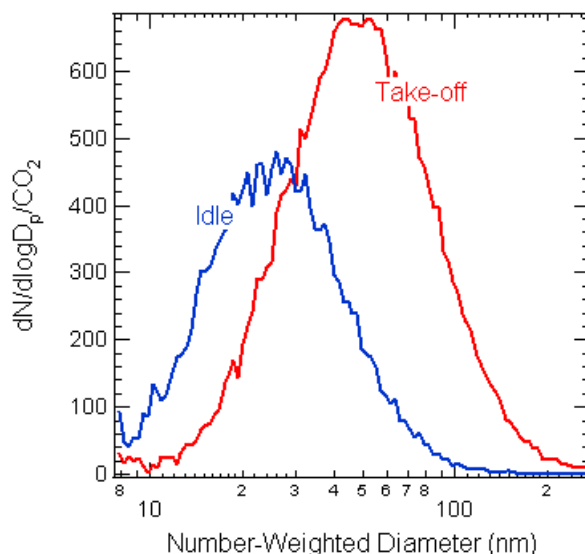


Figure B-3.3 Non-volatile size distributions for idle and take-off.

- The exhaust exiting the engine contains non-volatile PM and minor volatile gas constituents (precursors, organics and sulfur oxides) that have a propensity, as the gas cools, to nucleate and form volatile particles (new particle formation) and/or condense and coat non-volatile particles. There are no volatile particles in the exhaust at the engine exit plane, only their gas phase precursors. New particle formation and condensation can occur in the sampling line as the sample gas temperature is lowered through interaction with the cooler sample line walls. Sulfate material plays two important roles in particle microphysics of these condensation processes. Sulfate is the primary driver for new particle formation (AIR6037). Sulfate can also activate non-volatile particles causing their surfaces to be more effective for condensation of condensable gases. Organo-sulfur compounds naturally present in petroleum jet fuels are the source of particle sulfate materials in aircraft exhaust. During combustion, fuel sulfur compounds are oxidized quantitatively (> 99%) to SO_2 . A fraction of the SO_2 is oxidized further to SO_3 . SO_3 then combines with water vapor to form sulfuric acid, which has sufficiently low volatility to partition to the particle phase. Therefore, a key parameter is the SO_2 to SO_3 conversion efficiency. A number of studies have attempted to quantify SO_2 conversion, and the conversion efficiency seems to be on the order of 1%. Lukachko et al. (2008) recently performed a numerical simulation of SO_2 conversion and found it to be relatively independent of engine operating condition. Therefore, the quantity of SO_3 and condensable sulfuric acid present in exhaust gas is likely to be insensitive to engine power level.
- There are two primary forms of condensable organic materials, each with different dependencies on the engine power level condition. One is lubrication oil and the other form consists of products of incomplete combustion. Lubrication oil can be identified directly from AMS particle mass spectra due its unique composition (Timko et al., 2008). Lubrication oil emissions vary significantly from engine to engine and seem to depend on venting and recovery systems. Lubrication oil is vented into the exhaust flow downstream of the combustor and therefore not combustion related. Measurements attributable to mass-based emission index of oil do not vary strongly with engine power level condition. Depending on the engine, lubrication oil can be emitted directly as liquid droplets ($d > 100$ nm) or possibly as a vapor that condenses onto non-volatile PM. During the Methodology

Development Test, it was determined that lubrication oil was a negligible component of the condensable organic PM (< 10 wt %). Nonetheless, other military engines may emit lubrication oil making it an issue of concern with potential to influence the PM measurements.

- Products of incomplete combustion are identified as the residual in the AMS organic particle mass spectra after lubrication oil has been removed. The residual mass spectrum is consistent with a typical hydrocarbon mixture, similar to both unburned and partially burned fuel. Moreover, the ratio of lubrication oil to residual organic compounds is minimized for older technology, inefficient engines and at low power conditions. Just as mass-based emission index for CO (EIm-CO) and hydrocarbons (EIm-HC) are maximized at idle conditions, so too should the emission index of condensable organic materials produced during incomplete combustion. As the engine power level is increased beyond idle, EIm-CO and EIm-HC rapidly decrease by several orders of magnitude, ultimately reaching undetectable levels. The concentrations of other condensable gases from incomplete combustion should also decline roughly in parallel with EIm-CO and EIm-HC, though this has not been confirmed experimentally.

Table B-3.1 summarizes the expected trends of emission indices of non-volatile particles and gases that can partition to the particle phase as a function of engine power level.

Table B-3.1 Effects of Engine Power Level Conditions on the Emission Indices of Measured Particles and Condensable Gases.

Species	Effect of Engine Power Level
EIn-nvPM	generally higher at take-off than at idle, though each engine type may exhibit different profile trends
EIm-nvPM	generally higher at take-off than at idle, though each engine type may exhibit different file trends
EIm-area (total surface area)	generally higher at take-off than at idle, but the effect is weaker than for EIm-nvPM due to larger particle size at takeoff conditions.
EIm-SO ₃	relatively insensitive to engine power level
EIm-oil	insensitive to engine power level
EIm-organic	expected to be maximized at idle conditions and decrease rapidly by two or more orders of magnitude as the engine power level increases

B-3.2 SPATIAL VARIATION OF EXHAUST EMISSIONS

Gas turbine engine emissions cannot be assumed to be azimuthally symmetric. Therefore, spatial measurements are required to define a set of measurement points that can be used to represent the total emissions from the engine. Measurements were performed using a number of gas and particle probes distributed vertically along the rake. The rake was mounted on a traverse table that moved the rake horizontally. This allowed sequential measurements at a large number of spatial locations distributed across the lower half of the exhaust plume. Figure B-1.6 illustrates the translating probe rake assembly system.

This discussion focuses on spatially resolved data acquired during the same engine test run at two separate NFF settings, specifically NFF equal to 0.11 and 0.67. Figure B-3.4 and Figure B-

3.5 show EIn-nvPM measurements versus radial position within the core region of the exit plane for both NFF settings. The error bars reflect a 20% uncertainty in EIn-nvPM consistent with estimates reported for similar measurements in Schmid et. al, 2004. The solid red line represents the average EIn-nvPM for all radial positions at a fixed NFF. The dotted red lines represent associated standard deviations in the average value. Since both the error bars and the uncertainty in the average overlap, based on data for this run, it is reasonable to conclude that within the limit of experimental uncertainty, there is no statistically significant spatial variation in the value of measured EIn-nvPM for these engine power level settings.

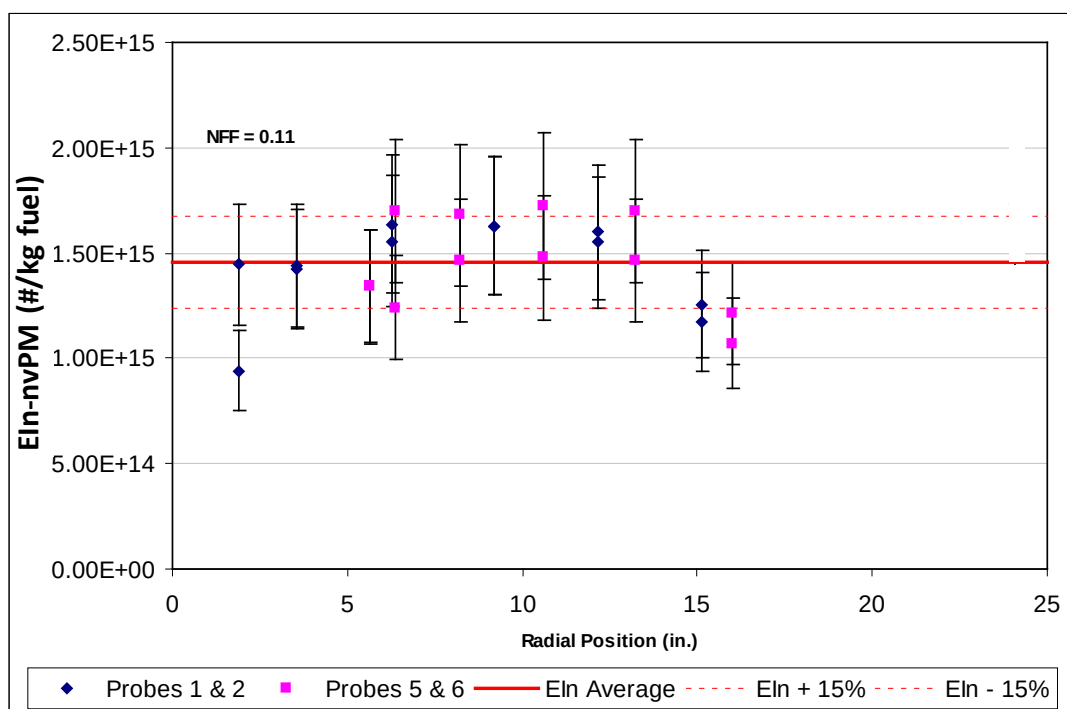


Figure B-3.4 EIn-nvPM versus radial position for 0.11 NFF.

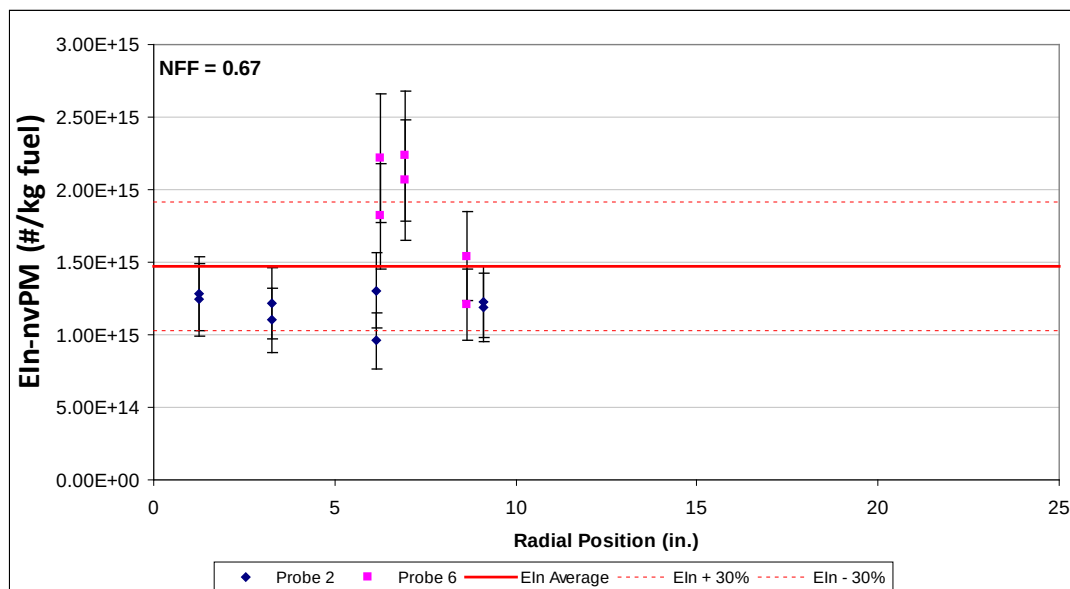


Figure B-3.5 EIn-nvPM versus radial position for 0.67 NFF.

B-3.2.1 Summary

To acquire emissions measurements representative of the engine, emissions mapping of the engine exhaust exit plane should be performed at a representative set of engine power conditions. Historical data for these types of military engines indicate that spatial profiles of emissions, at least for emission index, are similar over the range of engine power levels from idle to takeoff. This opens the possibility of defining a sampling protocol with detail spatial mapping of emissions at two nominal engine power settings and a reduced set of spatial point measurements at other engine power level conditions. For example, based on the data presented in Figure B-3.4 and Figure B-3.5, where no statistically significant spatial variation is reported, the sampling protocol could require only a measurement at a single location in the exhaust plane where the measured parameters best matched the average parameter value. Although this is an interesting outcome of this study, it is not recommended that measurements be limited to single locations per power setting for the interim PM test method. This concept will be examined further during the second test program, planned as a validation of the interim test method, for selecting a reduced number of measurement points at some power settings.

B-3.3 THE EFFECT OF ENGINE POWER LEVEL CONDITION ON THE MEASUREMENTS OF CONDENSABLE SPECIES VERSUS NON-VOLATILE PARTICLES.

Microphysical processing of condensable species in the sampling system (specifically formation of new particles and condensation on existing non-volatile particles) can lead to measurement bias errors. Formation of new particles in the sample system artificially inflates measurements of EIn-nvPM that is intended to be the emission index of the total number concentration of non-volatile particles only. Condensation on existing non-volatile particles artificially increases the diameter, volume, and mass. And, coatings of condensed materials can influence the optical properties of the particles. Optical properties are not specifically a part of the IPMTM, but this type of bias must be avoided. Therefore, the sampling system must be designed to minimize formation of new particles and condensation on existing non-volatile particles.

The rates of microphysical processes depend on the sample temperature, concentration (or dilution ratio), residence time, and the quantity of available non-volatile particle surface area. Increasing sample temperature or dilution ratio will decrease the vapor pressure of condensable gas species which tends to reduce the partitioning of the gas phase to the particle phase. Increasing the available non-volatile particle surface area will tend to increase condensation and – depending on the amount of condensable material available – has no effect on new particle formation. In some instances, condensation and new particle formation processes are competitive. In these instances, conditions which favor one process will tend to suppress the other. Additionally, newly formed volatile particles can collide with existing non-volatile particles and the condensed material contributes to the non-volatile particle coating. Most PM instrument techniques cannot distinguish between coagulation of newly formed particles and non-volatile particles, nor direct condensation of gaseous material on non-volatile particle surfaces.

B-3.3.1 Non-volatile Particles

During the engine test, the sample line dilution was varied from 4:1 to 15:1 at individual sample locations and the measured particle data assessed to determine the minimum dilution ratio suitable for the range of sampling and engine operating conditions. Figure B-3.6 shows EIm-nvPM measurements acquired during the Methodology Development Test; the figure shows three separate panels labeled (a), (b) and (c). In each panel, the vertical units are EIm-nvPM in units of mg kg^{-1} fuel. In panel (a), the data is shown as a function of NFF. In panels (b) and (c) the effect of dilution on non-volatile particle measurements is shown for NFF settings of 0.11 and 0.67, respectively. The blue points in the figure were collected using unheated sample lines while the red points were collected using heated sample lines.

As expected, based on previous measurement studies, the measured EIm-nvPM is greater at the take-off power level than at idle. Unlike many commercial engines which show a gradual increase in measured EIm-nvPM with increasing power level, the EIm-nvPM for the F100-220 measurements increases abruptly from a value on the order of $10\text{--}40 \text{ mg kg}^{-1}$ to a value $> 200 \text{ mg kg}^{-1}$ as NFF increases from 0.22 to 0.43. Figure B-3.6(b) and (c) shows EIm-nvPM for the 0.11 and 0.67 NFF conditions for various dilution levels. No systematic trend with respect to dilution level is apparent in the data – indicating that dilution levels were sufficient to prevent new particle formation and condensation, even for the lowest dilution levels employed.

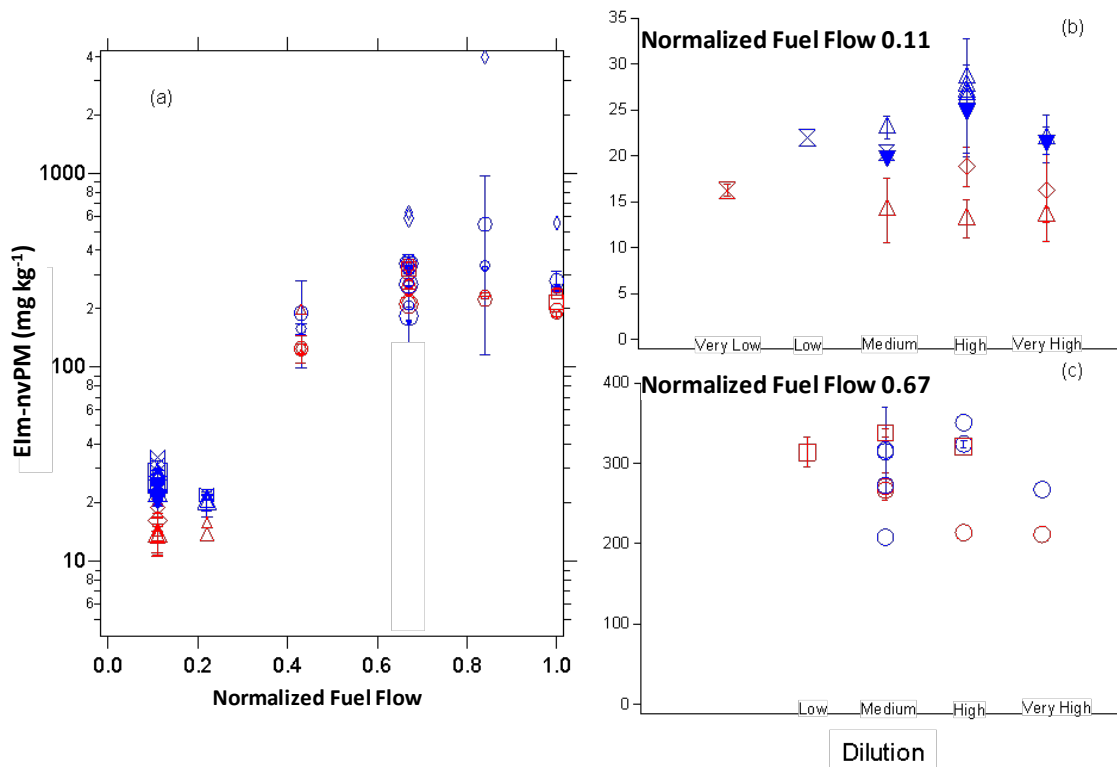


Figure B-3.6 MAAP black carbon emission index results.

B-3.3.2 Volatile Particle Material – New Particle Formation

Figure B-3.3 shows particle size measurements data collected at low (0.11) and high (1.0) NFF. At both NFF levels, the particle size data exhibit a single peak consistent with expectations for non-volatile particles. The data in Figure B-3.3 are representative of the entire data set. At all dilution and normalized fuel flow rate conditions, the presumed non-volatile particle peak concentration is the most intense feature in the particle size distributions, generally by a factor of 20 or more. New particle formation would be evident in the size distribution data as a second particle concentration peak at particle sizes smaller than the non-volatile peak. In some instances, a slight increase in particle number density was detected for particle diameters smaller than 15 nm. But, the mass (volume) of the particles was always much less than 5% of the total particle mass measured. Therefore, Figure B-3.3 provides evidence that new particle formation was suppressed in the sampling line. Furthermore, in agreement with differential mobility analyzer (DMA) measurements, AMS particle size data never showed evidence of condensed material on the non-volatile particles detected by the AMS.

Figure B-3.7 provides further evidence that new particle formation was suppressed in the sampling line. This figure includes measurements of the MAAP Elm-nvPM versus the total integrated DMA volume for all fuel flow rates. As expected for conditions of negligible new particle formation, the total particle volume varies linearly with Elm-nvPM. If new particles had formed in the line, the total DMA volume would not be linear with respect to Elm-nvPM. New particle formation would cause the DMA volume to increase more gradually (with respect to increased engine power level) than is shown in the Elm-nvPM data. Since total particle volume varies linearly with Elm-nvPM, it is concluded that new particle formation in the sample line had

negligible impact on integrated DMA measurements. Figure B-3.7 also contains information on sampling line temperature effects which is discussed in Section B-3.7.

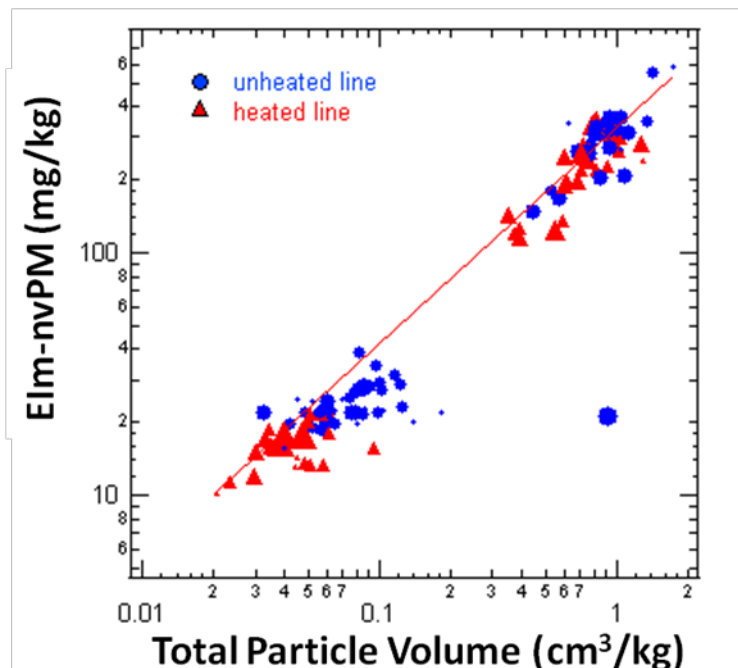


Figure B-3.7 Mass-based EI versus the volume-based EI measurements.

The CPC number measurement provides the most sensitive measurement of new particle formation. For this discussion, the emission index for the CPC measurement is represented as EIn-total, since the measurement is actually the summation of volatile and non-volatile particles and not just the non-volatile particle intended by the measurement. The CPC data in Figure B-3.8 shows EIn-total from measurements acquired during the Methodology Development Test and may show evidence of new particle formation. Panel (a) shows the total particle number versus NFF. In panels (b) and (c), the effect of dilution on EIn-total is shown for the 0.11 and 0.67 NFF test conditions, respectively. The measurements shown in panel (c) indicate that increasing the dilution ratio results in decreasing the EIn-total at the 0.67 NFF. This is consistent with the observations shown in Figure B-3.4 and Figure B-3.5 in the previous section. In contrast, the dilution has no apparent effect on the low thrust CPC data shown in panel (b). The observed effect on EIn-total for 0.67 NFF but not for the 0.11 NFF condition seems to contradict the expectation that new particle formation should be most important at lower engine power settings.

Integrating measured particulate size distributions provides a second measure of EIn-total. New particle formation was not apparent in the DMA-base particle size data and so the integrated EIn-total from the DMA data should be essentially free of the influence of new particles. Figure B-3.9 shows EIn-total from the CPC and the DMA in a parity plot. Figure B-3.9 does not indicate that the CPC EIn-total deviates systematically from the DMA EIn-total in a way that would indicate new particle formation. Therefore, it is concluded that the dilution effect on EIn-total shown in Figure B-3.8 is not likely due to new particle formation, which is suppressed by high dilution levels.

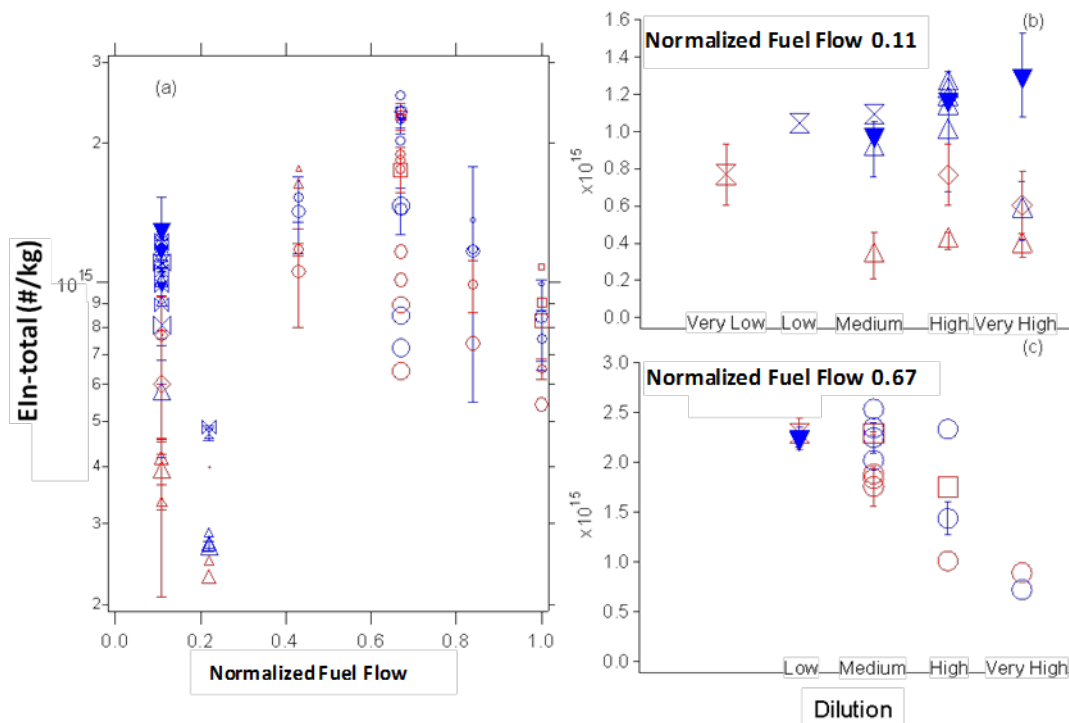


Figure B-3.8 Total particle number emissions, $E_{In-total}$ for the F100-220 engine during the Methodology Development Test.

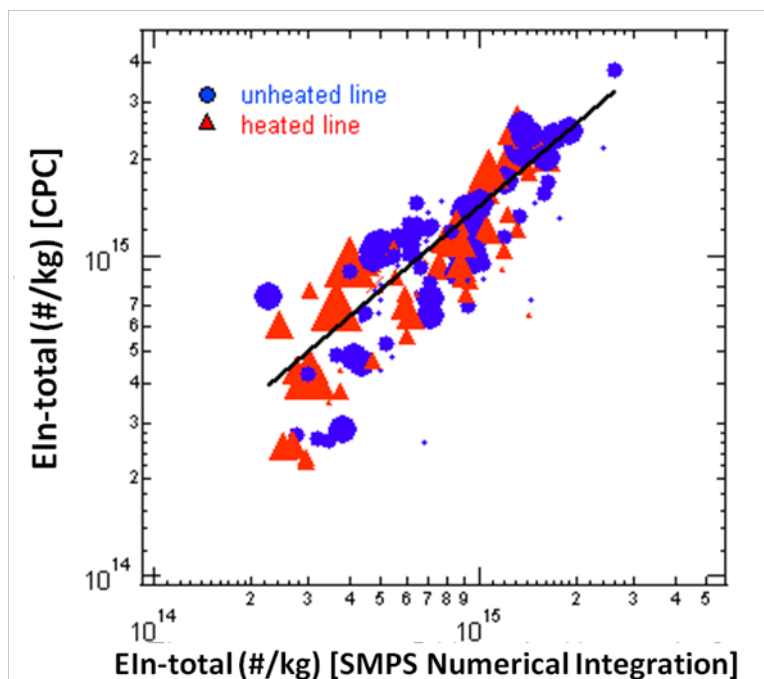


Figure B-3.9 Condensation particle counter data versus integrated scanning mobility particle sizer data.

B-3.3.3 Volatile Particle Material - Condensation on Existing Non-Volatile Particles

AMS data provide the most direct measurement of the volatile coatings acquired by the non-volatile PM. AMS particle size data conclusively show that organic materials are detected as a coating on non-volatile particles. Figure B-3.10 shows measured AMS organic PM size distributions corrected for sample dilution. The four panels represent different NFF settings. The organic mass loadings divided by CO_2 are plotted versus the vacuum aerodynamic diameter. Because this measurement is in mass space, these diameters should only be compared to the volume mode characteristics from a DMA measurement. The red lines indicate data acquired using heated sample lines and the blue lines data acquired using unheated sample lines. The AMS measured size distributions are consistent with the DMA particle size distributions for all engine power conditions. Admittedly, the signal/noise ratio at the lowest power condition (0.11 NFF) is only $\sim 2:1$, but the 40-60 nm peak in organic mass loading is consistent with coatings on non-volatile particles. The dilution level did not strongly influence AMS particle size. While new particle formation was largely suppressed during the tests, volatile materials did condense on the non-volatile particle surfaces in the sample lines. The effect of sample line temperature is discussed in Section B-3.6.

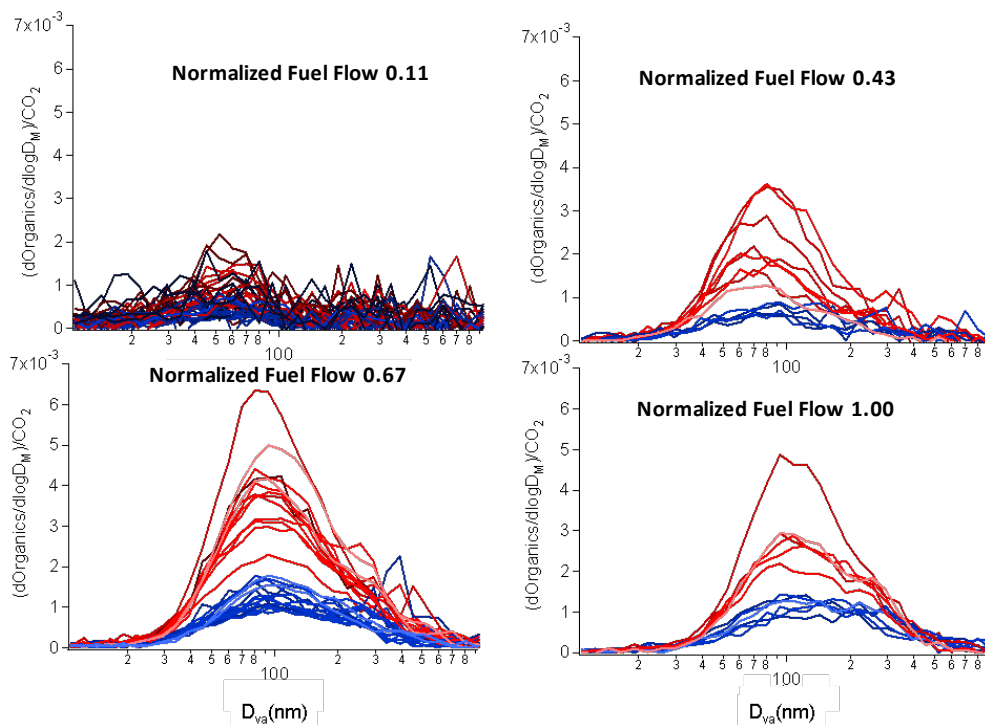


Figure B-3.10 Dilution-accounted AMS organic PM size distribution measurements.

Figure B-3.11 shows the sulfate mass emissions, EIm-sulfate, measured as a function of NFF and dilution level. Panel (a) shows the measured EIm-sulfate versus NFF while (b) and (c) show the effect of dilution at 0.11 and 0.67 NFF, respectively. Based on Figure B-3.11 (a), it is concluded that non-volatile particles have a negligible sulfate coating. Sample line temperature effects are discussed in detail in Section B-3.6, but note that heating the line to 150°C appears to have reduced the sulfate coating from a maximum of approximately 0.3 mg kg^{-1} to less than 0.05 mg kg^{-1} (at or near the AMS detection limit). The effects of dilution level on the sulfate coating, shown in Figure B-3.11 (b & c), appear to be insignificant. However, the data set contains single

measurements at low dilution levels for a NFF of 0.11. In summary, the sulfate coating contribution to total particle mass or volume is negligible compared to the non-volatile particle mass (<5%).

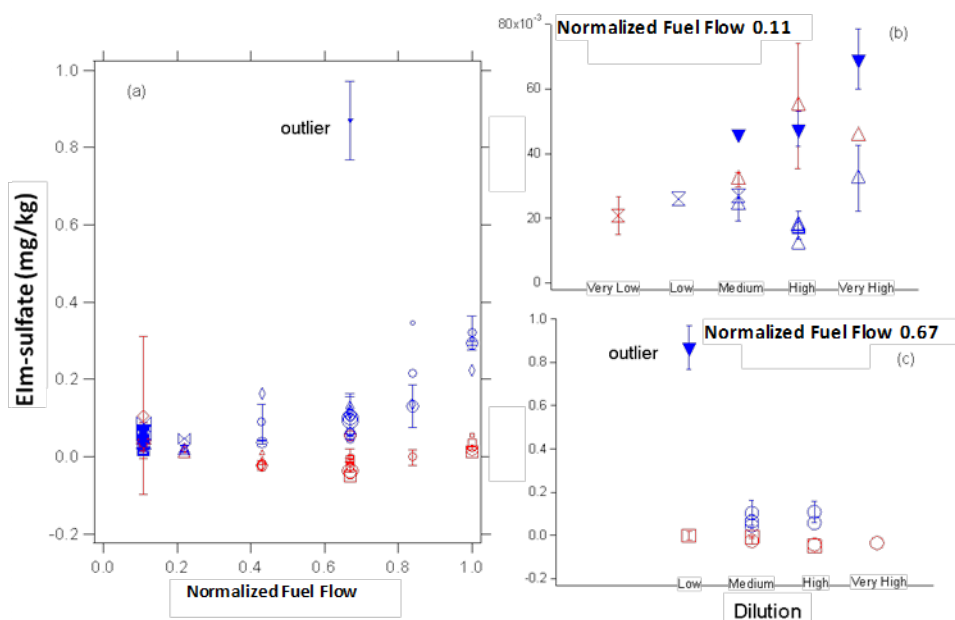


Figure B-3.11 Sulfate mass emissions, EIm-sulfate, as a function of NFF and dilution.

Figure B-3.12 shows the organic mass emissions, EIm-organic, as a function of NFF and dilution level. Panel (a) shows the measured EIm-organic versus NFF while (b) and (c) shows the effect of dilution level at 0.11 and 0.67 NFF settings, respectively. The AMS data in Figure B-3.12 indicate that the mass of organic material coated onto the non-volatile particles is approximately an order of magnitude greater than the mass of the sulfate coating. EIm-organic is at most approximately 10% of EIm-nvPM, and this occurs at low dilution and idle conditions. The AMS mass spectra data suggest that the organic coating is a hydrocarbon material and that lubrication oil constitutes less than 10% of the total organic particle mass. The effect of dilution on EIm-organic is negligible at 0.67 NFF. At 0.11 NFF, EIm-organic appears to increase as the dilution level increases from very low to very high levels. Note that the data set only contains single measurements at very low and low dilution levels. The qualitative trend with respect to dilution level at 0.11 NFF is counter-intuitive. Deposition of organic material on the sample line wall may be an important phenomenon that needs investigation.

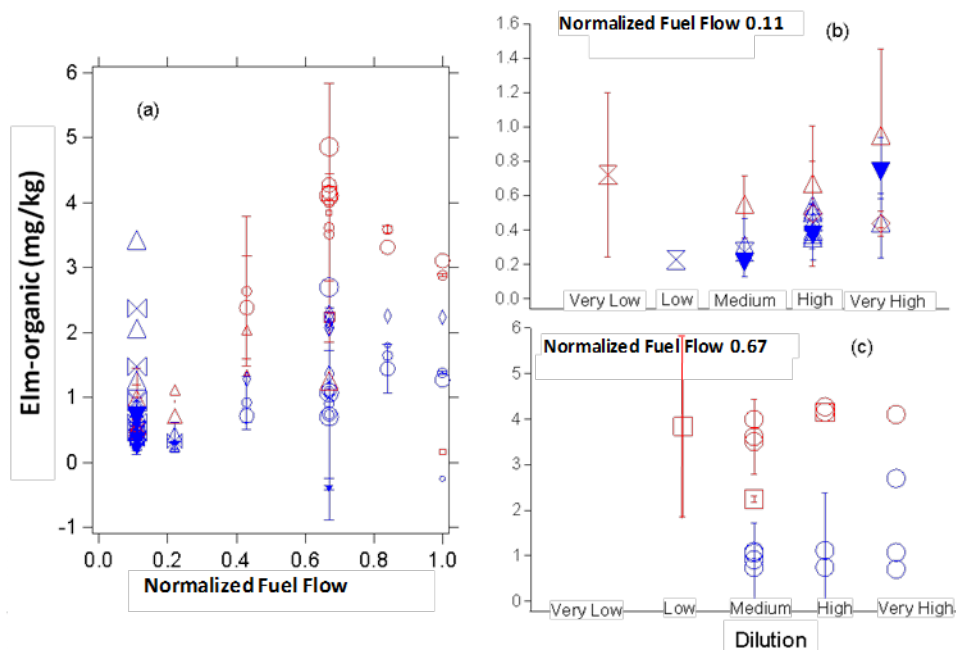


Figure B-3.12 Organic mass emissions, EIm-organic, as a function of NFF and dilution level.

B-3.3.4 Summary

- EIm-nvPM is greater at take-off conditions than idle and follows a general trend that has been reported in previous studies (Wey et al., 2007; Lobo et al., 2008);
- New particle formation in the sample lines has negligible effects on integrated mass and volume measurements at all dilution levels and engine power level conditions. Comparison of EIn-total measured by DMA and CPC instruments suggest that the total particle number emission index is not affected by new particle formation. However, CPC measurements of EIn-total exhibit a dependence on dilution level at the 0.67 NFF.
- Non-volatile particles acquire coatings during their transit through the sample line. Organic materials dominate the mass of the non-volatile particle coating material by a factor of approximately 10:1 over sulfate material. The organic material produced by this engine contains negligible lubrication oil (<10%). Counter-intuitively, the mass of the organic coating observed at idle conditions increased with increasing dilution.
- The correlation between EIm-organic and dilution level may be due to the deposition of organic materials on the walls of the sample line at low dilution conditions and onto particles at high dilution conditions.

B-3.4 OPTIMAL LOCATION FOR DILUTION INTRODUCTION (PROBE TIP VERSUS DOWNSTREAM DILUTION)

The location along the sample line that a dilution gas is introduced to the sample is an optimization variable in sample train design. To minimize particle loss and particle-wall interactions, the dilution point should be as close to the sample probe inlet as possible. However, sampling systems which dilute further downstream are easier to engineer and implement. The impact of introducing the diluent at a location downstream of the probe tip was evaluated. During the Methodology Development Test, PM measurements were performed using a gas

probe and a neighboring particle probe with the sample lines actively heated. For PM measurements on the gas probe, the dilution gas was injected at the rake base. These data were performed at identical engine operating conditions.

Figure B-3.13 shows the EIn-nvPM data for the 0.11 NFF. EIn-nvPM measured with probe tip dilution is found to be relatively constant $\pm 20\%$ over the range of dilution flow rates examined ($\leq$ factor of 3). In contrast, in the case the gas probe with downstream dilution, EIn-nvPM was a factor of up to 2 times the corresponding particle probe values and increased linearly with dilution ratio.

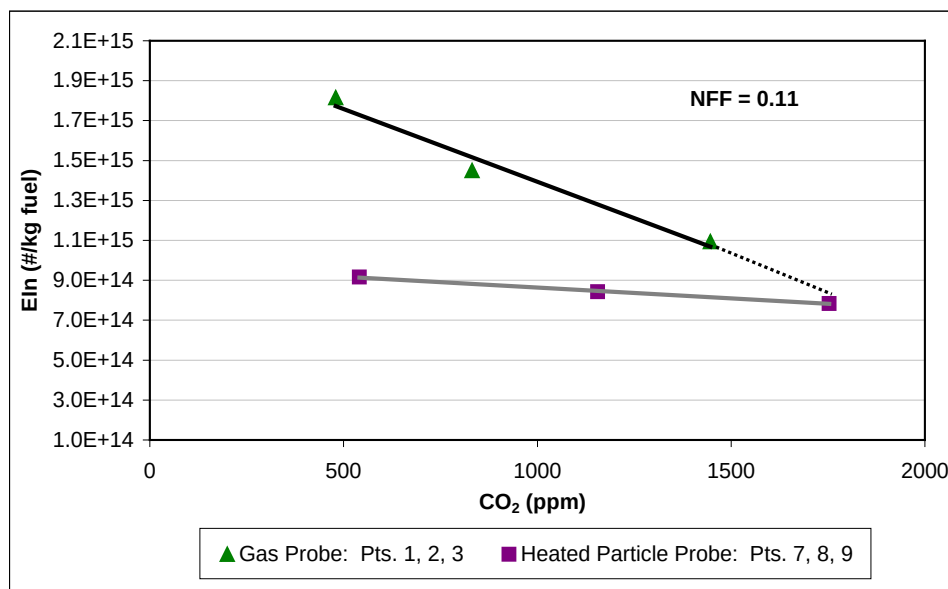


Figure B-3.13 Measurements of EIn at 0.11 NFF using a particle probe diluted near the tip and a gas sample probe diluted at the base of the rake.

Referring to Figure B-3.14, a similar result was not observed at the higher 0.67 NFF. It should be noted that the range of dilution levels was substantially smaller for this case.

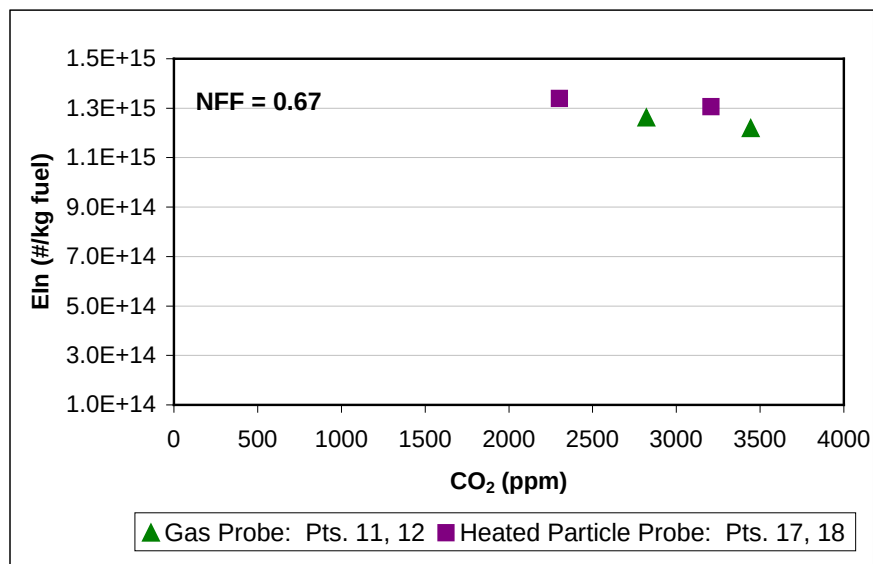


Figure B-3.14 Measurements of EIn at 0.67 NFF using a particle probe diluted near the tip and a gas sample probe diluted at the base of the rake.

B-3.4.1 Summary

Dilution at the probe tip location has been extensively used in previous engine exhaust sampling campaigns conducted over the last decade. These data indicate that probe tip dilution is necessary at low fuel flow rates where a large amount of condensable species are present. At higher fuel flow rates with nominal (or higher) dilution ratios, the requirement was not established; however, the range of dilution levels was limited. Therefore, based on this study, dilution at the probe tip is recommended for the interim test method at all engine power conditions.

B-3.5 EFFECT OF VARIATION OF PROBE TIP DILUTION ON PM PARAMETERS AND CHEMICAL SPECIATION

Extractive sampling of engine exhaust can be susceptible to gas-to-particle conversion processing, since particle growth and new particle formation are strong functions of supersaturation. Therefore, the exhaust sample must be sub-saturated at extraction and along the sample line. Maintaining sub-saturation throughout the sample line can be achieved by adding sufficient diluent gas (clean nitrogen) near the probe tip. Increasing the nitrogen dilution, while maintaining all other experimental variables at constant values, will decrease the concentrations of all condensable gas phase species. Decreasing the concentrations of condensable gas phase species will reduce both condensation on existing particles and formation of new particles. Increasing the nitrogen dilution level will also decrease the concentration of non-volatile particles, thereby reducing the amount of surface area available for condensation. During the test, measurements were performed to determine the optimal sample dilution level required to suppress gas-to-particle conversion while providing an acceptable signal-to-noise ratio.

Groups of measurements were identified that were performed at the same fixed engine and sampling conditions, but with varied levels of dilution. In these groups, it was assumed that adequate dilution was achieved when the total particle concentration value changed proportionately with CO₂ that was used as a tracer to quantify the amount of dilution gas in the

sample. Figure B-3.15 explores the relationship between the measured total particle concentration and diluted CO₂ value for NFF = 0.11. In the figure, a nominal (10:1) or higher dilution ratio was achieved when the diluted CO₂ < 2100 ppm. For nominal and higher dilution ratios, the relationship of total particle concentration and diluted CO₂ is linear. In cases of low nominal dilution ratio, this linear relationship was not preserved.

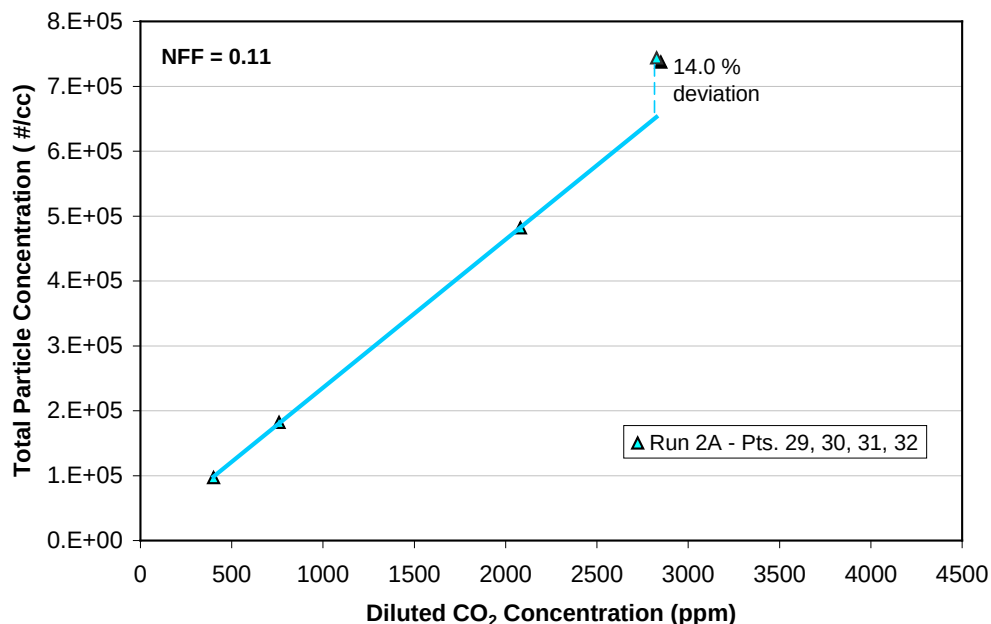


Figure B-3.15 Total particle concentration versus CO₂ concentration for NFF=0.11.

B-3.5.1 Summary

From this analysis, it is recommended that sample dilution ratios $\geq 10:1$ be used for jet engine exhaust sampling at the exhaust nozzle exit plane. At the NFF of 0.11, the concentration of CO₂ in the exhaust is approximately 1.7% (17,000 ppmv). The recommended dilution ratio of 10:1 would suggest that the target concentration of diluted CO₂ in Figure B-3.15 is approximately 1,700 ppmv.

B-3.6 EFFECT OF SAMPLE LINE TEMPERATURE (ACTIVE HEATING ON AND OFF) ON PM PARAMETERS AND CHEMICAL SPECIATION

Sample lines for measurements of gaseous emissions must be heated to prevent condensation of water during sample transport. But, since the sample for particle emissions measurements is diluted with dry nitrogen, the sample line heating requirement can be relaxed and still avoid water condensation. However, it is beneficial to specify a sample line temperature for the interim PM test method to eliminate line temperature as a variable in the sampling process. Heated sample lines also offer the potential benefit of reducing condensation of volatile gases during sample transport. With this in mind, a sample line heating study coupled with a dilution level study was conducted to experimentally investigate potential effects on PM measurements.

The non-volatile nature of carbonaceous particles emitted from gas turbine engines suggests there should be no influence of temperature on the EIm-nvPM. Typically, non-volatile particles from turbines are characterized by volume geometric size diameters between 40-120 nm. Particle penetration experiments generally show reasonably high sample line transmission fractions for

particles in this size range. The presumption was that sample line temperature should not influence non-volatile particle emissions measurements, unless there was an influence on gas-to-particle conversion and condensation of volatile gases.

To evaluate the effect of sample line temperature on the measured EIm-nvPM, two sample line conditions were examined: actively heated to 150 °C and no active heating. Without active heating, the sample lines equilibrated to ambient temperature which varied during the week of testing from 4-27 °C. The heated sample line temperature of 150 °C was chosen to be relatively consistent with the requirement of gas sample line temperature for engine certification testing. The evaluation data (test runs 2A and 2B) were performed on the same day while holding all other independent variables (engine power level, dilution level) constant.

Figure B-3.16 (lower panel) shows the MAAP EIm-nvPM measurements versus NFF for unheated and heated sample lines. The dashed lines connect the average measurements for the given fuel flow rates. The upper panel shows the difference in the results for the heated and unheated sample lines. The typical difference observed for NFF > 0.4 is ~20%. In general, non-volatile PM measurements increase as fuel flow rate increases from 0.11 to 0.67. For larger values of NFF, the emission measurements hold steady or taper slightly. Most of the variable dilution level experiments were conducted at 0.11 and 0.67 fuel flow rates. For data collected at 0.67, the difference between heated and unheated lines shows some overlap. However, the averages indicate that the heated-line EIs are about 20% lower than for unheated lines. Essentially, whenever the black carbon emission index is above 50 mg kg⁻¹, the difference is 20%. We conclude that this effect is real. The following discussions elaborate on this conclusion.

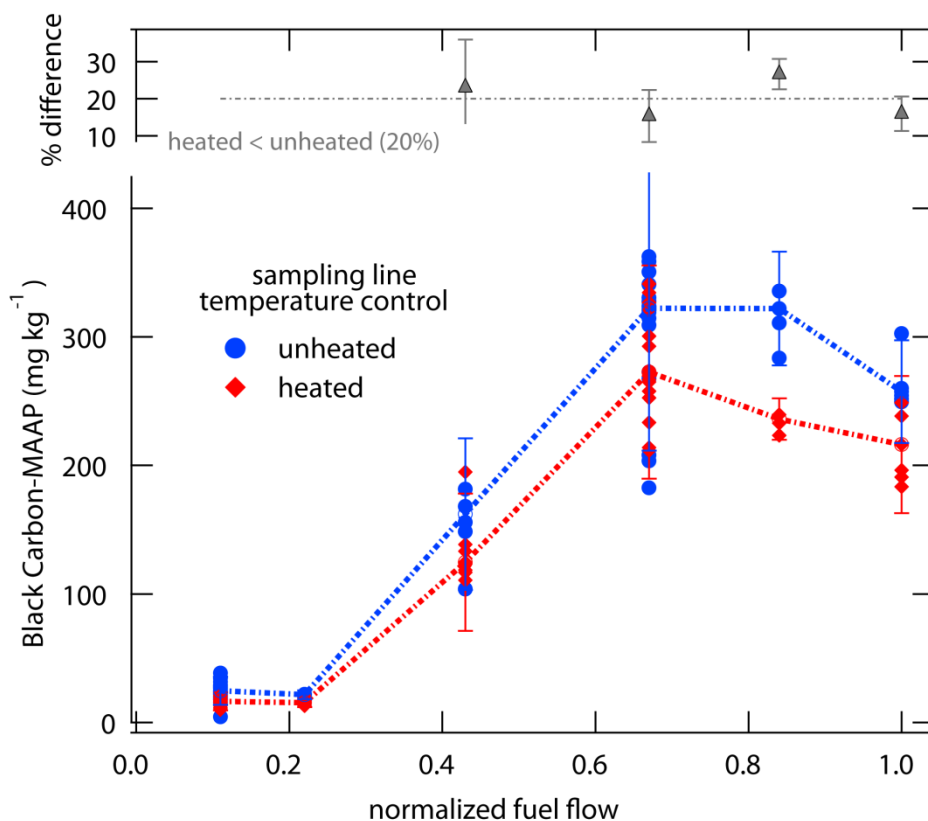


Figure B-3.16 Measured EIm-nvPM versus normalized fuel flow rate.

The fraction of volatile gases and thus the potential for new particle formation and condensation is greater at lower engine power settings (low NFF). Possible reasons for the behavior of non-volatile particle emissions measurements at low values of NFF include: instrument measurements artifacts, microphysical phenomenon in the sample line, and dependence of emissions on ambient temperature. These issues are addressed by answering the following questions.

- Does the Multi-angle absorption photometer (MAAP) have an artifact?
- Are microphysical processes occurring in the sample line?
- At 'idle', are the non-volatile particle emissions from the engine dependent on ambient temperature?

B-3.6.1 Does the Multi-angle absorption photometer (MAAP) have an artifact?

The presence of organic coatings on non-volatile particles could potentially produce an adverse influence on the MAAP measurement. The presence of a weakly absorbing organic coating can geometrically 'lens' the light into the black carbon particle core, effectively increasing the net absorption (Bond et al., *JGR* 2006). More absorption would increase the value reported as the measurement of mass. However, estimates of the available mass present in the coating (as measured by the AMS) suggest this would be a minor effect.

Since the DMA uses an analytical approach that does not rely on optical absorption, a comparison of the MAAP data to the mass determined from the DMA size distribution measurements was performed to offer insight to this issue. Figure B-3.17 shows DMA particle size distribution measurements for the unheated (blue) and heated sample line (red/orange) conditions for 2 different engine power settings. The total particle concentration measurements clearly decrease at both engine power settings when the lines are heated. The DMA is a particle classification instrument that counts particles. This means that the number based size distribution is the parent data recorded. A volumetric projection of this size distribution, an assumed particle density (1.0 g cm^{-3}) and correction for the dilution level during the measurement was used to synthetically estimate the DMA based EIm-nvPM assuming no condensation, coagulation or other microphysical processing.

The engine idle data points for the MAAP measurements are plotted in Figure B-3.18 versus the mass estimated from the DMA size distribution measurements. The one to one line is included as a red dashed line for guidance. Essentially, the MAAP and the DMA measurements agree and it is concluded that the Multi-angle absorption photometer (MAAP) does not have an artifact. The diamond data points were acquired with the sample line heated and are generally lower than the circle data points acquired with the line unheated. The fact that two different instrumental approaches agree is strong evidence that the sample line heating affects the measurement and is not an instrumental artifact.

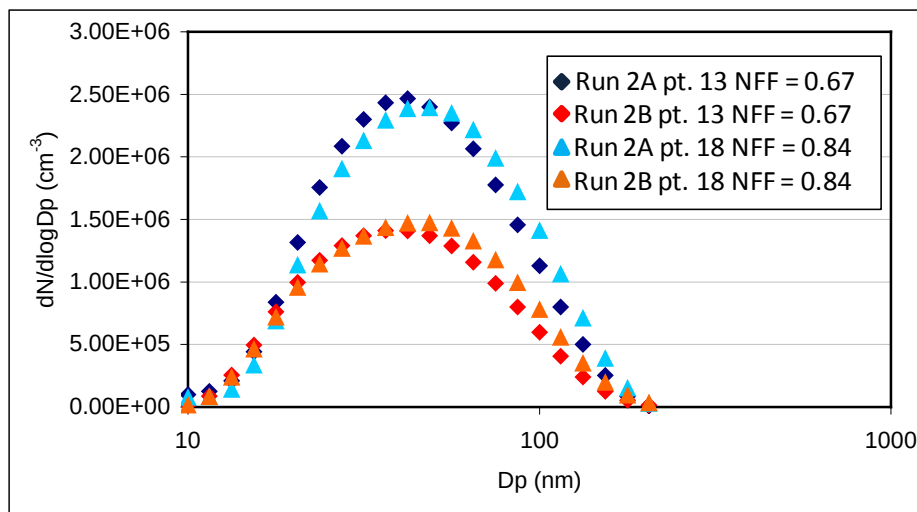


Figure B-3.17 Particle size distributions for heated (red/orange) and unheated (blue) sample lines.

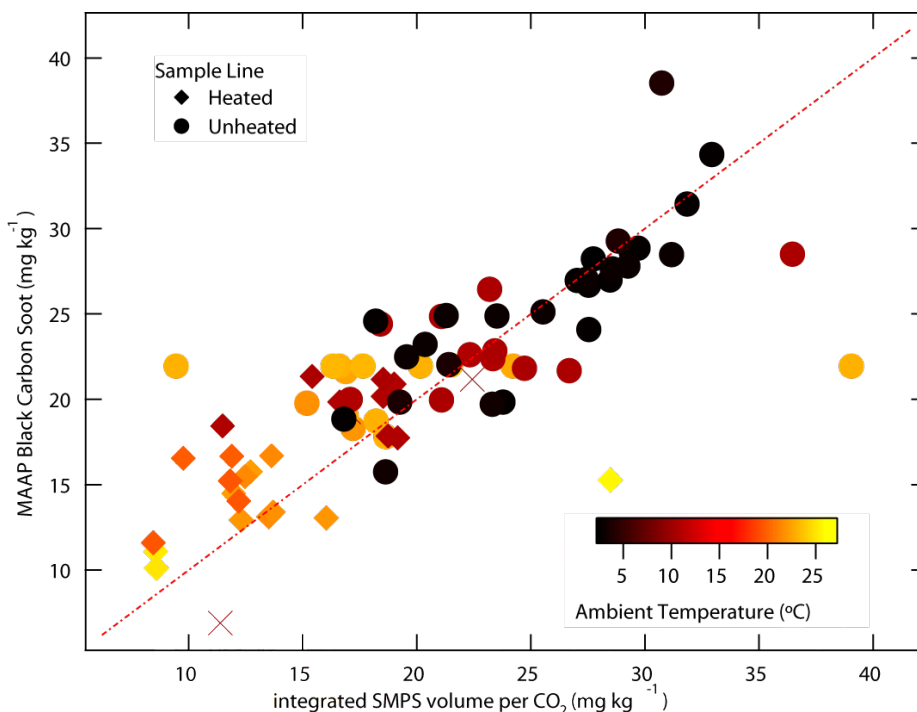


Figure B-3.18 Measurements of MAAP EIm-nvPM versus the synthetic emission index calculated from the DMA size distribution measurements for engine idle (NFF = 0.11).

B-3.6.2 Is there a microphysical phenomenon occurring in the sample line?

Microphysical processing in the sampling line might be expected to affect measurements of PM characteristics. As we concluded earlier, condensation on existing non-volatile particles is the only microphysical process which occurred in the sample lines. Differences in measured particle diameters might provide evidence for differences in condensation on non-volatile particles between the two operating modes. However, the volume based geometric mean diameters between the heated and unheated lines are not consistently different. With the stark difference in

mass exhibited for the ‘idle’ data in Figure B-3.16, if this were driven by condensation or evaporation of ‘semi-volatile’ compounds in the sample line, it would present differences in the mode diameters, which is not observed.

B-3.6.3 At ‘idle’, are the non-volatile particle emissions from the engine dependent on ambient temperature?

The data points in Figure B-3.18 are colored by the ambient temperature. The meteorological data were taken from a meteorological weather station located near the test site and approximates the temperature of the air coming in the engine intake. Measurements conducted on the unheated sample line during the coldest day of the test (dark black points) are all relatively high. This effect can explain most of the observed difference between the heated and unheated sample lines for the low engine power level conditions.

Based on several previous studies, the concentration of CO is also anticipated to have a strong dependence on the ambient ‘intake’ temperature. Figure B-3.19 shows EIm-nvPM as a function of EIm-CO. In the left panel, points are color coded by the sample line operating condition: heated (red) or unheated (blue). The unheated EIs are clearly higher than the heated EIs. However, in the right panel, the same data is color coded by ambient temperature. Colder ambient temperatures lead to larger EIs at idle. Based on this analysis, we propose that differences in ambient temperature explain the observed variations in EIm-nvPM with line condition at idle engine power. We performed a similar analysis at high engine power (0.67 NFF), but did not detect a dependence of EIm-nvPM on ambient temperature. Therefore, the apparent dependence of EIm-nvPM on line condition is “real” at high engine power and must be considered more carefully in future work.

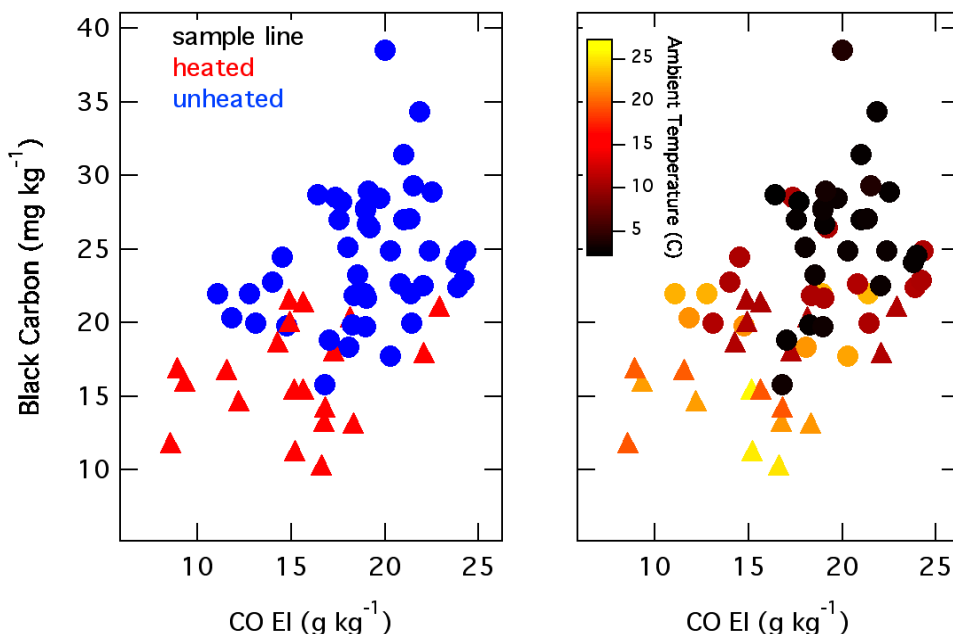


Figure B-3.19 Black carbon EIm-nvPM versus CO EI colored coded by the heated and unheated sample lines in the left panel and ambient temperature in the right panel.

B-3.6.4 Summary

The phenomenon that heating the sample line reduces the measured EIm-nvPM (relative to the unheated lines) by about 20% is a real observation. It is quantifiably observed in every PM characterization method used on this test. The difference in measured EI between hot and cold lines at the 'idle' engine condition is likely to be a result of non-volatile particle emissions differences based on the variation in ambient temperature. However, at higher fuel flow rates, the influence of ambient temperature is not responsible for the observed differences.

In Figure B-3.10 and Figure B-3.12 the organic PM mass emission index for heated sample lines are greater than for the unheated by a factor of 2. Based on evidence from other testing, it is currently surmised that this is due to the use of conductive silicone tubing. It is likely that this material absorbs organic compounds with low volatility and heating the lines releases a large reservoir of condensable material which has nothing to do with the emissions from the engine, but rather the history of gas exposure to the sample line. In a future test venue, the sample line heating experiment should be repeated with and without active heating of the conductive tubing to test this hypothesis.

B-3.7 EFFECT OF PROBE TIP COOLING, INDEPENDENT OF RAKE COOLING

During the Methodology Development Test, water cooling was employed to cool the probe tips and sample rake using the same hardware of the APEX1 and JETS-APEX2 test programs. Generally, the motivation for using probe tip and sample rake cooling is not for the sake of the sample, but rather the survivability of the sampling hardware over a variety of engines and exhaust temperatures. During the APEX3 campaign, an uncooled probe-rake system was used. An analysis of data from the thermocouple mounted inside the rake housing suggests that for higher thrust levels of larger engines, the sample line wall temperatures reached nearly the total temperature of the exhaust despite the probe tip dilution. The strongest and most clear evidence that this may not be desirable comes from an examination of the relative abundances of aromatic compounds. The more functionalized aromatic compounds, such as the dimethyl benzenes or the xylene compounds are somewhat more reactive than benzene itself. Quite clearly the measured ratio of xylene to benzene is lower in APEX3 data sampled near the engine exit on the uncooled probe tip/sample rake than observed at the downstream 30 meter sampling location. This ratio was also lower than typically observed at exit plane measurements in the APEX1 and JETS-APEX2 test campaigns. This can be explained by the fact that hot metal surfaces have greater reactivity or support more reactive radicals than the combined quenching effects of dilution, cooled probe-tip and cooled sample rake. Ongoing analysis is directed at understanding the probe and rake cooling effects on non-volatile PM emissions. Due in large part to the greater variability observed in non-volatile PM emission measurements, the evidence of effects is not yet clear. In the absence of more conclusive data, water-cooled probes are recommended for the interim PM test method.

B-3.8 EFFECT OF SAMPLE LINE VELOCITY INFLUENCED BY ENGINE POWER SETTINGS AND SAMPLE EXTRACTION VARIABLES

Under extreme circumstances it may be possible for sample line velocity to modify the sample PM characteristics. For instance, low line velocities could lead to enhanced diffusional loss because of long transit times. On the other hand, high line velocities can lead to particle loss due to impaction. The potential for these effects are investigated by focusing on the measurements of

EIn-nvPM and EIm-nvPM as a function of sample line velocity. Changes in sample line velocity were accomplished by varying the amount of dilution flow; i.e., more dilution gas yields higher velocity of the sample. Since both EIn-nvPM and EIm-nvPM vary with engine power level, line velocity effects are investigated at fixed engine power level settings. A directly proportional behavior between the dilution ratio and linear velocity is demonstrated by the two series of data: test runs 2A (unheated lines) and 2B (heated lines) shown in Figure B-3.20. Line velocities were varied from 280 cm/s to 1350 cm/s over the NFF range of 0.11 to 0.84. In all cases, no statistically significant dependence was observed for the measured EIs. Figure B-3.21 and Figure B-3.22 provide example EIn-nvPM and EIm-nvPM data for the 0.43 NFF case.

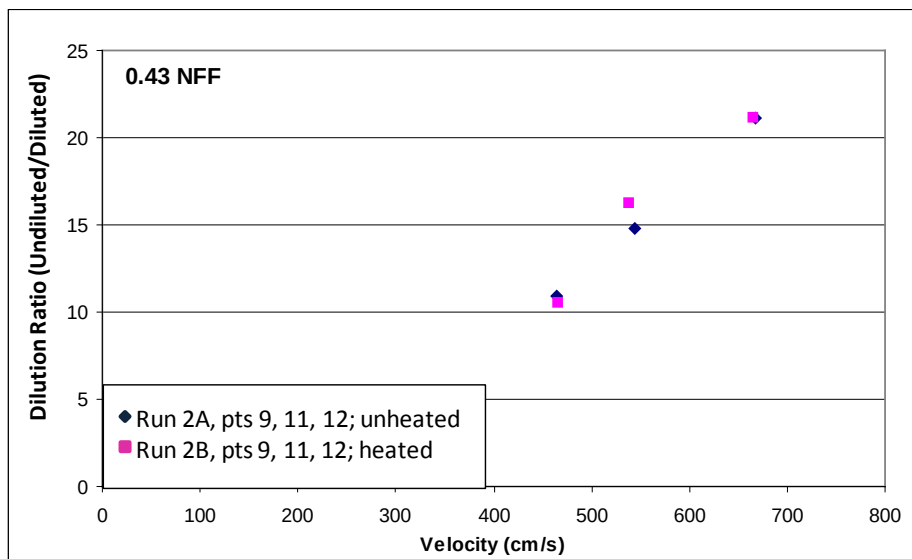


Figure B-3.20 Correlation between dilution ratio and sample line velocity demonstrating proportional relationship.

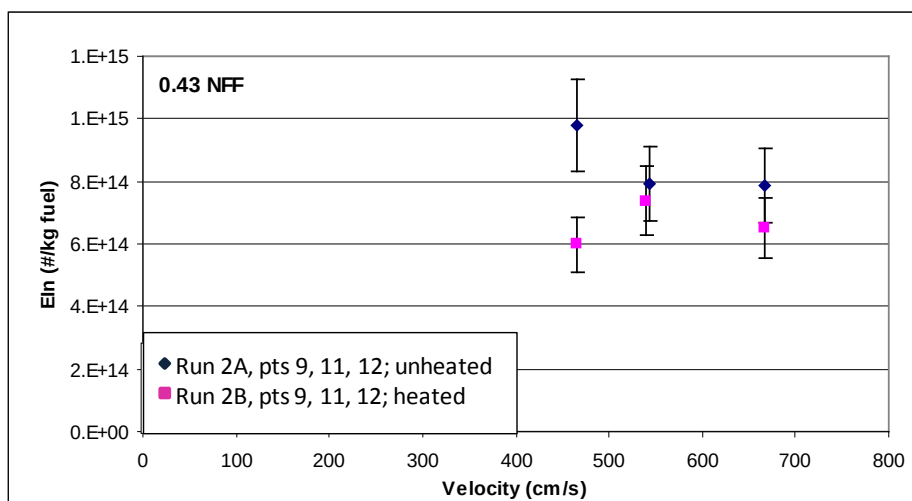


Figure B-3.21 Correlation between EIn-nvPM and line velocity at NFF = 0.43.

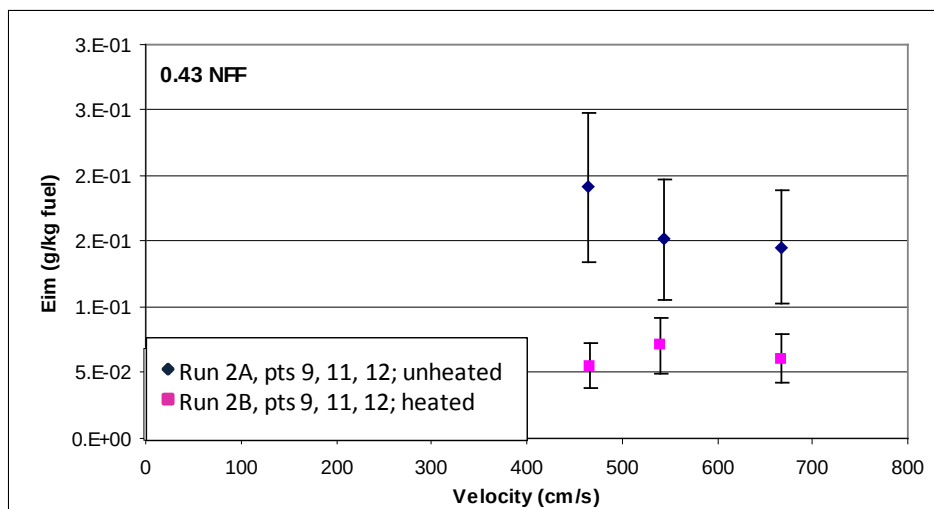


Figure B-3.22 Correlation between EIm-nvPM and line velocity at normalized fuel flow rate 0.43.

B-3.8.1 Summary

Over the range of dilution flow rates and engine power level settings explored during the Methodology Development Test, no PM parameter dependence on line velocity was observed. Hence, no line velocity artifacts should be expected within the velocity range of 280 cm/s to 1350 cm/s.

B-3.9 EFFECT OF VARIATIONS IN SOURCE PRESSURE AND TEMPERATURE

The engine exhaust pressure and temperature vary as engine operating conditions change, and these parameters impact the sampling system operation. In the sampling train the sample gas temperature and pressure must be brought to within the operating ranges of the measurement instruments. The design and operation of the sampling train must account for the ranges of the engine exhaust flow gas pressure and temperature.

The sample pressure at the particle probe inlet is the ram pressure at the sampling location in the engine exhaust and depends on engine power level setting. The ram pressure can range from near ambient to more than 1.5 atmospheres. Most diagnostic instruments require sample pressures near 1 atm, therefore at high exhaust ram pressures, the sample pressure must be reduced before delivery to the instruments. This was successfully accomplished by venting the sample line outlet to ambient atmosphere for higher ram pressures thereby increasing the sample flow rate to achieve a pressure drop across the particle probe inlet orifice. This solution requires that the diluent supply system deliver a correspondingly large diluent flow rate (i.e., a factor of 10 greater than the sample flow rate).

The sample temperature is naturally reduced by its passage through the long (several meters) sample line maintained at approximately room temperature.

B-4.0 SUMMARY OF THE OBJECTIVES AND RECOMMENDATIONS FOR THE IPMTM

The purpose of the Methodology Development Test was to experimentally investigate unresolved issues with sampling, instrument comparisons, instrument calibrations, sample line penetration and engine data representativeness. This section explains each specific issue and motivation for the research, and summarizes the recommendations for the IPMTM resulting from analysis of the Methodology Development Test data.

B-4.1 OBJECTIVE 1: DETERMINE THE MINIMUM ACCEPTABLE PROBE-TIP DILUTION

Dilution is introduced to the probe tip to minimize particle-particle and particle-wall interactions and suppress gas-to-particle conversion within the sampling system. In the case of unheated sample lines, probe-tip dilution also prevents water condensation. With a fixed probe inlet area, the sample flow into the probe increases with engine power due to increased exhaust ram pressure. To maintain a fixed dilution ratio, the dilution flow must be increased significantly at high engine power. In some cases this may be difficult to achieve. Too little dilution can allow condensation of water and/or volatile gases. Too much dilution can decrease the PM concentrations to below detectable limits or greatly decrease the signal-to-noise ratio for instruments used to characterize PM and chemical speciation. The objective is to determine an acceptable range of sample dilution.

Recommendation 1

During the engine test, the sample line dilution was varied from 4:1 to 15:1 at individual sample locations and the measured particle data assessed to determine the minimum dilution ratio suitable for the range of sampling and engine operating conditions encountered. A dilution ratio $\geq 10:1$ was sufficient to adequately suppress new particle production and growth due to condensation of condensable gaseous species and maintain an acceptable signal-to-noise ratio for the measurements.

B-4.2 OBJECTIVE 2: ASSESSMENT OF PROBE-TIP VERSUS DOWNSTREAM DILUTION

Probe and sampling systems used for conventional gas sampling do not typically incorporate sample dilution. The sampling lines for conventional gas sampling are heated to 160 °C to prevent water condensation. Researchers prefer probe tip dilution for preserving the state of particles during sampling. This obviates the need for sample line heating to prevent water condensation. To minimize particle-particle and particle-wall interactions, researchers prefer the sample be diluted at the probe tip. Probe-tip dilution requires specialized probes and is complicated by the process of delivery of the diluent to the probe tip. Adding the diluent downstream of the probe tip greatly simplifies the sampling system design. Limited data acquired during the APEX tests suggests that dilution downstream of the probe tip fosters condensation of gas phase species. Assessment of probe-tip dilution versus downstream dilution is desired for potential simplification and flexibility in sample system design.

Recommendation 2

During this engine test, data were acquired using particle probes with probe-tip dilution and a conventional gas probe with the dilution introduced to the sample line at the base of the rake, a couple meters from the probe tip. For unheated sample line experiments, care was taken to add the downstream dilution at a location before the sample temperature had dropped sufficiently to allow water condensation. Comparison of these data indicates little difference in the PM measurements acquired using probe-tip dilution or dilution just outside the exhaust flow. However, since the introduction of diluent at a location where the line temperature criterion cannot be guaranteed for all testing configurations, probe-tip dilution is recommended for the IPMTM.

B-4.3 OBJECTIVE 3: ASSESSMENT OF SAMPLE LINE VELOCITY

The linear sample velocity influences sample residence time and thus particle diffusion and inertial loss mechanisms. High linear velocities tend to suppress diffusional losses but can contribute to inertial loss. The sensitivity of the PM sample to sample velocity is important to the design and operation of the sample system.

Recommendation 3

The sample line velocity is not an independent variable in the sample line operation. During this engine test, data were acquired at fixed spatial points with varied dilution flow and varied exhaust ram pressure (engine power) while maintaining an approximate ambient pressure at the instrument end of the sample line. The sample velocity ranged from 280 to 1350 cm/s over the range of dilution flows and engine power level settings. These data were assessed to determine sample velocities that minimize both diffusional and inertial loss mechanisms. No PM parameter dependence on line velocity was observed. It appears that with sufficient dilution, the sampling system proposed for the interim PM test IPMTM method is insensitive to sample velocity. However, it is recommended that, when feasible, sample velocity should be maintained within the range of 280 to 1350 cm/s for the IPMTM.

B-4.4 OBJECTIVE 4: SAMPLE LINE TEMPERATURE (ACTIVE HEATING ON AND OFF)

The E-31 Committee has suggested heating the PM sample lines to a constant temperature above any foreseen maximum ambient temperature to eliminate sample line temperature as a variable. Also sample line heating was planned for the dilution study (Objective 1) to prevent water condensation at low dilution levels. Unheated PM sample lines were used in APEX, JETS-APEX2 and APEX3 campaigns. Although no effect was expected, it was deemed important to verify that that unheated and heated lines produce the same PM measurement results.

Recommendation 4

The engine test measurements were performed with and without the PM sample lines actively heated. PM data acquired using unheated sample lines followed expected trends predicted by theoretical and empirical models and experimental penetration studies. However, heated sample lines produced unexpected effects on measured PM parameters and chemical speciation. Detailed analyses of full data sets acquired with and without heated sample lines were explored to better understand the anomalous PM loss/generation mechanisms encountered. However, the data

acquired specifically to address the heated line issue are confounded by extreme variations in ambient engine inlet air temperature. Engine emissions characteristics are known to be influenced by variations in the engine inlet temperature, but in the case of PM this is not well understood by the research community. Since variations in ambient temperature can produce changes in the absolute values of the engine emissions which in turn obscure the effects associated with active sample line temperature control, the issue of heated sample line effects remains unresolved. Until heated line effects are better understood, unheated lines are recommended for the IPMTM.

B-4.5 OBJECTIVE 5: IMPACT OF ENGINE POWER LEVEL ON PM SAMPLING PARAMETERS

The temperature and pressure of the exhaust vary as engine operating conditions change, and these variations impact sample system parameters. In the sampling system, the sample temperature and pressure must be brought to within the operating ranges of the measurement instruments. The design of the sampling system must account for the ranges of pressure and temperature which must be accommodated.

Recommendation 5

The sample pressure at the PM probe inlet is controlled by the exhaust ram pressure at the sampling location, which in turn depends on engine power level setting. At high engine power levels, the sampling pressure can exceed 1.5 atmospheres. Most diagnostic instruments require sample pressures near 1 atm. Therefore the sample pressure must be reduced before delivery to the instruments. Pressure reduction was successfully accomplished by bypassing excess sample to the ambient atmosphere thereby increasing the sample flow rate and achieving a pressure drop across the PM probe inlet orifice. This solution requires a correspondingly large diluent flow rate to maintain the recommended dilution ratio (i.e., a factor of 10 greater than the sample flow rate). The sample temperature is naturally reduced by its passage through a cooled probe and long unheated sampling line. Sample pressure and temperature measurements are recommended at the inlet of each instrument to assure proper operational parameters during measurements.

B-4.6 OBJECTIVE 6: ASSESSMENT OF VOLATILE PM FORMATION DURING SAMPLING

Researchers believe that volatile particles have not formed at the engine exit plane due to the high temperature of the exhaust. Therefore, volatile particles at the instruments are artifacts of the sampling process caused by gas phase condensation. Gas phase condensation would form new particles and coat non-volatile particles during transit through the sample system. The sampling process should be designed to mitigate these processes. The objective is assessment of sample system conditions that allow volatile PM formation for understanding and subsequent mitigation during JSF engine testing.

Recommendation 6

There are sample system conditions that result in volatile particle formation within the sample line through the condensation of volatile gases. During the Methodology Development Test, the dilution ratio was varied to assess its sensitivity on volatile particle formation. The data indicate that condensable gas phase species may have impacted the non-volatile particle measurement results at some engine power level conditions. Measurements of condensable gas phase species

were reviewed to quantify microphysical processing through the sampling system, the effects on non-volatile particle measurements and to determine how the effects might be minimized through proper dilution and sample handling. The emission index of EIm-nvPM followed a general trend anticipated from previous studies; EIm-nvPM is greater at the engine take-off power than at idle. And as expected, the sample dilution level had little effect on the measurements of EIm-nvPM.

Although new particle formation was observed and believed to be attributed to condensation processes in the sample line (not in the exit plane exhaust), there were negligible effects on integrated mass and volume measurements as a function of dilution level and engine power setting. Comparison of DMA and CPC measurements suggest that the emission index of total particle number (EI_n -total) is not affected by new particle formation, but CPC measurements of EI_n -total exhibit a surprising dependence on dilution level at the 0.67 normalized fuel flow rate. Gas condensation causes non-volatile particles to acquire coatings during their transit through the sample line. Of the small coating amount, organic materials dominate the mass by a factor of about 10:1 over sulfate material. The organic material contained negligible lubrication oil (<10%). Counter-intuitively, the mass of the organic coating observed at idle conditions increased with increased dilution rate. The trend between EIm-organic and dilution level may be due to deposition of organic materials on the walls of the sample line under low dilution conditions and on the particles at high dilution conditions.

Since these studies support recommendation 1, from the perspective of volatile particle formation, the recommendation is a dilution ratio of 10:1.

B-4.7 OBJECTIVE 7: DEFINE A FIELD METHOD FOR SAMPLE LINE PENETRATION, PM INSTRUMENT CALIBRATION AND SYSTEM PERFORMANCE CHECKS

During each of the former APEX campaigns, there were attempts to perform sample line penetration measurements during field measurements. But often the sample lines were carried back to the laboratory for penetration characterization. A test method needs field-ready processes for sample line penetration, PM instrument comparisons and calibrations and system performance checks that can be applied intermittently throughout multiple days of testing.

Recommendation 7

A field-ready, transportable system was developed to provide known distributions of particles for sample line penetration, instrument comparisons and system performance checks. The system was employed and successfully demonstrated during the Methodology Development Test. Improvements were identified that will be incorporated before the validation test for this project.

B-4.8 OBJECTIVE 8: ENGINE DATA REPRESENTATIVENESS

Emissions from gas turbine engines cannot be assumed azimuthally symmetric. Spatially resolved measurements across the engine exit plane are necessary at several steady state engine power level settings to represent the emissions from the engine. Highly resolved spatial measurements at each engine power level setting can be costly due to the engine run time required, but are not always necessary. A process should be developed for quickly assessing spatially resolved PM data at predetermined engine power level settings and recommending a

reduced set of spatial locations for subsequent engine power settings. The final data set must represent the PM emissions for the engine (engine data representativeness).

Recommendation 8

A method was defined for area-weighted spatial averaging of PM emission factors for each engine power level setting separately and then for all engine power settings combined. If it is necessary (or desired) to reduce the engine run time requirements, it is recommended that a spatial mapping of exhaust emissions parameters be performed at a minimum of two nominal engine power level settings, mid-low and mid-high. The engine manufacturer should be consulted for selection of proper engine power level settings. The spatially detailed data can be used to define a reduced set of spatial measurements for other engine power levels that should provide comparable averages to high spatial resolution measurements.

B-5.0 FUEL ANALYSIS DATA FOR THE METHODOLOGY DEVELOPMENT TEST

Samples of the fuel were collected after each run (Run 1, Run 2, Run 3A and Run 3B) of the Methodology Development Test and analyzed by Aerospace Testing Alliance (ATA) at the AEDC Chemistry Laboratory. The analyses of the fuel samples showed no significant deviations in fuel density, flashpoint, free water, gross heat of combustion, net heat of combustion, hydrogen content, sulfur content and viscosity. The reported fuel properties in Figure B-5.1 are representative for all samples. Fuel samples from test Runs 1 and 3B were analyzed for the solids content and the results are shown in Figure B-5.2 and Figure B-5.3.



ATA Chemistry Laboratory Report of Analysis

Report # 07-1806

Report Date: 24-May-2007

445 Von Karman Rd, Arnold Air Force Base, TN 37389-3400

Client Name: Robert Howard

MS-9013

Work Order/ Task: 0397238/01

Chem Lab Sample #: 07-1806-001

Client ID: Post-Test Run #1

Sample Collection Date: 4/2/2007 0:00

Client No: Post-Test Run #1

Sample Receipt Date: 5/22/2007

Site: Tinker AFB

Sample Type: Fuel

Test Name	Test Results	Units	Method	Date of Analysis	Analyst
Density (60°F)	0.80586	g/cm3	ASTMD4052	5/24/2007	CRB
Density (100°F)	0.78957	g/cm3	ASTMD4052	5/24/2007	CRB
Flash Point	140	°F	T.O. 42B1-1	5/24/2007	CRB
Water, Free (AEL)	0	ppm	TO 42B1-1	5/24/2007	CRB
Heat of Combustion, Gross	19868	BTU/lb	ASTMD4809	5/24/2007	CRB
Heat of Combustion, Net	18607	BTU/lb	ASTMD4809	5/24/2007	CRB
Hydrogen Content of Fuel	13.82	% by wgt.	ASTMD3701	5/24/2007	CRB
Sulfur (S)	0.073	% by wgt.	ASTMD-4298-	5/24/2007	CRB
Viscosity (60°F)	2.094	cSt	ASTMD445	5/24/2007	CRB
Viscosity (100°F)	1.458	cSt	ASTMD445	5/24/2007	CRB

Figure B-5.1 ATA Chemistry Laboratory report showing the fuel properties representative for all engine test runs.



ATA Chemistry Laboratory Report of Analysis

Report # 07-1806

Report Date: 24-May-2007

445 Von Karman Rd, Arnold Air Force Base, TN 37389-3400

Client Name: Robert Howard

MS-9013

Work Order/ Task: 0397238/01

Chem Lab Sample #: 07-1806-005

Client ID: Solid Analysis (JP8)

Sample Collection Date: 4/2/2007 0:00

Client No: Post-Test Run #1

Sample Receipt Date: 5/22/2007

Site: Tinker AFB

Sample Type: Fuel

Test Name	Test Results	Units	Method	Date of Analysis	Analyst
Filtration Time	5	minutes	T.O. 42B-1-1	5/24/2007	CRB
Solids Content of Fuel	4.25	mg/gal	T.O. 42B-1-1	5/24/2007	CRB

Figure B-5.2 ATA Chemistry Laboratory report showing the solids content of the fuel for engine Test Run 1.



ATA Chemistry Laboratory Report of Analysis

445 Von Karman Rd, Arnold Air Force Base, TN 37389-3400

Report # 07-1806

Report Date: 24-May-2007

Client Name: Robert Howard

MS-9013

Work Order/Task: 0397238/01

Chem Lab Sample #: 07-1806-006

Client ID: Solid Analysis (JP8)

Sample Collection Date: 4/5/2007 20:00

Client No: Post-Test Run #3B

Sample Receipt Date: 5/22/2007

Site: Tinker AFB

Sample Type: Fuel

Test Name	Test Results	Units	Method	Date of Analysis	Analyst
Filtration Time	9	minutes	T.O. 42B-1-1	5/24/2007	CRB
Solids Content of Fuel	0.45	mg/gal	T.O. 42B-1-1	5/24/2007	CRB

Figure B-5.3 ATA Chemistry Laboratory report showing the solids content of the fuel for Run 3B.

B-6.0 REFERENCES

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B-7.0 APPENDIX: FILTER SAMPLING OF THE PARTICULATE EMISSIONS FROM A MILITARY AIRCRAFT ENGINE

This section describes the work conducted by John S. Kinsey of U. S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory Research Triangle Park, NC 27711.

B-7.1 PROJECT DESCRIPTION AND ORGANIZATION

Under Project No. WP-1538 of the Strategic Environmental Research and Development Program, the U. S. Air Force's Arnold Engineering Development Center (AEDC) is developing an interim test method for non-volatile particulate matter (PM) specifically for the Joint Strike Fighter (JSF) that is more accurate, less expensive, and less time consuming than EPA Reference Test Method 5. AEDC is proactively working with the Environmental Protection Agency (EPA), Department of Defense (DoD), Federal Aviation Administration, National Aeronautics and Space Administration, Society of Automotive Engineers E-31 Committee, and academia to develop this test method. The new PM test method will allow prompt replacement of older aircraft with the JSF, save the DoD time and money, and further the science of PM measurement.

As part of this project, PM measurements were conducted on an F100-220 engine installed in a test cell at Tinker Air Force Base (AFB), OK, in April 2007, primarily to address unresolved

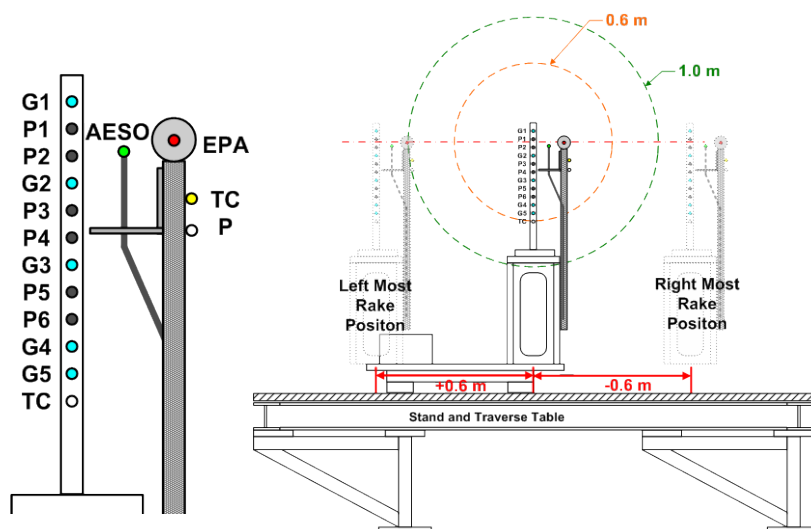
sampling issues. The F100 class of engine was preferred for the sampling study because it more closely simulates the JSF engine (F-135) exhaust conditions. A second test for interim PM methodology validation and demonstration is planned for November 2008 on the same engine type, also to be conducted at Tinker AFB. These tests include a comparison of available instrumentation to determine the most appropriate methods of measuring the mass emissions of non-volatile particles at the engine exit.

To support this program, the EPA's National Risk Management Research Laboratory (NRMRL) was requested to conduct Teflon[®] filter sampling and gravimetric analyses to determine the PM mass emissions using a direct gravimetric method in lieu of on-line instruments with their inherent limitations. This brief appendix describes the NRMRL measurements made during the April 2007 testing at Tinker AFB.

B-7.2 FIELD SAMPLING AND ANALYSIS

B-7.2.1 Sampling Equipment and Measurement Points

Filter sampling was conducted using the measurement system illustrated in Figure B-7.1 and Figure B-7.2. As shown in Figure B-7.1, the sample enters the system through a dedicated, water-cooled dilution probe, referred to in this report as a "particle sampling probe." The particle sampling probe was installed ~ 12 cm to the right side (looking into the engine exit) of the main rake (Figure B-7.1), ~ 0.3 cm below the horizontal nozzle exit centerline and ~ 31 cm downstream of the nozzle exit plane. The diluted sample from the probe was then transmitted to the filter sampler (Figure B-7.2) through a ~ 30-m stainless steel line heated to a nominal temperature of 150 °C. Dry nitrogen was used as the diluent, which was metered to the probe tip by a mass flow controller operated by personnel of the Missouri University of Science and Technology. The dilution rate was adjusted to achieve a target CO₂ concentration in the diluted



sample of ~ 3,000 to 9,000 ppm (volume) depending on engine power.

Figure B-7.1 Location of the EPA dilution sampling probe (view looking into the engine exit) relative to other probes and engine nozzle cross sections for several engine power level settings.

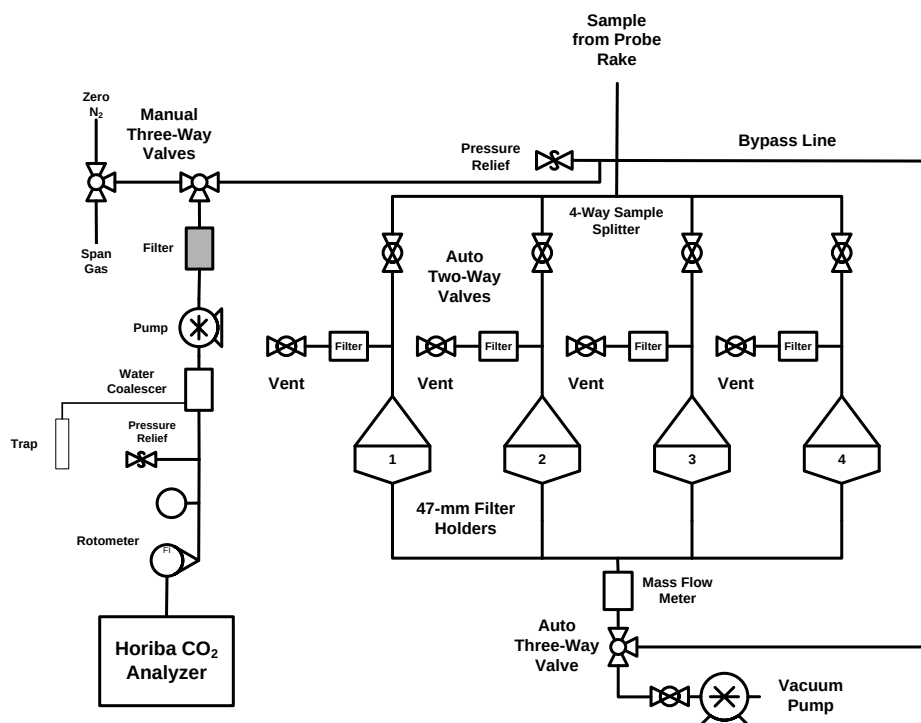


Figure B-7.2 NRMRL filter sampling system.

Upon entering the filter sampler (Figure B-7.2), the sample was either sent through a 47-mm Teflon filter installed in a stainless steel filter holder or by-passed to the atmosphere. Control of the sample flow was achieved by means of a series of automated valves controlled by a laptop computer running the DASYPAB software package. The flow through the filters was measured by a calibrated mass flow meter with the output signal logged by the DASYPAB software. A pressure test of the entire sampling system was performed prior to the first engine run to assure leak free operation. A background filter sample was also collected during removal of the probe rake and sample distribution system. No attempt was made to heat, insulate, or temperature control the filters during sample collection.

Four individual filter samples (marked as No. 1 to 4 in Figure B-7.2) were collected during each test run. In order to collect enough mass for gravimetric analysis, each filter sample represented the engine operating at one or more engine power conditions.

A Horiba carbon dioxide analyzer was also added to the filter sampling system (Figure B-7.2) later in the project for calculation of the fuel-specific emissions index (mg/kg fuel). A multi-point calibration was performed on the analyzer before deployment to the field with zero and span checks conducted twice daily. Certified standard gases were used for all calibrations and span checks performed in the study.

During the first test run, the engine operating conditions were set according to the power lever angle (PLA) and the fuel flow rates recorded for each PLA. Each PLA represented a particular cockpit throttle setting indicative of actual in-flight operation. For the remaining experiments, engine powers were set to match the previous fuel flow rate settings. Note that due to other factors such as ambient temperature and humidity, the actual PLA varied slightly from run to run for the same fuel flow rate setting. Table B-7.1 describes the experimental conditions for each run conducted in the project along with the engine PLA(s) for which each sample was collected.

As can be seen from Table B-7.1, no two sets of test conditions were exactly repeated making a determination of method precision difficult.

Table B-7.1 Summary of experimental conditions and engine power level settings for each filter sample.

Run Number	Run Condition	Filter No. 1		Filter No. 2		Filter No. 3		Filter No. 4	
		PLA (deg)	% Fuel Flow ^b	PLA (deg)	% Fuel Flow ^b	PLA (deg)	% Fuel Flow ^b	PLA (deg)	% Fuel Flow ^b
1A ^a	Rake traverse w/cooled probes and heated lines	16	11	35 & 50	22 & 43	65	67	75 & 84	84 & 100
2A	Rake stationary w/cooled probes and unheated lines	16.5 & 35.2	11 & 22	19.7 & 63	43 & 67	73.5	84	81.4	100
2B	Rake stationary w/cooled probes and heated lines	18.5 & 35	11 & 22	50 & 62.5	43 & 67	72.9	84	79.8	100
3A	Rake stationary w/cooled EPA sample probe and heated line ^c	16.6	11	60.8	67	76.5	100	16.5 & 21.5	11
4A	Rake traverse w/cooled probes and lines initially unheated then heated up during the last 16 PLA power condition	16.5	11	34.9 & 49.1	22 & 43	58.6	67	16.7	11

(a) This engine test run established the target PLAs and fuel flows for the study.

(b) Percent of maximum rated fuel flow with 100% being full thrust (without afterburner).

(c) Only separate EPA probe was operated with a heated line during this engine test run.

B-7.2.2 Media Preparation and Storage

All sampling media was prepared in the NRMRL Fine Particle Characterization Laboratory (FPCL) before leaving for the field. The filters were weighed before and after the field testing campaign to determine the total mass of PM collected. Prior to analysis, Teflon filters were weighed in accordance with Miscellaneous Operating Procedure (MOP) 2503 using a Sartorius microbalance located in the climate-controlled clean room.¹ This method requires that the filter samples be conditioned before weighing by exposure to air that is maintained at $22^{\circ} \pm 1^{\circ}$ C and relative humidity of 35 ± 1 % for a minimum of 24 hours.

During preparation of the sample collection media, a unique identification number stamped on the ring of each filter was recorded in a bound laboratory notebook and kept as a permanent record for the study. Prior to and after sampling, the Teflon filters were stored inside plastic petri dishes in a -20 °C freezer. During transport and in the field laboratory, all sampling media were stored in a small freezer operated at a nominal temperature of -20 °C as monitored using a digital thermometer. This portable freezer was also used as the primary shipping container for the sampling media to and from the test site (the unit was operated on auxiliary DC power supplied by the transport truck engine en route).

¹ MOP 2503: Procedure update for mass measurements of blank and exposed substrates. Revision 0, February 2005.

B-7.2.3 Sample Collection Procedures

At the time of loading the media into each filter holder, the laboratory identification number was entered on a special field data form. These forms list the identification number and sampling system details. These forms, as well as the samples collected in the field, were transferred to the FPCL upon returning from the field.

Sample collection was performed using the DASYLAB software package described previously. The software allowed the operation of each filter by means of a mouse-activated button indicated as either "SAMPLE" or "BYPASS." The necessary valve sequence and delays were programmed into the software thus freeing the operator to focus on the start and stop time for each engine power change. In addition, the time at which the sample stream or bypass flow was activated was also logged by the computer for later analysis. Proper operation of the software was verified before deploying to the field with a copy of the original program used for sampler operation archived.

A field project notebook and data forms were used to record operational parameters of the sampling system and engine during testing. The data forms consisted of a daily equipment start-up/shut-down checklist as well as a run sheet to record engine operating parameters. All electronic data were stored on the field computer as well as backed up daily on compact disc (CD).

B-7.2.4 Sample Analysis

After being returned from the field, all sampling media were stored continuously at -20 °C until analyses were performed. The samples maintained at this temperature in sealed containers may be safely stored for long periods of time prior to analysis without degradation. The exposed Teflon filters were then equilibrated in the clean room and weighed using the Sartorius microbalance described previously to $\pm 3 \mu\text{g}$.

B-7.2.5 Documentation

Analysis documentation included the use of bound laboratory notebooks to record experimental conditions, data, and pertinent observations. Hard copies of instrumental analysis records including calibration, daily QC checks, and raw data from sample analysis were archived in the project master file. Minor changes to the laboratory MOP for analysis on this project were documented in the laboratory notebook. Hard copy printouts of selected data files generated from the study were stored in a ring binder as part of the permanent record.

B-7.3 DATA REDUCTION AND REPORTING

B-7.3.1 Data Reduction

The PM mass collected on Teflon filter substrates during sampling was determined by weighing the filter before and after sampling. The total PM mass concentration was obtained by dividing the PM mass collected on the filter by the total air volume pulled through the filter during sampling. The flow rate of sample gas through the Teflon filters was measured by the mass flow meter with the total volume of sample gas between two consecutive readings calculated by:

$$V_i = Q_i(t_{i+1} - t_i) \quad (\text{Eq. B-7.1})$$

where: V_i = flow volume over the time between t_i and t_{i+1} (l)
 Q_i = flow rate reading at $t = t_i$ (slpm)

The total flow volume is then the sum of the time-interval flow volumes over the entire sampling time. Thus, the total PM mass concentration is given by:

$$C_{PM} = \frac{M_{PM}(1000)}{\sum V_i} \quad (\text{Eq. B-7.2})$$

where: C_{PM} = total mass concentration (mg/m³)
 M_{PM} = PM mass collected on the filter (mg)
 $\sum V_i$ = sum of total flow volume (Eq 1) calculated over sampling period

A background correction is made by subtracting the PM concentration determined from the background sample from the total PM mass concentration obtained above.

The PM emission index, EIm, expressed in particulate mass per kg of fuel burned, was calculated from the particle mass concentration using:

$$EIm(mg / kg) = \frac{200.3 \bullet C_{PM}(mg / m^3) \bullet f_c}{C_{CO_2}(\%)} \quad (\text{Eq. B-7.3})$$

where: C_{PM} = background corrected particle mass concentration (mg/m³)
 C_{CO_2} = background corrected CO₂ concentration at sampling point (%)
 f_c = fraction of carbon in fuel (g/g fuel)
 200.3 = a combined constant for unit volume, and weight corrections

All applicable calculations were performed in an Excel spreadsheet. Each spreadsheet calculation was first checked by hand to ensure accuracy before calculating the final results. Assumptions were also noted as comments in the spreadsheet calculations.

B-7.4 RESULTS

The results of the filter sampling conducted during the F100-220 test are provided in Table B-7.2. Note that these results have not been background-corrected although a filter sample was collected during system removal. When this sample was analyzed, an abnormally high PM concentration was obtained. Upon further evaluation, it was determined that the high background concentration was associated with PM generated by forklifts and other equipment during engine and equipment removal thus invalidating the sample. Therefore, the background measurement was discarded during calculation of the emission indices (EIs). In addition, time and resources did not allow for the determination of particle line losses which would also tend to reduce the calculated EIs. Therefore, the values shown in Table B-7.2 must be considered as upper bounds and used with caution.

One of the major findings of the research team during this engine test study was that unheated, ambient temperature (cold) sample lines produced higher measurements of PM EIs than lines

heated to 150 °C (hot). This is exactly opposite to that predicted by aerosol theory as described by numerous investigators such as Montassier et al.² To illustrate this effect, Figure B-7.3 shows data for selected test runs using either cold or hot sampling lines. As shown in this figure, except at 84° PLA for Run 2B, cold lines consistently produced higher PM EIs as compared with hot sampling lines.

² Montassier, N., Boulaud, D., and Renoux, A. (1991). Experimental study of thermophoretic particle deposition in laminar tube flow. *J. Aerosol Sci.*, 22:5, 677-687.

Table B-7.2 Summary of experimental results ^a

Test Number	Filter Sample Number	Blank Corrected Sample Weight (mg)	Total Sample Volume (liters)	Diluted PM Concentration (mg/m ³)	Target Power Lever Angle	BG-corrected Average CO ₂ (ppmv)	Engine Outlet PM Concentration (mg/m ³)	Fuel Carbon Content (g/g fuel)	Total PM Emission Index (mg/kg)
1A	1	0.342	1054.6	0.324	16	4707	1.21	0.862	119
	2	0.245	359.6	0.681	35 & 50	4990	3.04	0.862	236
	3	1.227	2322.2	0.528	65	5948	2.75	0.862	153
	4	0.289	426.9	0.677	75 & 84	9439	2.72	0.862	124
2A	1	1.72	1462.4	1.18	16 & 35	4336	4.01	0.862	468
	2	0.792	1177.5	0.673	50 & 65	7202	2.39	0.862	161
	3	0.355	432.0	0.822	75	9301	2.85	0.862	153
	4	0.196	250.0	0.784	84	9554	2.80	0.862	142
2B	1	0.806	998.5	0.807	16 & 35	4257	3.51	0.861	327
	2	0.493	1253.4	0.393	50 & 65	7002	1.64	0.861	96.9
	3	0.228	358.2	0.637	75	9065	2.61	0.861	121
	4	0.418	338.5	1.23	84	9452	5.16	0.861	225
3A	1	0.088	1099.1	0.0801	16	4201	0.320	0.862	32.9
	2	0.79	1539.7	0.513	65	7458	2.14	0.862	119
	3	0.559	1042.8	0.536	84	9088	2.15	0.862	102
	4	0.171	2462.1	0.0695	16 & 23	4228	0.266	0.862	28.4
4A	1	0.142	1683.7	0.0843	16	3477	0.324	0.862	41.9
	2	0.092	352.4	0.261	35 & 50	4774	1.09	0.862	94.4
	3	0.85	1490.4	0.570	65	5641	2.46	0.862	175
	4	0.09	691.6	0.130	16	4121	0.511	0.862	54.5

^(a) Not corrected for background or line losses (see text). Also note that the target PLA is shown instead of the exact values shown in Table D-7.2.1 for ease of comparison.

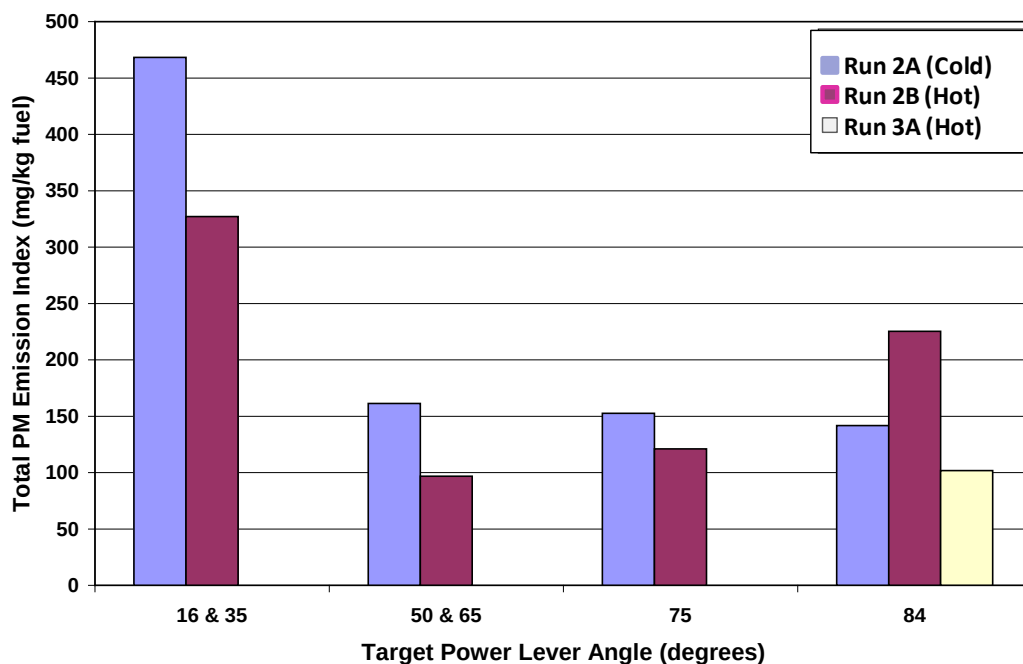


Figure B-7.3 Comparison of PM EIs for cold versus hot sample lines.

Finally, in an attempt to evaluate method precision, Figure B-7.4 shows all EIs obtained at a target PLA of 16°. Looking at the “hot” line Runs (1A, 3A, and 4A), the two similar (but still not exactly the same) measurements conducted during Run 3A agree to within 15% (relative percent difference) of each other. Such was not the case when all runs at 16° PLA are considered, however, where differences of greater than a factor of 4 were observed. Many of these differences may be attributed to variations in sampling system operation as shown in Table B-7.1 above.

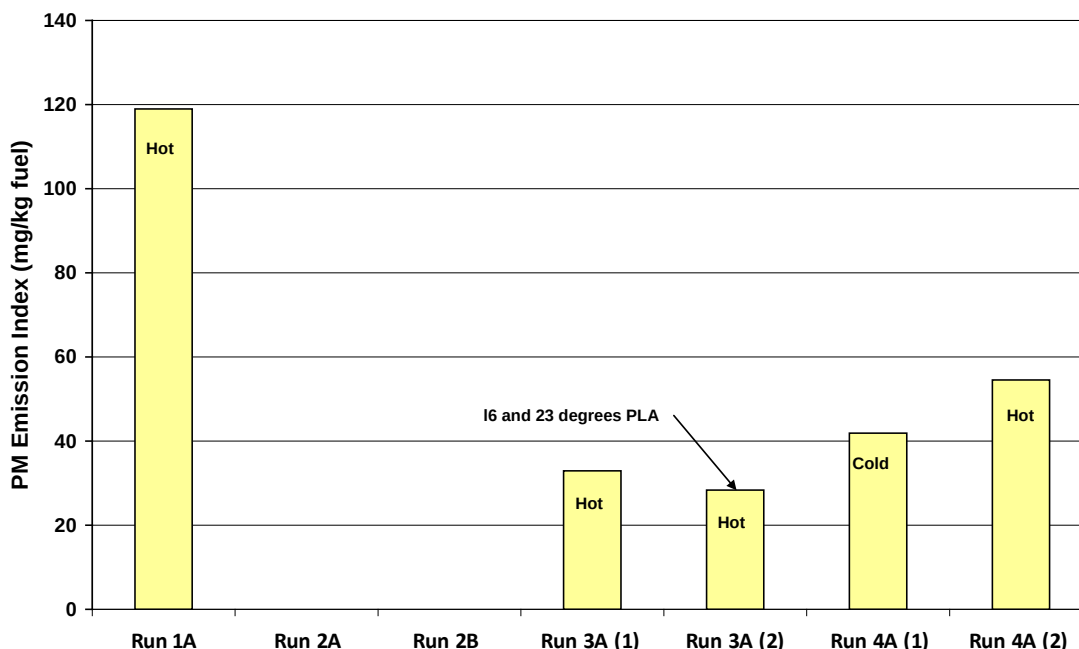


Figure B-7.4 Comparison of PM EIs obtained at target PLA of 16 degrees.

B-7.5 QUALITY ASSURANCE/QUALITY CONTROL

B-7.5.1 Data Quality Indicators

The data quality indicator (DQI) goals for the sampling conducted in the study are shown in Table B-7.3 for precision, accuracy, completeness, and detection limit as compared to actual performance. As can be seen, all goals with the exception of gravimetric precision were either met or exceeded during the measurements conducted at Tinker AFB. Considering the relatively high PM concentrations observed in each run (Table B-7.2), the very slight lack of precision of the gravimetric analyses was not considered to adversely affect the results of the study.

Table B-7.3 DQI goals for filter sampling.

Experimental Parameter	Measurement Method	Precision		Accuracy ^b		Completeness		Detection Limit or Range	
		Goal	Actual	Goal	Actual	Goal	Actual	Goal	Actual
Volumetric air flow rate	Mass flow meter	10% ^a	0.2%	± 10%	- 4.8%	90%	100%	0-60 lpm	0-60 lpm
PM mass	Gravimetric analysis	3 µg ^c	4 µg	± 15 µg	- 6 µg	90%	100%	2 µg	1 µg

^a Calculated as the relative standard deviation of the reference measurements obtained at a constant flow rate setting.

^b Average variation between the reference measurements and the instrument readings as determined over the entire operating range.

^c Determined as the standard deviation of the results of multiple analyses of the same filter on the same microbalance.

B-7.5.2 Quality Control Checks

A total of 60 Teflon filters were prepared in advance in accordance with MOP 2503. Laboratory blank samples (i.e., analyses of unexposed sampling media retained in the laboratory) were also analyzed by the FPCL. Results from the analysis of unexposed sampling media retained in the

laboratory set the absolute minimum contamination level anticipated for field sampling episodes. Also, a field blank sample was collected by installing a filter in the sampling system and then immediately recovering the media in the same manner as was done with the other filter samples collected. Collection of the field blank allowed for the quantification of filter handling artifacts associated with the field sampling.

Field and laboratory blanks were analyzed in parallel with all source samples. Analysis of laboratory blank substrates indicates if there is any cross-contamination between samples and if there is any contamination from improper techniques. For both field and laboratory blanks, the same analytical protocol was followed as for actual field samples.

Laboratory QC included initial calibration, daily QC sample checks, and verification of instrument performance. These QC requirements are described in the MOP 2503 as well as in Section 6 of the FPCL Quality Assurance Project Plan (QAPP).³

Although CO₂ measurements were not originally planned or included in the QAPP, these were later found to be necessary for calculating emission indices. Therefore, for quality control purposes, an initial calibration and twice daily zero and span checks were conducted in the program. Table B-7.4 shows the results of those checks. As can be seen, high quality CO₂ data were collected in the study.

Table B-7.4 QC checks for CO₂ Analyzer.

EPA Test No.	Pre-test accuracy (% bias)	Post-test accuracy (% bias)	Pre-test precision (% RSD)a	Post-test precision (% RSD)a
1	0.058	0.33	0.058	0.047
2	-0.015	(b)	0.058	(b)
3	(b)	0.51	(b)	0.090
4	-0.096	-0.042	0.043	0.036
5	-0.036	(c)	0.044	(c)

(a) RSD = relative standard deviation.

(b) Runs 2 and 3 conducted on same day. Instrument was zeroed and spanned in AM and PM of each test day.

(c) No post-test zero and span conducted during system removal.

B-7.6 CONCLUSIONS

As shown by Table B-7.2, the measured EIs varied from approximately 30 to 470 mg/kg of fuel burned depending on engine thrust and sampling conditions. Comparison of these results to those obtained by study collaborators is highly desirable but has not been performed, however, due to lack of access to their data.

Of particular importance was the observation that the use of ambient temperature (cold) sampling lines produced a significantly higher EI at a given engine output than heated (hot) sampling lines. Thermophoretic deposition from the hot sample gas to the cold sampling lines would tend to increase particle losses thus lowering both the measured PM concentration and resulting EI. In this study, the opposite effect was observed which cannot be explained by

³ *Chemical Analysis of Fine Particulate Matter*, Quality Assurance Project Plan, Revision 7, QTRAK # 99002/III, Emissions Characterization Branch, National Risk Management Research Laboratory, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 2005.

current aerosol theory. This is one area in which further empirical investigation is definitely needed prior to proceeding with the development of an interim PM test method for the JSF.

APPENDIX C

IPMTM - VALIDATION TEST

SERDP Project WP-1538

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ABSTRACT

A measurement test method using modern PM measurement techniques has been developed to replace EPA Method 5 for reporting PM emissions of gas turbine engines for the Joint Strike Fighter Program. These test method is to be applied at the engine exit plane in a manner similar to regulatory measurements of gas species on commercial engines. A ground-level engine test campaign on a military F100-220 turbine engine was conducted to evaluate and validate the PM test method using the diagnostic probe-rake and sampling system hardware developed for the JSF F135 engine particle characterization measurements. The results of the Validation Test will be used to finalize the interim PM test method document.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Defense through the Strategic Environmental Research and Development Program (SERDP) and the Office of the Chief of Naval Operations (N45). It is a pleasure to acknowledge Mr. Bruce Sartwell, Dr. Jeffrey Marqusee, Mr. Charles Pellerin and Mr. Jeff Houff for their leadership and enthusiastic support of this project. We are also thankful to the advisory council for their oversight and advice.

We appreciate the efforts of the Air Force Management at Tinker AFB for making available piggy-back test opportunities for the Validation Test; in particular Mr. David P. Hughes and Mr. Jeffrey L. Copeland for coordination, and the staff who directly supported our research group. We are grateful for the use of the probe-rake system developed by the Arnold Engineering Development Center (AEDC) and jointly funded by the JSF F135 Test Program through Jeff Albro and AEDC.

And there are several organizations and individuals with valuable contributions providing support with planning, measurements or technical collaboration. We gladly acknowledge:

Dr. Stephen O. Andersen - US EPA, Director of Strategic Climate Projects, Office of Air and Radiation

Research Laboratory; Technical Liaison to the Project, SAE E31

Mr. William Voorhees - Naval Air Systems Command, Director of Science and Technology, Propulsion and Power Engineering Department

Mr. Steven Hartle - Naval Air Systems Command, Propulsion and Power Engineering Dept.

Mr. Curtis Kimbel - Naval Air Systems Command, Propulsion and Power Engineering Dept.

Mr. Triet Nguyen - Navy Aircraft Environmental Support Office (AESO), SAE E31

Dr. Xu Li-Jones, CTR FRC-SW, 08212, AESO, SAE E31

Ms. Jean Hawkins - Joint Program Office, JSF, Environmental, Safety and Health Manager

Dr. Anuj Bhargava - Pratt & Whitney (JSF PM Measurement Requirements), SAE E31

Dr. David Liscinsky – United Technologies Research Center, SAE E31

Dr. Chowen Wey - Army Research Lab, SAE E31

Dr. Bruce Anderson - NASA Langley Research Center

Dr. W. Berk Knightington – Research Professor – Montana State University

Dr. Wayne Miller - University of California-Riverside

Dr. Dave Gemmill - Quality Assurance Consulting, LLC

Mr. Roy Carroll, Mr. Gary Storey and Mr. Brad Besheres – ATA/AEDC, Arnold AFB

Mr. Ben Baker, Mr. James M. Cress, Brian L. Catron and Mr. Dave Satterfield – Missouri S&T

Dr. Yu Zhenhong, Mr. Ryan McGovern and Mr. Robert Prescott – ARI

Mr. Keith Skaggs, Mr. Gary Paetow, Mr. Tuong Nguyen – AESO

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LIST OF ACRONYMS

AEDC	Arnold Engineering Development Center
AESO	Aircraft Environmental Support Office
AFB	Air Force Base
APEX	Aircraft Particle Emissions eXperiment
ARI	Aerodyne Research Inc.
ATA	Aerospace Testing Alliance
COE	Center of Excellence
CPC	Condensation Particle Counters
DMA	Differential Mobility Analyzer
DMS	Differential Mobility Spectrometer
FID	Flame Ionization Detector
GMD	Geometric Mean Diameter

HFID	Heated Flame Ionization Detector
ICAO	International Civil Aviation Organization
IPMTM	Interim Particulate Matter Test Method
JSF	Joint Strike Fighter
LPM	Liters per Minute
MAAP	Multi-Angle Absorption Photometer
MASS	Mobile Aerosol Sampling System
MGA	MultiGas TM Analyzer
Missouri S&T	Missouri University of Science and Technology
MW	Molecular Weight
NASA	National Aeronautics and Space Administration
N	Instantaneous Total Particle Number Concentration
PM	Particulate Matter
PTR-MS	Proton-Transfer Reaction Mass Spectrometer
PTFE	Polytetrafluoroethylene
QC-TILDAS	Quantum-Cascade Tunable Infrared Laser Differential Absorption Spectrometer
SAE	Society of Automotive Engineers
SAE E-31	SAE E-31 Aircraft Exhaust Emissions Measurement Committee
SAM	Seconds after Midnight
SERDP	Strategic Environmental Research and Development Program
SMPS	Scanning Mobility Particle Sizer TM
SS	Stainless Steel
THC	Total Hydrocarbons
TILDAS	Tunable Infrared Laser Differential Absorption Spectrometer

LIST OF TERMS AND SYMBOLS

D_{geomM}	Mass-based Geometric Mean Diameter
D_{geomN}	Number-based Geometric Mean Diameter
EI	Emission Index
EIm	Mass-based Emission Index [g/kg-fuel]
EIm-nvPM	Mass-based emission index [g/kg-fuel] of non-volatile Particulate Matter

EIm-x	Mass-based Emission Index for species “x” [g/kg-fuel]
EIn	Number-based Emission Index [number/kg-fuel]
EIn-nvPM	Number-based emission index [g/kg-fuel] of non-volatile Particulate Matter
EIn-x	Number-based Emission Index for species “x” [number/kg-fuel]
M	(Total) particle mass concentration (derived from integral of number size distribution)
M(N ₀)	Mass of Aerosol per Unit Volume of Exhaust Sample
M(X)	Mass of a Substance X per Unit Volume of Exhaust Sample
n	(Logarithmic) differential number concentration
N	(Total) number concentration of the particle size distribution
NFF	Normalized Fuel Flow

C-1.0 INTRODUCTION

The US Department of Defense is required to measure and report the gaseous and particulate matter (PM) emissions from military turbine engines as a part of federal, state and local environmental reporting requirements. This information is critical for determining the allowable number of aircraft based at military installations. In lieu of EPA Method 5 that has been used for reporting particle emissions from military engines and sea-level test facilities, the DoD is developing a PM test method for the Joint Strike Fighter (JSF) Program that implements modern particle measurement techniques. These techniques are to be applied at the engine exit plane in a manner similar to regulatory measurements of gas species on commercial engines. Modern particle measurement techniques offer improved accuracy in PM reporting, provide additional information such as the particle size distribution, and require shorter engine run times at significantly reduced costs. The overall program objective is development of an Interim PM Test Method (IPMTM) to replace EPA Method 5 for use in reporting PM emissions for the JSF Program.

The IPMTM development plan called for two ground-level engine test campaigns on military turbine engines. The first, called the Methodology Development Test (Appendix B) was conducted in 2007 to experimentally address unresolved measurement issues identified as a result of prior NASA PM characterization studies (APEX test series, and etc.). The second test program, called the Validation Test, was conducted to demonstrate and evaluate the interim test method on a military engine using the probe-rake and sampling system hardware developed for the JSF F135 particle characterization measurements. The results of the Validation Test measurements will be used to finalize the interim method document.

Investigators from the Arnold Engineering Development Center (AEDC), Missouri University of Science and Technology (Missouri S&T) and Aerodyne Research, Incorporated (ARI) planned and conducted the Validation Test. These investigators are responsible for the development of the interim PM test method. The measurements were conducted in collaboration with the U.S. EPA, NASA and the Navy Aircraft Environmental Support Office (AESO), who also preformed PM characterization measurements. Results from the EPA, NASA and AESO measurements that supported this effort were incorporated through collaboration and technical workshops. However, the explicit measurements and data are not reported here.

The primary objectives of this study, (1) evaluate and demonstrate a new interim PM test method for PM measurements and, (2) use the demonstration testing opportunity to address certain sampling issues that were identified as research needs by the SAE E31 committee. Both objectives were successfully met. The first objective was met through substantiation and results for finalization of the IPMTM document (Appendix A). The deliverable of the second objective is the main body of this report. This report describes the Validation Test and PM emissions data for the F100-220 engine using the modern measurement techniques. The test was conducted November 2008 on an F100-220 engine in test facility at the Tinker Air Force Base, OK.

C-1.1 TEST OBJECTIVES

The primary objective of this Validation Test study was to evaluate and demonstrate the interim PM test method on a military engine using the probe-rake and sampling system hardware developed for later JSF F135 particle characterization measurements. An important secondary

objective was to experimentally address, as feasible, sampling research needs identified by the SAE E31 committee.

C-1.2 TEST CONFIGURATION

The Validation Test was conducted in Building 3703 at Tinker Air Force Base in Oklahoma City, OK. The test cell control room was located adjacent to the test cell as shown in Figure C-1.1. An F100-220 engine was mounted on a test stand in the Test Cell 3 sea-level engine test facility, Figure C-1.1 and Figure C-1.2. The engine exhaust was vented through the diffuser duct (also called augmentor tube) and after several meters was turned vertically and vented through the roof of the facility. Figure C-1.3 shows the outside facility wall just beyond the vertical exhaust stack. The trailers were parked there during the test. The engine used in this study was the same type used in the Methodology Development Test (Appendix B).

The sampling probes were mounted between the engine exit and the exhaust diffuser duct as shown in Figure C-1.1 and the photograph in Figure C-1.2. The rake and probes are shown in better detail in Figure C-1.4. Sample lines were routed from the probes in the test cell, through wall feed-through ports into the machine room, and down the hallway to the particle and gas analyzer instruments located in the trailers and vans parked outside the building. The Missouri S&T, ARI, AEDC and AESO trailers and vans were parked along the wall near the Test Cell 3 hallway opening as illustrated in Figure C-1.1. AESO measurement data are not reported here.

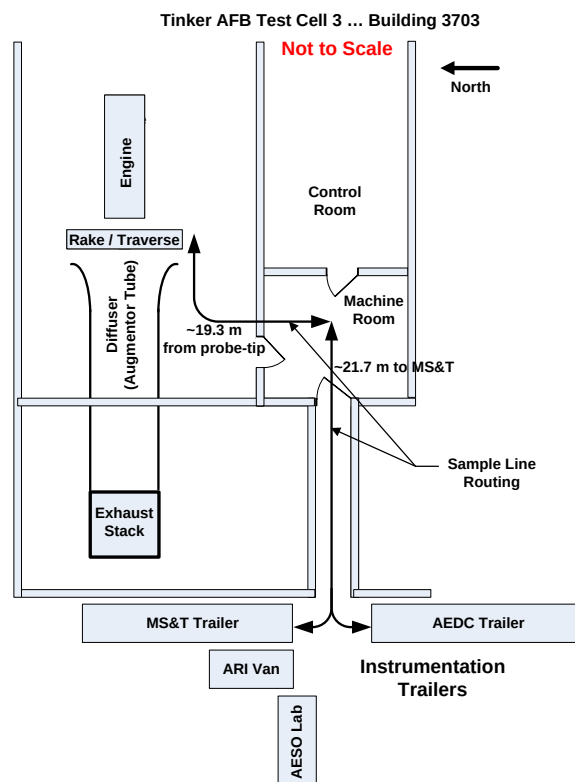


Figure C-1.1 Illustration of the Test Facility and Measurement Layout.

Measurements were performed at steady-state engine power settings ranging from idle to maximum (non-afterburning). The chosen metric for setting engine power was fuel flow rate. The fuel flow rate was normalized to the maximum fuel flow rate measured during the check out

run. A normalized fuel flow (NFF) rate greater than 1.0 indicated that the engine setting deviated from the intended set point. Normalized fuel flow rates, not absolute values, are reported in this document.

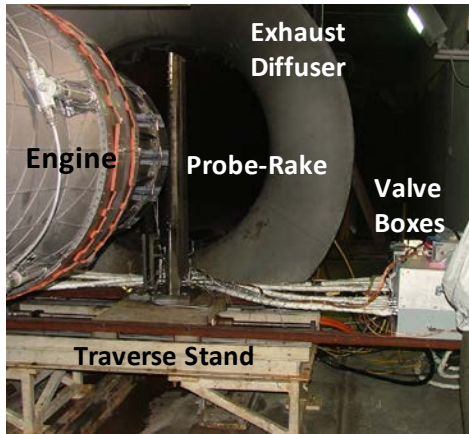


Figure C-1.2 Relative positions of the engine, probe-rake traverse stand and the exhaust diffuser.



Figure C-1.3 Tinker Test Cell 3 before trailers were positioned.

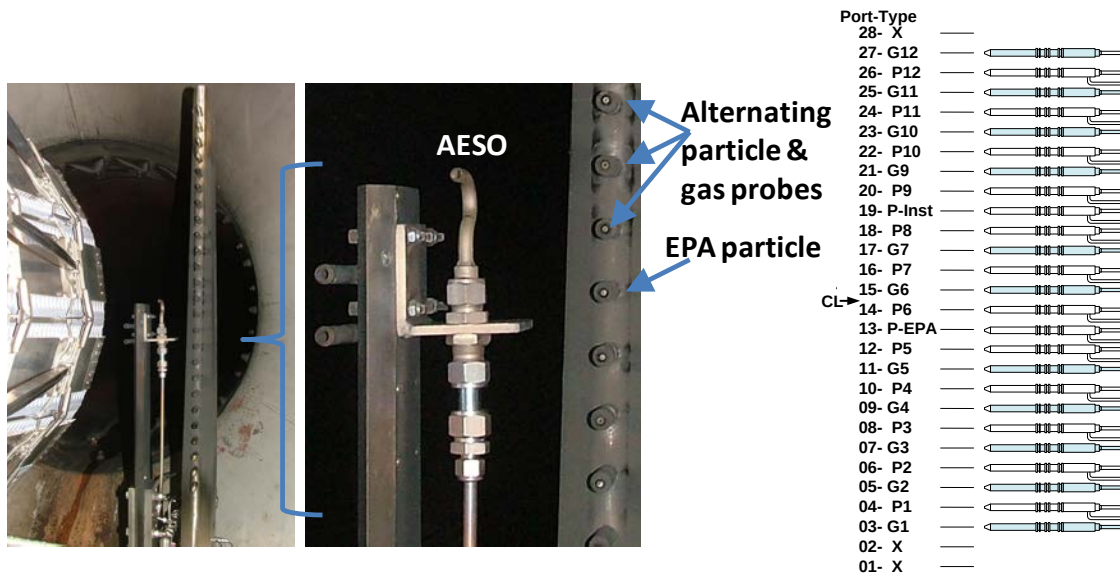


Figure C-1.4 Photograph of the rake and probes, looking downstream, and a schematic configuration for the AEDC probe-rake used during the Validation Test.

C-1.3 RAKE, PROBE AND TRAVERSE SYSTEMS

Probe support structures were attached to a traverse stand mounted between the engine and the exhaust diffuser duct, Figure C-1.1 and Figure C-1.2. The probe tips were placed at an axial position within a few inches of the nozzle exit plane of the engine. During the test, the probes were traversed to fixed horizontal positions across the nozzle exit plane to perform spatial profile

measurements. At horizontal rake positions, measurements were performed at vertical probe locations along the rake.

The photograph in Figure C-1.4 shows the rake and probes used for the Validation Test (view looking downstream from the engine). The right-most rake was water cooled and contained the primary sampling probes for the Validation Test. The rake was developed by AEDC specifically for future JSF engine PM measurements. The schematic in the right of Figure C-1.4 shows that the probe configuration for this test. The rake has 28 probe ports spaced at 3.81 cm (1.5 in) intervals along the rake structure. Probe ports 1, 2 and 28 were not used for sampling on this test. These ports contained “dummy” probes that filled the port and allowed cooling water to flow properly through the rake. The rake was configured with alternating particle and gas probes except for a particle probe in port 13 dedicated solely to EPA and a particle probe in port 19 that was instrumented with thermocouples. The particle probes have the capability to add dilution gas to the sample near the probe tip as illustrated in Figure C-1.5. The gas sampling probes do not have dilution capability and were used primarily for conventional gas species concentration and smoke number measurements.

The left most probe-support strut in Figure C-1.4 supports the “button hook” probe used by AESO. AESO measurements complemented this effort but were performed independently and the data are contained in this report. Two probes were welded to the left side of the strut; one a thermocouple probe for measuring total exhaust temperature and the other a pitot probe for measuring the exhaust total pressure.

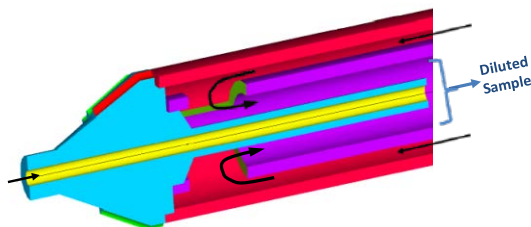


Figure C-1.5 Cross-section view of the particle probe sampling concept.

Figure C-1.6 illustrates the rake mounted to the traverse stand behind the engine. The small circles on the primary rake represent the probe locations. The gas probe at port 15 was approximately coincident with the vertical centerline of the engine. The large inner and outer circles illustrate the approximate smallest (0.6) and largest (1.0 m) nozzle exit diameters for the range of engine power settings during the test. The nozzle was most fully open at ground idle (~1.0 m), decreased to about 0.71 m diameter at flight idle, and further to 0.6 m at the highest power setting. The probes in the primary rake fully spanned the nozzle diameter at the horizontal-centerline rake position (except at ground idle). The primary rake was traversed during steady-state power level conditions (nozzle diameters-fixed) to perform spatial measurements across the exit plane of the exhaust nozzle.

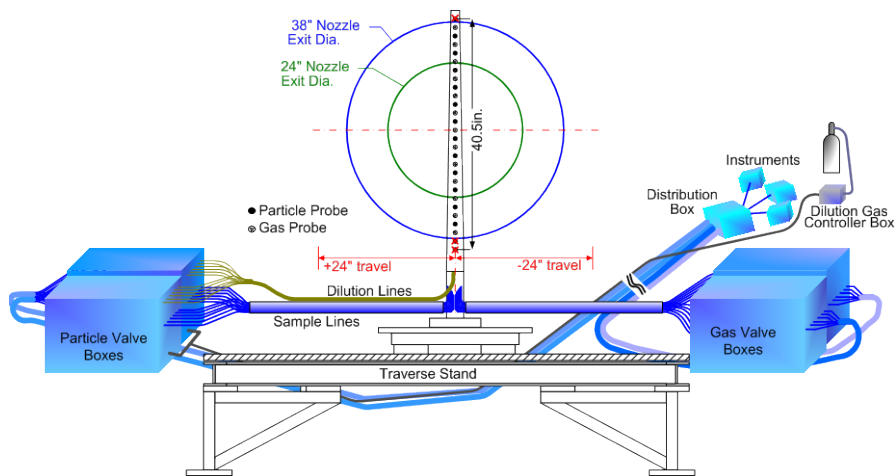


Figure C-1.6 Rake and probes in relation to the nozzle exit (aft-looking-forward).

All primary measurement techniques used in the sampling study required in situ exhaust sampling. As discussed earlier, the rake contained dilution probes designed specifically for particle sampling by introducing dilution gas (dry N₂) within the probe tip as shown in Figure C-1.5. The rake also contained undiluted gas sampling probes for measurements of conventional gas species concentrations and smoke number measurements. During a traverse operation, probes positioned outside the physical dimensions of the nozzle were seldom sampled. The particle probes were operated functionally as recommended in the interim PM test method. The dilution control system developed for the Methodology Development Test (Appendix B) was also used for this test, assuring more accurate and semi-automated control of the amount of dilution gas. Carbon dioxide (CO₂) measurements were performed on the diluted particle probe sample and the undiluted gas probe sample to accurately determine the operating dilution ratio in the particle sample line.

C-1.4 SAMPLING SYSTEM

The primary components of the particle sampling system used for the IPMTM development team are illustrated schematically in Figure C-1.6. Exhaust gas entering a particle probe is mixed with a diluent gas (dry, particle-free N₂) introduced within the tip of the probe and continued through a sample line to a valve box containing three-way valves that allow remote selection of one or more probes to be sampled. A valve box had multiple (up to 6) input lines, but only one sample line out that was referred to as the trunk line. For each input line, the box contained a three-way valve that either directed the sample through the box to the trunk line (for a selected probe), or connected the input line to a source of relatively high-pressure purge gas. The purge gas flowed back through the sample line and out the probe tip to prevent exhaust gas from entering the sample line. The sample from the selected probe, or probes, traveled along the trunk line to the Missouri S&T instrument trailer to a valve distribution system used to distribute the sample to the various instruments in the different trailers.

The gas sampling system used to transport sampled exhaust to gas analyzers was similar, except that no dilution was provided to the sampled exhaust.

For the primary rake, the sample line sections from the particle and gas probes to the base of the rake were made of 0.64 cm (0.25 in) dia. stainless steel (SS) and ranged in length from 0.74 m (bottom most probe) to about 1.6 m for the upper most probe. Sample lines from the base of the

rake to the valve box were made of 0.95 cm (0.375 in) diameter SS about 3 m in length. The sample path within the valve box was about 0.6 m. Unlike the first Methodology Development Test conducted at Tinker for this project, the valve boxes for this test were installed onto the traverse stand. Thus, only one flexible line per valve box was required to accommodate traversing, rather than one flexible line per probe. The first section of the each trunk line was made of 1.8 m length, 1.9 cm diameter flexible electrically-conductive Polytetrafluoroethylene (PTFE), commonly called Teflon® tubing. The remainder of the trunk lines, from the end of the first section to the Missouri S&T trailer, were made of 1.9 cm (0.75 in) diameter SS, approximately 29 m overall length and built from 6.1 m (20 ft) SS sections. All of the sampling lines from the primary probes were wrapped with electrical heater strips and insulated. For validation of the interim PM test method, these sample lines were not actively heated. However, research measurements were performed with and without active heating. The main trunk lines were routed through wall ports from the test cell into the machine room as shown in Figure C-1.1. From the machine room, the main trunk lines were routed up and over a hallway door, down the hallway and out of the building through the wall opening shown in Figure C-1.3.

The gas probe sampling system was configured and operated in a similar manner, but without adding diluent gas to the sampled exhaust flow. An exception was experimental measurements using a gas probe for particle measurements. In that case, diluent gas was introduced into the sample line at the base of the rake stand approximately 2 m from the probe tip. Gas probe sample lines were always heated to approximately 150 °C to prevent water condensation.

Optimized sampling parameters for both particle number detection and sample line flow rate can require simultaneous sampling from two particle probes for low power level settings. The particle sample system was designed to control diluent flow individually to one or two simultaneous particle probes as needed.

C-2.0 DIAGNOSTIC MEASUREMENT SYSTEMS

C-2.1 MISSOURI S&T DIAGNOSTIC MEASUREMENT SYSTEMS

The Missouri S&T Center of Excellence (COE) in Particulate Matter Research developed a diagnostic facility optimized for jet engine exhaust characterization that relies on extractive sampling. This facility has been refined over the last 26 years (Lilenfeld et al., 1995; Hagen et al., 1997; Whitefield et al., 2002). An overall review of the Missouri S&T diagnostic suite and PM characterization methodology has been reported elsewhere (Schmid et al., 2004, Lobo et al. 2007).

Condensation Particle Counters (CPC) (TSI 3022 and 3025) are used to measure total particle concentration. Particle size distributions are measured with Differential Mobility Spectrometers (DMS) (Cambustion DMS500) and Differential Mobility Analyzers (DMA) (TSI 3071). The DMA uses a single channel which is swept through different sizes over time, and the newer multi-channel electrometer-based instrument, DMS500, measures a full set of sizes simultaneously. Missouri S&T employs two of the new, fast instruments which run in parallel, one being downstream of a thermal denuder. This allows both the total and non-volatile components of the PM to be measured simultaneously. This combination of information can be used to characterize the PM's volatility, assess the sampling train for anomalous particle generation and to characterize plume processing of the emission PM size distribution. The older,

slower DMA sizing instrument is normally run in parallel with the faster ones in order to accomplish a quality check on the data. Also, the DMA is more sensitive to low particle concentrations and better assures measurements in the case of very clean engines where the particle concentration may be insufficient for the newer instruments. These fast mobility instruments also yield total particle concentration measurements which complements those from the CPC. The DMS500 instruments cover a broad size range from 5 nm up to 1 μm in diameter.

The CO_2 concentration is measured in the diluted sample line and an undiluted sample line to determine an accurate level of the dilution. The dilution level information is necessary to correct the measured PM measurements. The undiluted CO_2 concentration is also used to evaluate emission index values for the particle data.

The DMS500 instrument is a relatively new device which depends on electrical mobility for particle sizing (Biskos et al. 2005), and has been used primarily for investigation of fast changing spectra such as diesel engine emissions, drug delivery systems such as inhalers, and roadside ambient PM sampling. In this instrument, the PM sample is passed through a cyclone separator to remove particles larger than 1 μm , and then given a known charge distribution using a corona charger. The PM is injected into a clean laminar flow air stream, and subjected to an electric field which deflects (in a size dependent manner) the particles toward electrometer rings. The currents resulting from the charge transported to the electrometer rings by the particles are measured and the current-electrometer data matrix is converted into particle number and size classification. Since the various electrometer currents are measured simultaneously rather than sequentially, the measurement is fast, up to 10 Hz.

The Missouri S&T diagnostic instrument list for the methodology development test included the following:

- Two fast particle size spectrometers (Cambustion DMS 500, 5-1000 nm, 1Hz)
- Thermal denuder set at 300 $^{\circ}\text{C}$ to precede one of the DMS 500 for non-volatile PM monitoring
- TSI CPC's (2 each of model numbers 3022, 3025)
- Tandem DMA system for hydration property analysis (soluble mass fraction)
- Fast CO_2 concentration monitors
- Laser Particle counter
- Relative humidity monitors
- Sample flow distribution and dilution control system
- Weather station

C-2.2 ARI DIAGNOSTIC MEASUREMENT SYSTEMS

Aerodyne Research, Inc. (ARI) provided real-time instrumentation for measuring size and composition resolved distributions of PM particles (MAAP, AMS) and a tunable infrared laser differential absorption spectrometer (TILDAS) for measuring gas-phase exhaust constituents. A proton transfer reaction mass spectrometer (PTR-MS) was also used on the diluted sample to measure hydrocarbon constituents in the exhaust including those which can condense to the non-volatile phase and the volatile PM.

The ARI AMS provides quantitative real-time inorganic and organic particulate mass and size-resolved compositional analysis of PM particles in the size range 0.04 to ~ 1.5 μm diameter. The

AMS consists of an aerodynamic lens (Liu et al. 1995) that focuses sub-micron particles (30 nm to 1 μm diameter) into a differentially pumped vacuum chamber (Jayne et al., 2000). Particle velocity (measured via time-of-flight between a mechanical chopper and the detector) determines the aerodynamic diameter of the PM particles. The detector consists of a resistively heated vaporizer placed directly in the electron impact ionizer of a quadrupole mass spectrometer. Volatile and semi-volatile components are flash-vaporized and are analyzed (12 – 600 amu mass range) by a mass spectrometer. The advantage of this approach is that particle vaporization and gas plume detection are separated, enabling quantification (via straight forward calibrations) of vaporized PM species. Moreover, electron-impact ionization-generated mass spectra can be directly compared with standard mass spectral libraries. Elemental carbon (EC), including engine non-volatile PM, does not vaporize at the 600-1000 $^{\circ}\text{C}$ temperature of the detector.

The ARI TILDAS instrument provides rapid time response optical measurements of exhaust gas species, such as NO, NO₂, CO, and SO₂, and reactive trace species, such as HONO and formaldehyde. The TILDAS can measure up to four species simultaneously, with a response time that is limited only by the sampling system flow and the optical volume (1/3 liter). The TILDAS system is among the world's best gas phase species detection systems that can be deployed in the field. For a sampling speed of one Hz, the detection limit for all of the species measured is less than a few ppb. The instrument works by a direct wavelength sweep in the vicinity of one or more infrared absorption features. The resulting baseline resolved absorption profile is curvefit to a Voigt absorption model, which accounts for the known innate line strength and the broadening due to pressure and Doppler effects. The concentrations measured by TILDAS are tied only to the known line strength in a database such as HITRAN. Though no calibration of this system is required once the line strengths are known, at the Validation Test, calibration standards were used for NO, NO₂ and CO measurement accuracy validation.

A key aspect of the ARI measurements is the combination of the AMS and TILDAS data with that of other instruments aboard the Lab. For example, CO₂, which serves as the plume 'dilution' tracer, is measured by a commercial LiCOR instrument. Both the AMS and the TILDAS instruments provide data with a time response of seconds, allowing transient behavior and variation in emission performance to be quantitatively tracked in real time.

The following list of ARI instruments were used for the Validation Test:

- Aerosol Mass Spectrometer (AMS);
- Condensation Particle Counter (CPC);
- Scanning Mobility Particle Sizer (SMPS);
- Multi-Angle Absorption Photometer (MAAP);
- Licor CO₂ measurement;
- NO by Chemiluminescence (NO_x box)
- Tunable Infrared Laser Differential Absorption Spectrometers (TILDAS) for species such as NO₂, CO, HCHO (formaldehyde), C₂H₄ (ethylene);
- Proton Transfer Reaction Mass Spectrometer (PTR-MS) for species such as acetaldehyde, propene, acrolein, benzene, other aromatic compounds and hydrocarbons up to a molecular weight of ~150 amu.

C-2.3 AEDC DIAGNOSTIC MEASUREMENT SYSTEMS

Gas species concentrations and smoke number measurements were performed primarily for data quality assurance. If irregularities were found in the PM data, gas measurements could be used to diagnose engine combustion efficiency in those regions and smoke number measurements compared to legacy data for assessment of the anomalous behavior. AEDC provided real-time instruments for measuring gaseous constituents and the standard filter-extraction based instrument for smoke number. AEDC also provided the probe-rake system and sample system traverse as described in Section C-1.3, and data acquisition systems for thermocouple and pressure transducer measurements.

The gaseous concentrations measurements were performed using MKS Model 2030 MultiGasTM Analyzers (MGA) capable of measuring a large number of infrared-active gas species (CO, CO₂, H₂O, NO, NO₂, SO₂, and lighter hydrocarbons from CH₄ to C₄H₁₀). Total unburned hydrocarbons (THC) were measured using a Model 300 Heated Flame Ionization Detector (HFID) analyzer made by California Analytical Instruments. Smoke number (SN) measurements were performed using procedures defined in the SAE Aerospace Recommended Practices (ARP) 1179.

AEDC provided the following instruments and hardware for the Methodology Development Test:

- MultiGasTM Analyzer (MGA)
- Flame Ionization Detector (FID)
- SAE Smoke Meter (SM)
- Thermocouples (TC)
- Pressure Transducers
- Video Cameras
- Probe-Rake System
- Traverse System

C-3.0 INTERIM PM TEST METHODOLOGY (IPMTM) VALIDATION

C-3.1 INTRODUCTION

The Validation Test was conducted to evaluate and demonstrate the interim PM test method on a military engine using sampling hardware developed for eventual measurements of the F135 engine exhaust. This section describes the implementation of the IPMTM for performing measurements on an F100-220 engine in a Tinker Air Force Base engine test facility. The data are reported in terms of emission index (EI) defined as the “quantity” of emissions of a given constituent per thousand mass units (kg) of fuel burned. The mass emission index of PM, E_{Im}, is the mass of PM per thousand grams of fuel burned. The number emission index of PM, E_{In}, is the number of particles per kg of fuel burned.

C-3.2 SAMPLING TRAIN, RAKE STAND, TRAVERSE AND DILUTION SYSTEMS

The recommended practice for sample train, rake stand, traverse, and dilution systems design, fabrication, calibration, and operation as set out in the IPMTM were implemented for this

demonstration. PM and gas samples from an array of locations in the engine exit plane were acquired in real time with this system and delivered to the diagnostic instrumentation suite. Adhering to the IPMTM recommendations assured: (1) sample concentrations above the sensitivity limit of the diagnostic instruments and below levels that would lead to agglomeration and (2) flow rates sufficient to inhibit diffusion losses.

C-3.3 INSTRUMENTATION

C-3.3.1 Particulate Matter Species

The following instruments, specified in the IPMTM for PM size and number characterization, were employed in the validation study.

- CPC: Saturator-condenser type Condensation Particle Counters (CPCs), TSI models 3022A and 3025A, were used for particle number measurements.
- DMA: Commercial Differential Mobility Analyzers (DMAs) were used for size distribution measurements.
- MAAP: Black Carbon (BC) PM mass was measured using a Thermo Electron Multi-Angle Absorption Photometer (MAAP) [Petzold and Schonlinner, 2004; Petzold et al., 2005]. The MAAP measures particulate black carbon by collecting PM onto a 2 cm² quartz fiber filter tape. The transmission and scattering of 630 nm wavelength LED light are monitored by multiple photodetectors. A two-stream radiative transfer calculation separates the scattering from the absorption component for the total particle loading on the filter tape. The instantaneous loading is computed by the derivative of the total.
- Smoke meter: AEDC provided the standard filter-extraction based instrument for smoke number measurements. Smoke number measurements were acquired in accordance with procedures defined in the SAE Aerospace Recommended Practices (ARP) 1179 and ICAO ANNEX16. Smoke number measurements were performed primarily for data quality assurance. If anomalies were encountered in PM measurements, a comparison of smoke number measurements with legacy data might offer evidence that corroborates or dispels potential issues with the modern PM test method instrumentation.

C-3.3.2 Trace Gas Measurement Instrumentation

Non-volatile particle measurements are the primary focus of the current methodology. In support of that primary focus, trace gas and volatile particle properties were measured using the suite of instruments described in Table C-3.1.

Table C-3.1 Trace Gas Instruments Deployed during the Validation Test

Instrument	Species Detected	Detection Limit^a	Time Resolution
Licor 6262 Licor 820	CO ₂ CO ₂ (high range)	300 ppb 2 ppm	1 sec
NO _x Chemiluminescence Analyzer ThermoElectron (model 42C)	NO NO _x ^b	0.5 ppb 0.5 ppb	1 sec/20 sec 20 sec
QC-TILDAS ^{c,d}	NO ₂	0.5 ppb	1 sec
	C ₂ H ₄	2 ppb	1 sec
	CO	2 ppb	1 sec
	HCHO	1 ppb	1 sec
	HONO	2 ppb	1 sec
PTR-MS ^e	acetaldehyde, propene, benzene, toluene, styrene, C ₂ -benzene ^f , phenol, naphthalene, methylnaphthalene, dimethylnaphthalene	2-5 ppb	8 sec

^a Detection limits are quoted as 2 times instrument noise level.

^b The measurement of NO_x using catalytic reduction of NO₂ to NO (most chemiluminescence analyzers) also measures higher nitrogen oxides such as HNO₃, HONO, and organic nitrates.

^c quantum-cascade tunable infrared laser differential absorption spectrometer (Aerodyne Research, Inc.).

^d tunable infrared laser absorption spectrometer (Aerodyne Research, Inc.).

^e proton-transfer reaction mass spectrometer.

^f C₂-benzene includes *o*-xylene, *m*-xylene, *p*-xylene, and ethylbenzene.

C-3.4 DATA ACQUISITION SYSTEMS

The data acquisition system described in the IPMTM (Appendix A) was implemented for the validation study. All measurement data was recorded in real time on multiple hard drives. Selected data were displayed in real time to help ensure stable engine operation and proper operation of the sample gas extraction and distribution systems. Similarly all trace gas measurements (including CO₂), key PM properties, total non-volatile PM mass and total particle number and concentrations of important volatile PM species (sulfuric acid/sulfate and organics) were displayed in real time.

C-3.5 PROCEDURE

C-3.5.1 Pre-test activities

C-3.5.1.1 Leak checking / sample line integrity

Leak checking/sample line integrity tests were performed according to the methods described in detail in the IPMTM document.

C-3.5.1.2 Instrument and line loss calibration

The aerosol generation system shown in Figure C-3.1 was used in the Validation Test studies. It provided challenge aerosols to determine the detection efficiency of the condensation particle

counters, the sizing accuracy of the various instruments, and the penetration of particles through the long sample delivery lines. The methods employed to achieve these calibrations are described in detail in the IPMTM document.

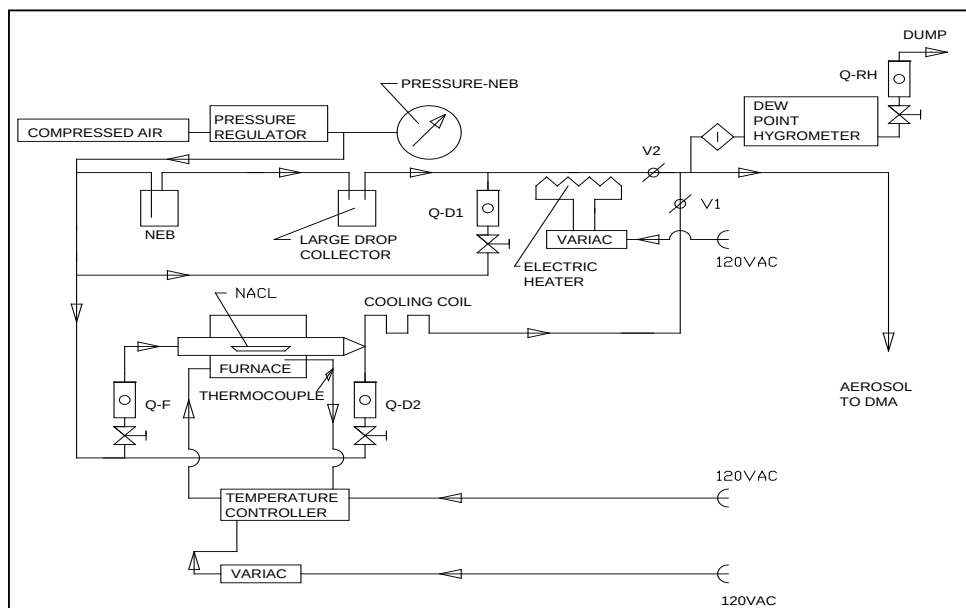


Figure C-3.1 Calibration aerosol generation system for sample system penetration measurements.

Line loss experiments were performed according to the IPMTM procedure to determine the size dependent penetration function (probability that a particle of given size which enters the sample train will arrive at the instrument) for the three primary Missouri S&T instruments. The results are shown in Figure C-3.2.

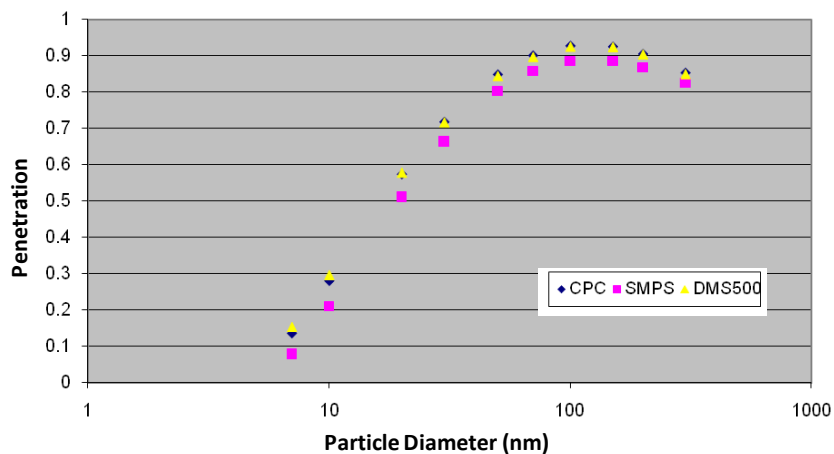


Figure C-3.2 Sample train penetration, as a function of particle diameter, from the probe to the instrument.

The size spectrum instruments (SMPS and DMS500) were calibrated against size standards (PSL spheres and silver particles sized with electron microscopy) as described in the IPMTM. Figure C-3.3 shows the static calibration result for the SMPS; xcor denotes the particle diameter reported by the instrument vs. the true diameter, xtru.

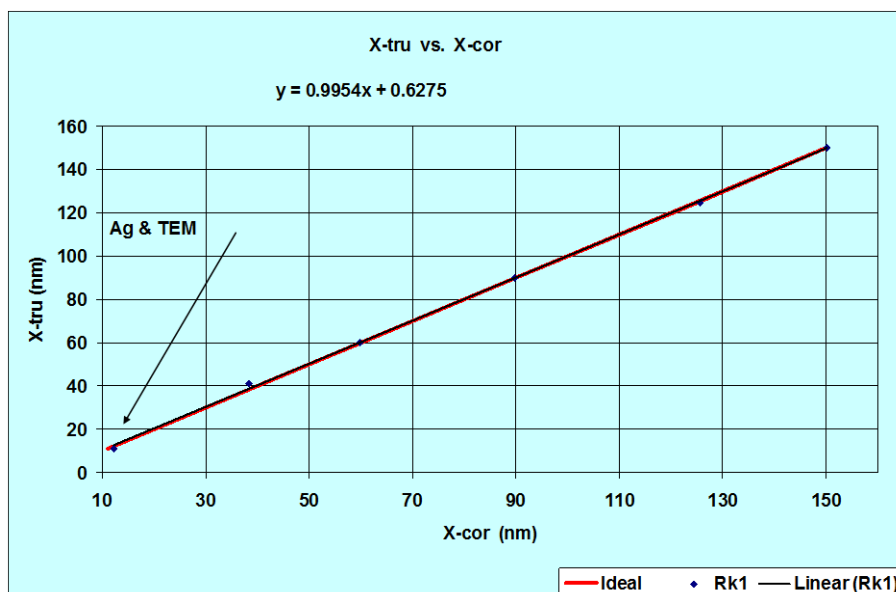


Figure C-3.3 SMPS static calibration results.

Figure C-3.4 shows results from the SMPS dynamic calibration (size sweeping mode). The x-axis represents the natural logarithm of the particle diameter reported by the instrument and the y-axis represents the natural logarithm of the true particle diameter.

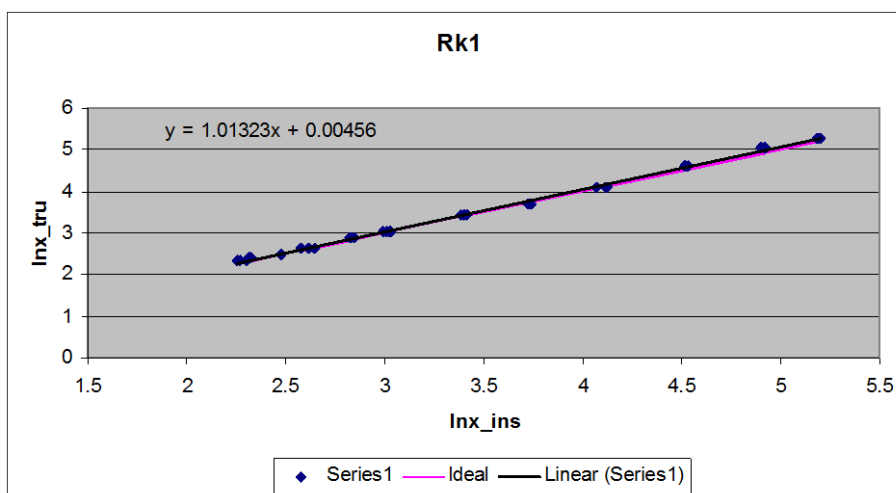


Figure C-3.4 SMPS dynamic calibration results.

The DMS500's can be calibrated only in the dynamic mode. Calibration results for the DMS500 are shown in Figure C-3.5.

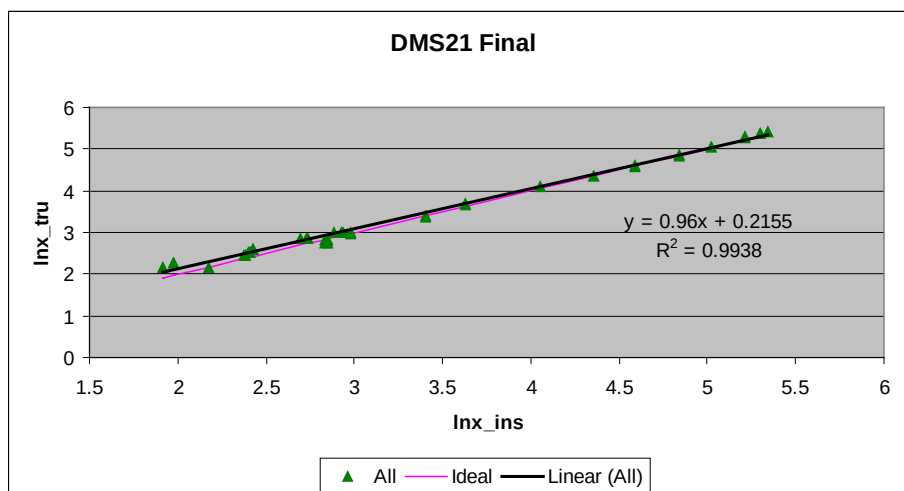


Figure C-3.5 DMS500 dynamic mode calibration results.

In all cases the performance of the particle sizing spectrometers is close to ideal, i.e. the instruments were reporting correct particle sizes.

The butanol-based CPC's (Condensation Particle Counter) were calibrated against an electrometer as described in the IPMTM. Calibration results are presented in the form of the ratio of the true particle concentration as reported by the electrometer divided by that given by the CPC, as a function of particle concentration, in units of thousands of particles per cubic centimeter. These results are shown in Figure C-3.6 for the back-up CPC (3022-296), Figure C-3.7 for the primary CPC (3022-659), and Figure C-3.8 for the CPC (3025-1088) used in conjunction with the SMPS. The x-axis represents particle concentration and the y-axis the ratio particle concentration reported by the electrometer to that given by the CPC. The vertical red line at concentration 10^4 particles/cm³ indicates the transition from single particle mode to photometric mode.

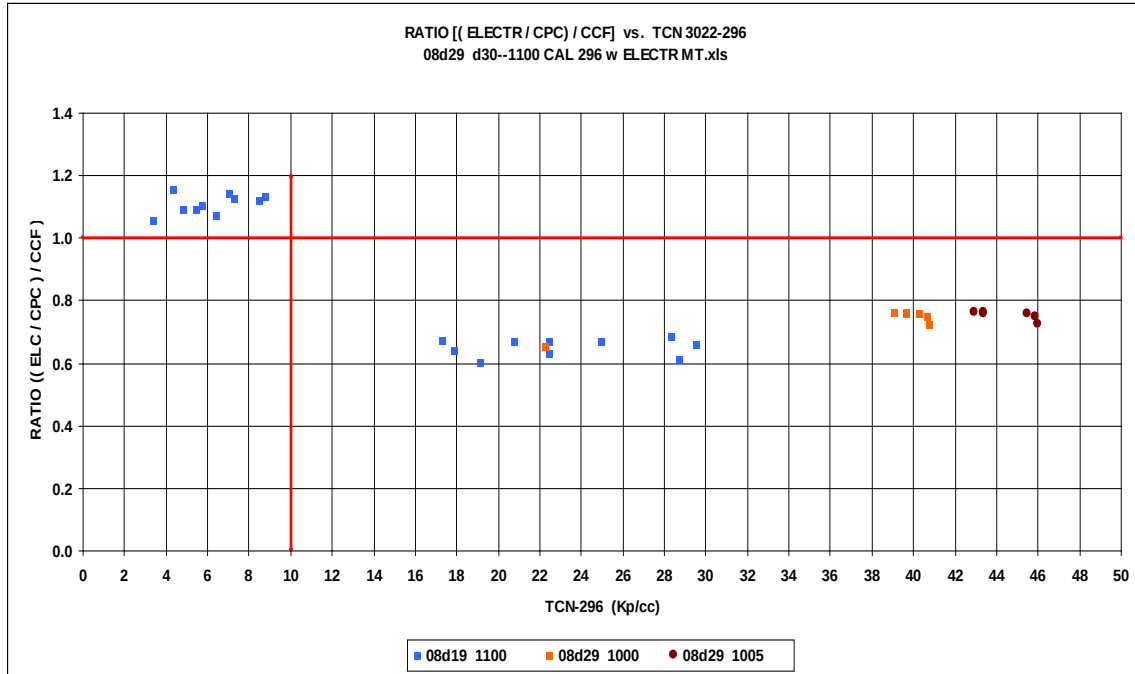


Figure C-3.6 Instrument Calibration results for CPC 3022-296.

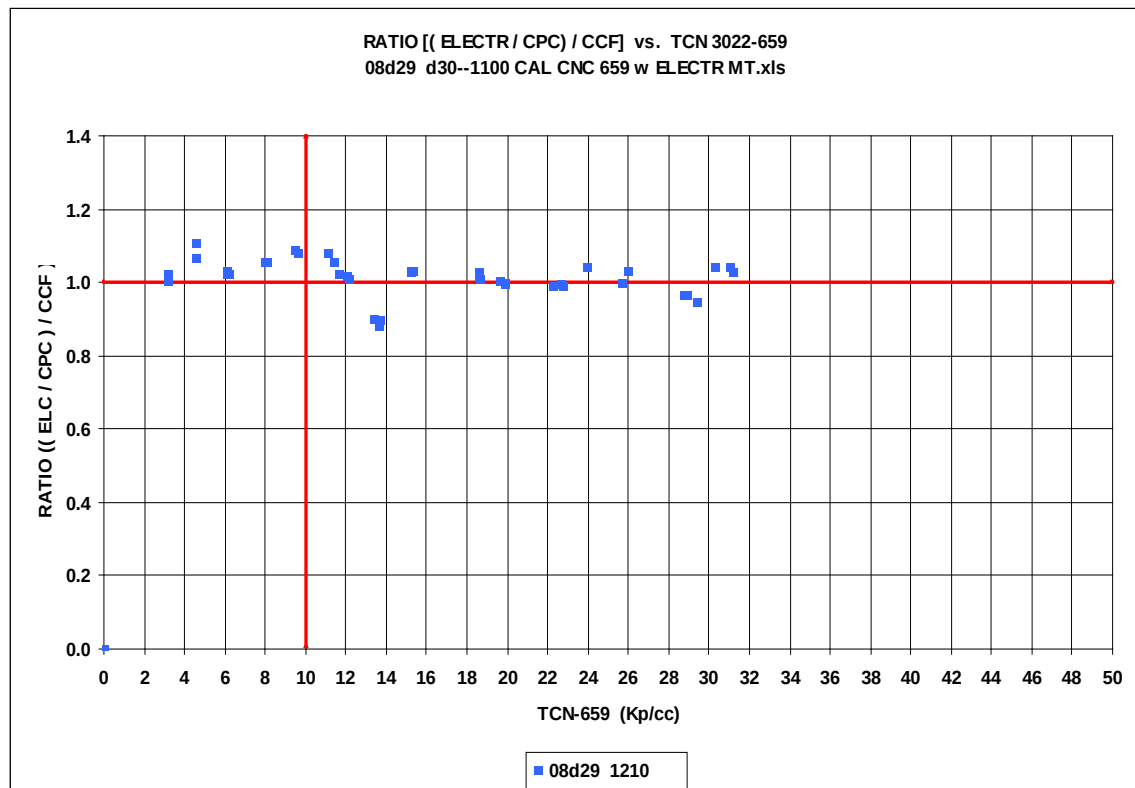


Figure C-3.7 Instrument Calibration results for CPC 3022-659.

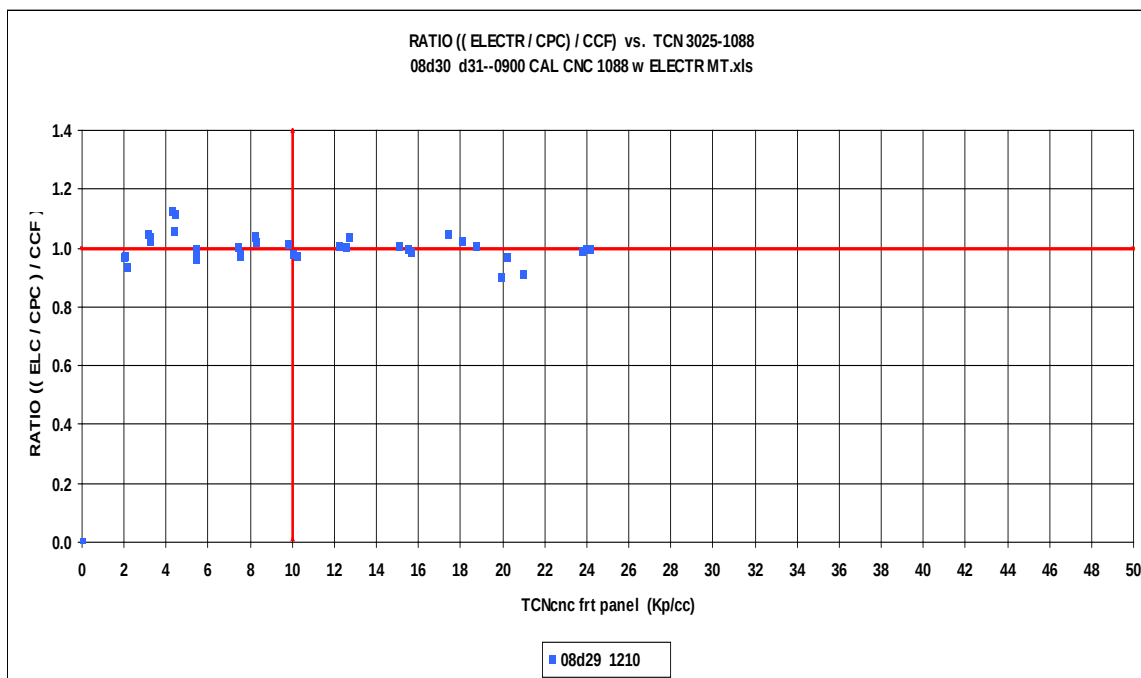


Figure C-3.8 Instrument Calibration results for CPC 3025-1088.

C-3.5.1.3 Dilution System Check

The ability of the dilution system to deliver approximately 120 LPM of diluent to the sample train, when the pressure at the probe tip is at ambient pressure, was verified.

C-3.5.1.4 Sample Train Operation Check

Sample Line Pressure and Control

Most analyzer instruments are designed to work at ambient atmospheric pressure, so the sample handling system must deliver particle laden gas to the instruments at near atmospheric pressure. Further, changes in particle microphysical processing (e.g., particle wall loss, coagulation, condensation/evaporation, new particle formation) may result if the sample pressures deviate too much from atmospheric pressure, reinforcing the need for a standard measurement pressure. In accordance with the IPMTM procedures for sample train operation, sample line pressures at the instrument end of the sample line were maintained between 0.85 and 1.02 atm.

Sample Line Temperature and Control

In accordance with IPMTM procedures for sample line temperature control, the sample lines were maintained at a temperature between 25 ± 15 °C. The particle probe was water cooled during engine test runs.

Dilution System

Dilution ratios in the range of 5-20 were employed in the validation studies thus suppressing gas-to-particle conversion processes in the sampling system. The last three columns in Table C-3.2 are sample dilution factor data for the Nov. 10, 2008 mapping study, and are typical of dilution factors employed throughout the demonstration phase of the campaign.

C-3.5.1.5 Engine test facility shakedown and test matrix optimization

The system was operated over a range of engine loads as prescribed by the engine manufacturer to verify functionality of all aspects of the system including the data acquisition system. During engine start the sampling system was back-purged with dilution gas to prevent pre-ignition unburned fuel from fouling the sampling system.

A test matrix for the demonstration study was created using the guidelines set out in the IPMTM document. Following the test matrix assured the acquisition of emissions characterization measurements for replicate engine operating conditions and sampling durations. Table C-3.2 is an example segment of the test matrix spreadsheet for the demonstration study.

Table C-3.2 Example segment of mapping test matrix, Nov 10, 2008.

MST Data Suite			Probe Position (from engine center)					Start time	End time	Dil CO2	UnDil CO2	Dil fac
Run	Assigned	Normalized	Horiz	Vertical	Radial		Heated					
Date	Name	Test Pt.	Fuel Flow	Position	Position	Position				ppm	ppm	(Undil/Dil)
11/10/2008	1	1088	0.22	-5	2.13	5.43	N	8:26:59 PM	8:29:15 PM	2011	17291	8.6
11/10/2008	1	1089	0.22	-5	5.13	7.16	N	8:30:48 PM	8:33:05 PM	1746	17266	9.9
11/10/2008	1	1090	0.22	-5	8.13	9.54	N	8:34:28 PM	8:36:45 PM	1181	5738	4.9
11/10/2008	1	1091	0.22	-5	11.13	12.20	N	8:37:53 PM	8:40:00 PM	740	9957	13.5
11/10/2008	1	1092	0.22	-5	17.13	17.84	N	8:40:44 PM	8:43:25 PM	1521	17368	11.4
11/10/2008	1	1098	0.22	-10	17.13	19.84	N	8:45:50 PM	8:48:20 PM	1295	8402	6.5

C-3.6 EMISSIONS TESTING

C-3.6.1 Optimum sampling locations via mapping tests at two powers

Mapping experiments were performed at several engine power conditions: normalized fuel flow (NFF) rate = 0.11, 0.43, 0.67, 0.84, and 1.0. As described in the IPMTM, measurement data from two power conditions (NFF = 0.11 and 1.0) were used to determine optimum sampling locations representative of an area weighted average of the full suite of spatially measured PM-derived parameters (number-based geometric mean diameter, mass-based geometric mean diameter, geometric standard deviation, number-based emissions index, and mass-based emissions index). The result did show a dependence on these parameters. An optimum sampling position was found to be (x, y) = (-5", -3.13") with a 12% deviation from optimum. Here, "x" denotes the horizontal rake position and "y" denotes the location of probes vertically along the rake (Figure C-1.6); (x,y) = (0,0) denotes the center of the engine exit plane.

C-3.6.2 Data acquisition and back-up

The raw emissions data were acquired in accordance with the test matrix. Raw data were simultaneously stored on individual computers dedicated to separate instrument operations, and a central computer dedicated to data display. At the end of every series of test runs, raw data were copied onto an external hard drive which was stored off-site. The external hard drive was packaged and shipped separately from the instrument computers to provide redundant data backup protection during shipping.

C-3.7 POST-TEST DATA REDUCTION AND ANALYSIS

C-3.7.1 Conversion of Raw Data to Final Format

C-3.7.1.1 *Data Synchronization*

Transport times of the exhaust sample from probe tip to instrument varied with instrument location along the sample train. Furthermore, each piece of diagnostic equipment had its own sampling frequency and processing time. A post-test activity was the synchronization of these data streams and was achieved using the methods described in the IPMTM. Figure C-3.9(a) shows an example of a time shift between total PM concentration and CO₂ concentration. These two parameters are plotted as functions of time, SAM (Seconds After Midnight). The time shift is evidenced by the different locations of step changes in exhaust concentrations as recorded by each instrument. A constant time shift is applied to the CO₂ data, and then the step changes occur simultaneously for the two instruments, as shown in Figure C-3.9(b).

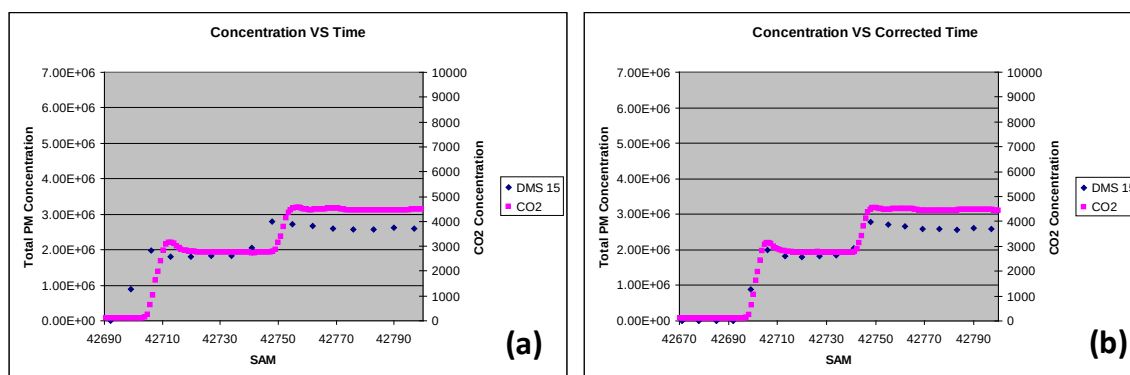


Figure C-3.9 Example time series of PM and CO₂ concentration measurements (a) before and (b) after time synchronization.

C-3.7.1.2 *Application of Calibration Corrections*

Calibration corrections acquired during the pre-test period were applied to the raw data as described in the IPMTM.

C-3.7.1.3 *Application of line loss corrections*

The line loss correction functions derived in the pre-test period were applied to the raw data as described in the IPMTM.

C-3.7.1.4 *Test Point Averages and Standard Deviations*

The measured size distribution data from the corrected synchronized data set were examined to define the times after which the emissions had reached equilibrium. A subsequent time interval was selected. Using the data acquired between these times, a test point average and standard deviation were computed for each size bin in the distribution.

C-3.7.1.5 *Uncertainty Estimates*

Standard statistical methods were employed to determine uncertainty estimates.

C-3.7.1.6 *Calculation of Derived Parameters*

The characterization of the exhaust PM was accomplished using the following parameter set.

(1) The size distribution is described by a differential concentration function $N(D_p)$, dependent on particle diameter (D_p), which specifies the concentration of particles, dn , having the logarithm of their diameters between $\log D_p$ and $\log D_p + d\log D_p$ to be $N * d\log D_p$. The logarithmic scale is used since PM diameter covers such a large size range.

$$dn = N * d \log D_p \quad (\text{Eq. C-3.1})$$

(2) Number-based geometric mean diameter (D_{geomN}) is defined by the equation

$$\log D_{geomN} = \frac{1}{n_0} \int_0^{\infty} \log D_p * dn = \frac{1}{n_0} \int_0^{\infty} \log D_p * N * d \log D_p \quad (\text{Eq. C-3.2})$$

where n_0 denotes the total particle concentration,

$$n_0 = \int_0^{\infty} N * d \log D_p \quad (\text{Eq. C-3.3})$$

(3) Geometric standard deviation (Sigma) is defined by

$$\log \sigma_g = \left(\frac{\int_0^{\infty} \left(\log \left(\frac{D_p}{D_{geomN}} \right) \right)^2 N d \log D_p}{n_0 - 1} \right)^{1/2} \quad (\text{Eq. C-3.4})$$

(4) Mass-based geometric mean diameter (D_{geomM}), is defined by

$$\log D_{geomM} = \frac{1}{\int_0^{\infty} D_p^3 * N * d \log D_p} \int_0^{\infty} \log D_p * D_p^3 * N * d \log D_p \quad (\text{Eq. C-3.5})$$

(5) The number based emission index (EIn) and the number of particles per kilogram fuel burned can be calculated by

$$EIn = EI_{CO_2} \frac{N_0}{M(CO_2)} \quad (\text{Eq. C-3.6})$$

where EI_{CO_2} denotes the mass emission index of CO_2 (for aircraft engines $EI_{CO_2} = 3160$ g/kg; (Schulte and Schlager (1996)). $M(CO_2)$, the mass of CO_2 per volume exhaust sample, is calculated by multiplying measured CO_2 mixing ratios with (44/29) pair, where pair is the air density and 44/29 is the molar mass ratio of CO_2 and air. Strictly speaking, the values of both N_0 and $M(CO_2)$ in Eq. C-3.6 must be above ambient levels, i.e., enhancements over the

background signal. However, for measurements close to the engine exit plane of gas turbine engines, the background signal levels are negligibly small.

(6) Mass-based emission index (EIm) is the mass of particles per kilogram fuel burned and its calculation is analogous to that for EIn; given by

$$EIm = EI_{CO_2} \frac{M(N_0)}{M(CO_2)} \quad (\text{Eq. C-3.7})$$

where $M(N_0)$ is the mass of PM per unit volume of exhaust sample.

These derived parameters were extracted from the corrected and synchronized size distributions.

C-3.7.2 Final Data Format – the master spreadsheet

A master spreadsheet containing PM engine emission parameters, ambient conditions, engine operating conditions and associated gas phase measurements and uncertainty estimates was assembled. These data were recorded for each test point defined in the test matrix and are archived.

C-4.0 DETAILED DATA ANALYSIS

C-4.1 ANTICIPATED PM MEASUREMENT RESULTS WITH RESPECT TO ENGINE POWER CONDITION

The primary purpose of the Validation Test is to demonstrate and evaluate the interim PM test method on a military engine using the probe-rake system hardware developed for JSF F135 engine emissions characterization measurements. But before reviewing the Validation Test data, it is prudent to review the expected dependence of particle measurements on engine operating conditions, based upon the results of the Methodology Development Test (see Appendix B) conducted on the same engine type.

As a reminder, the exhaust exiting the engine contains non-volatile PM and minor volatile gas constituents (precursors) that have a propensity, as the gas cools, to nucleate and form volatile particles (new particle formation) and/or condense and coat non-volatile particles. There are no volatile particles in the exhaust at the engine exit plane, only their gas phase precursors. The new particle formation and condensation occurs naturally in the downstream exhaust plume as the exhaust gases mix with bypass and ambient air and cools. New particle formation and condensation can also occur in the sampling line as the sample gas temperature is lowered through interaction with the cooler sample line walls. The objective of the interim PM test method is to define a sampling process by which the non-volatile PM can be measured accurately by eliminating or accounting for the interference of new particle formation and condensation. The approach in the development of the interim PM test method is the addition of a dilution gas as the sample enters the sampling probe (probe-tip dilution, Figure C-1.5) to eliminate, or mitigate, new particle formation and condensation in the sampling line over all engine power level conditions.

The changes in non-volatile PM and precursor gas species production summarized below are based primarily on observations from the Methodology Development Test (Tinker 1) conducted on this project (see Appendix B):

As power increases, the non-volatile PM (black carbon) emission index (EIm-nvPM) will be expected to increase, reaching a maximum at NFF > 0.67. This is evidenced in the MAAP measurements of non-volatile mass (expressed as EIm-nvPM) versus the normalized fuel flow (NFF) rate of the F100-220 engine during the 2007 Methodology Development Test campaign (see Appendix B). These data are shown in Figure C-4.1.

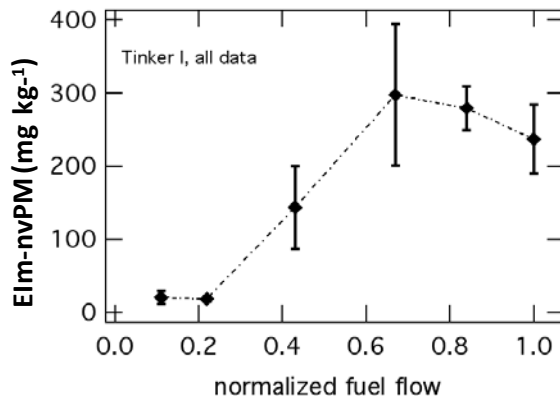


Figure C-4.1 Non-volatile PM emission index as a function of NFF for the 2007 Methodology Development Test (Tinker I).

The particle size of non-volatile black carbon particles will be expected to increase with increasing fuel flow rate. There will be a greater relative increase in mass due to the cubic dependence of particle mass on diameter. The result will be similar for particle surface area due to its quadratic dependence on size. This is evidenced in Figure C-4.2 where the measured particle size distribution, normalized to the emitted CO₂ for two normalized fuel flow rate conditions from the first (Tinker I) test campaign for this project; NFF=0.11 (idle power) and NFF=1 (take-off power), is presented.

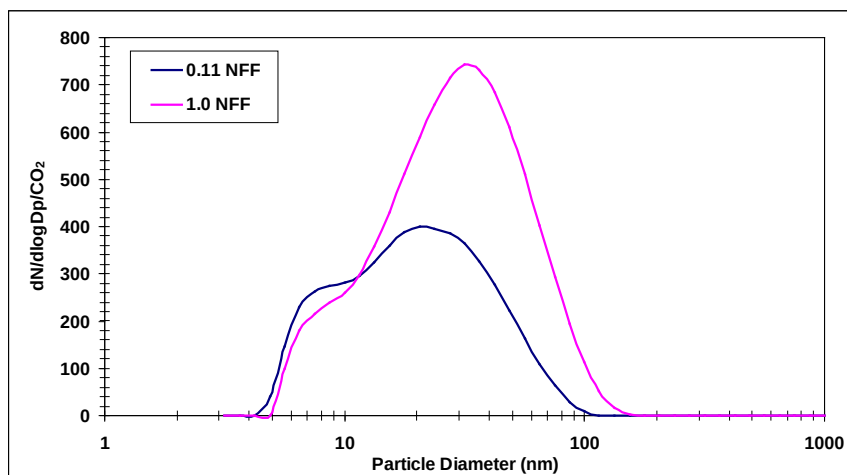


Figure C-4.2 Non-volatile size distributions for idle and take-off engine power settings for the 2007 Methodology Development Test (Tinker I).

As the engine power level increases, particle number emission index (EIn) will be expected to increase reaching a maximum at NFF > 0.67 as shown in Figure C-4.3 from the first Tinker test.

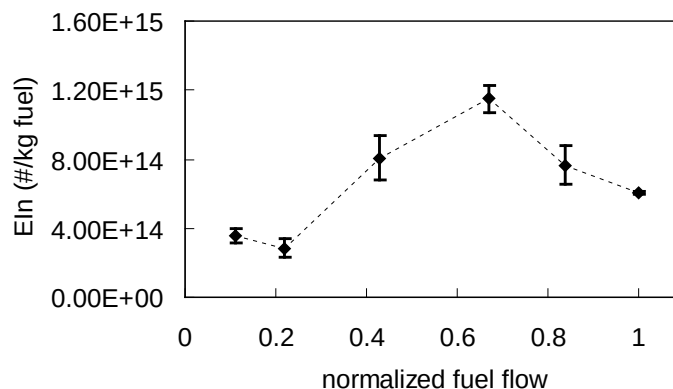


Figure C-4.3 Number based emission index as function of NFF for the 2007 Methodology Development Test (Tinker I).

The quantity of SO_3 and condensable sulfuric acid present in exhaust gas is likely to be insensitive to power condition. Particle sulfate material plays two important roles in particle microphysics. First, sulfate is the primary driver for new particle formation (Zhao et al. 1995 & Karcher et al. 1996). Second, sulfate may activate non-volatile particles, making them more effective surfaces for condensation of condensable gases. Organo-sulfur compounds naturally present in petroleum jet fuels are the source of particle sulfate materials in aircraft exhaust. During combustion, fuel sulfur compounds are oxidized quantitatively ($> 99\%$) to SO_2 . Only a small fraction of the SO_2 is oxidized further to SO_3 . The SO_3 then combines with water vapor to form sulfuric acid, which has sufficiently low volatility that it partitions to the particle phase. The key parameter therefore is the SO_2 to SO_3 conversion efficiency. A number of studies have tried to quantify SO_2 conversion, and the conversion figure seems to be on the order of 1%. Lukachko et al. (2008) recently performed a numerical simulation of SO_2 conversion and found it to be relatively independent of engine operating condition.

The emission index of precursor organic materials (EIm-vPMorganic) produced during incomplete combustion will be maximized at idle power conditions. During the Methodology Development Test, products of incomplete combustion were identified and measured using the AMS. The residual mass spectrum is consistent with a typical hydrocarbon mixture, similar to both unburned and partially burned fuel. Just as EIm-CO and EIm-HC are maximized at idle conditions, the same is expected for the emission index of condensable organic materials produced during incomplete combustion.

As the engine power level increases beyond idle, EIm-CO and EIm-HC rapidly decrease by several orders of magnitude to undetectable levels. The concentrations of precursor gases are expected to also decrease roughly in parallel with EIm-CO and EIm-HC, though this has not been confirmed experimentally.

Table C-4.1 summarizes the expected effects of power condition on the EIs of non-volatile particles and on gases that can partition to the particle phase.

Table C-4.1 Effects of Engine Power Level on Measured Particle Parameter EIs.

Species	Effect of Power
EIn	generally higher at take-off power than idle, though each engine type may exhibit different qualitative trends
EIm-nvPM (non-volatile PM)	generally higher at take-off than idle, though each engine type may exhibit different qualitative trends
EIm-volume (total volume)	generally higher at take-off power than idle, but the effect is similar to EIm-nvPM
EIm-SO ₃	relatively insensitive to power condition
EIm-vPMorganic	expected to be maximized at idle power, also with the largest uncertainty and decreases rapidly as the engine power level increases

C-4.2 MAPPING MEASUREMENTS

The characteristics of the PM exhaust emissions can be spatially non-uniform over the engine exit plane. The IPMTM report describes the methodology to characterize the spatial non-uniformity and to determine optimum sampling locations in the engine exit plane.

C-4.2.1 Non-volatile PM emissions

In the Validation Test campaign (Tinker 2), dependence of particulate matter and gaseous emission indices upon sampling rake and probe location was systematically investigated. Spatial mapping was performed by moving the sampling rake in the horizontal direction to fixed locations and selecting different particle probes located at different vertical positions. Particle measurements performed at a probe location near the vertical center of the engine as the rake was traversed horizontally showed that the number emission index (EIn) is maximum at horizontal engine centerline (x=0) and tends to decrease in either horizontal direction (Figure C-4.4). However the difference between sampling locations is not statistically significant in the core region of exhaust flow (-10 to +10 inches) since the error bars overlap. The points at (±15 inches) appear to be predominantly bypass air as evidenced by their statistically lower values. A similar trend is observed in the mass-based emission index shown in Figure C-4.5.

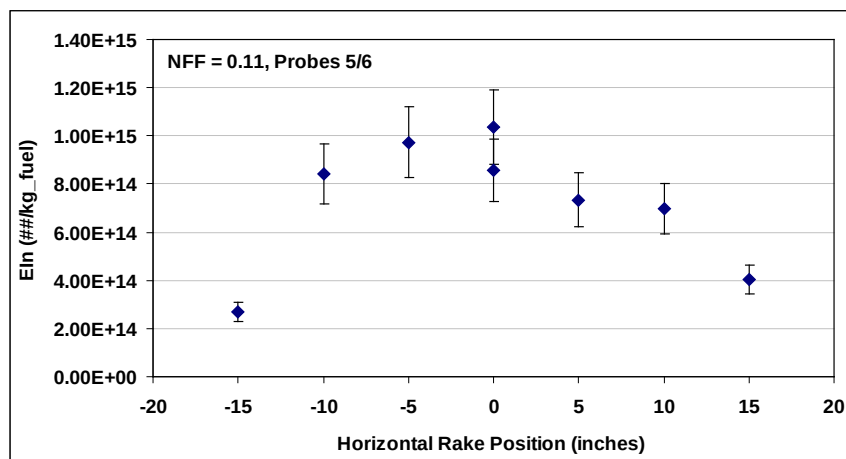


Figure C-4.4 EIn versus sampling rake position for F100-220 engine measurements during the 2009 Validation Test (Tinker 2).

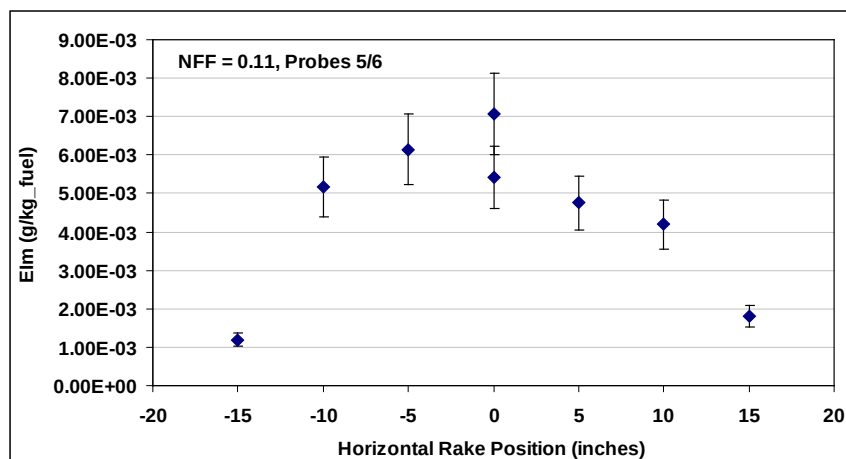


Figure C-4.5 EIm versus sampling rake position for F100-220 engine measurements during the 2009 Validation Test (Tinker 2).

The particle number and particle mass emission indices as a function of radial sampling position are shown in Figure C-4.6 and Figure C-4.7. The data points beyond the 15 inch radial position fall outside the core flow boundary and were not used in the computation of the engine averages depicted by the solid red lines. The dotted red lines represent the error bands for each emission index ($\pm 15\%$ for EIn, $\pm 30\%$ for EIm). These results are consistent with those obtained during the 2007 Methodology Development Test (Tinker-1) campaign (Appendix B).

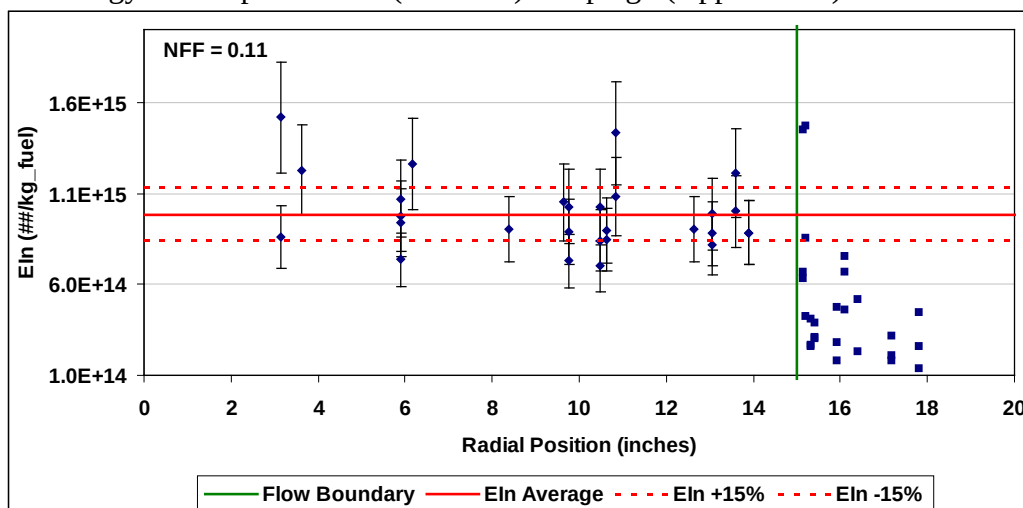


Figure C-4.6 EIn versus radial sampling position for F100-220 engine measurements during the Validation Test (Tinker 2).

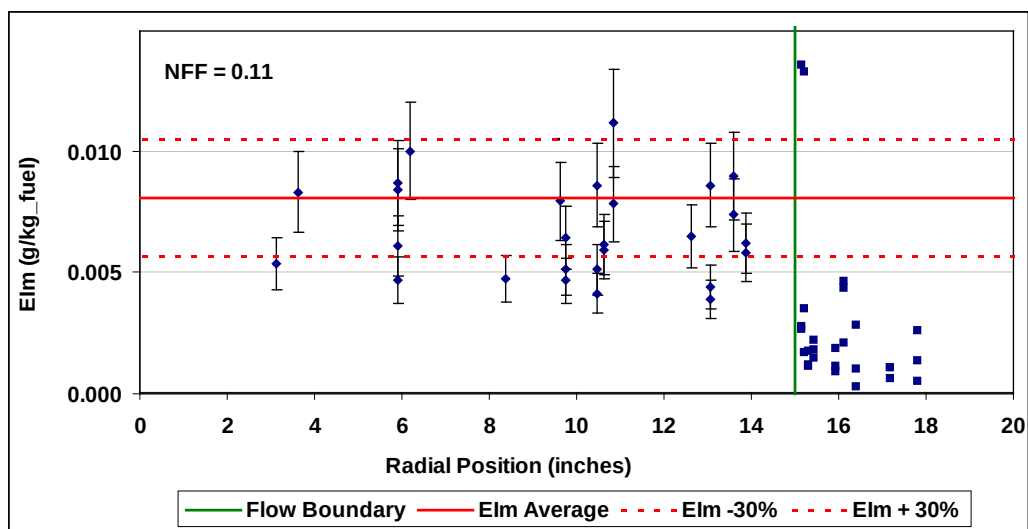


Figure C-4.7 EIm versus radial sampling position for F100-220 engine measurements during the Validation Test (Tinker 2).

C-4.2.2 Volatile Organic Carbon (VOC) emissions

Measurements of emission indices for formaldehyde (HCHO) and ethene (C₂H₄) at NFF = 0.11 as a function of vertical particle probe location at the centerline-rake position are shown in Figure C-4.8. Measurements are presented for both heated and unheated sample lines. These data indicate that the volatile organic compound (VOC) emission indices do not vary significantly with radial position of the sampling probe.

Sample line temperature does appear to affect the measurement. The C₂H₄ and HCHO VOC emission indices were typically 5 – 15% higher when sampled through heated lines. Similar results were observed for most of the chemical species measured by the PTR-MS instrument. This similarity is illustrated in Figure C-4.9, where acetaldehyde (CH₃CHO) emission indices appear to be well correlated with corresponding HCHO EIs.

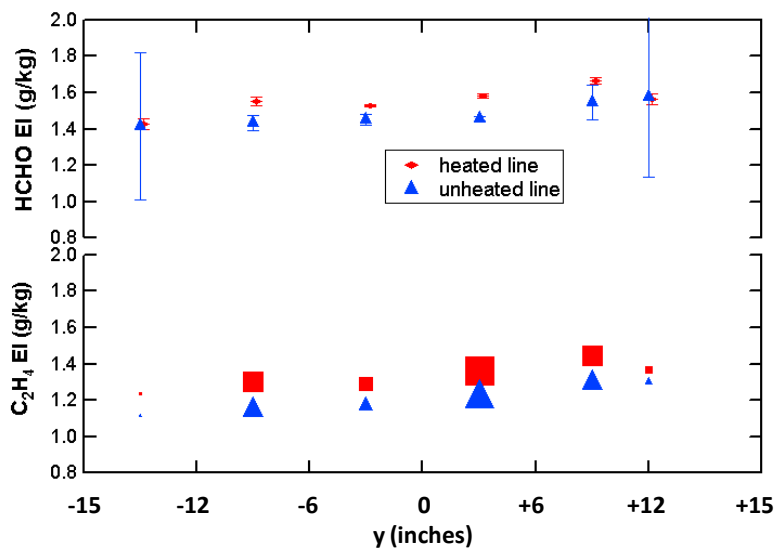


Figure C-4.8 HCHO and C₂H₄ EI's versus radial position along the vertical axis at engine centerline.

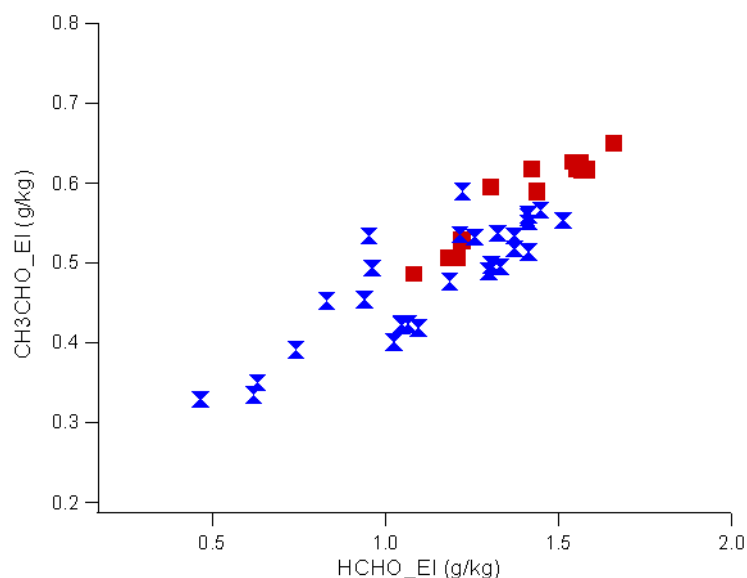


Figure C-4.9 Formaldehyde-acetaldehyde correlation for NFF=0.11.

The emission indices of the higher molecular weight, lower volatility compounds measured by the PTR-MS appear to have a dependence on the sample probe position. This behavior is demonstrated using naphthalene (MW = 128 g/mole) as an example in Figure C-4.10 where the naphthalene emissions generally appear to increase as the sample probe is moved away from the center of the engine. In this figure, the symbol size has been scaled to the measured naphthalene concentration. This is done to deemphasize data that has the greatest uncertainty, such as the measurements made at the largest radial distances. For these conditions, retention of naphthalene in the sample lines and in the PTR-MS may be responsible for the elevated emissions. While there appears to be considerable scatter in the data the variability is not random. Specific rake and probe combinations showed similar behavior on both the heated and unheated sample line experiments. While the effects observed in naphthalene emission are real, it is uncertain whether

these effects are due to sampling artifacts or reflect real differences in the spatial emission profile.

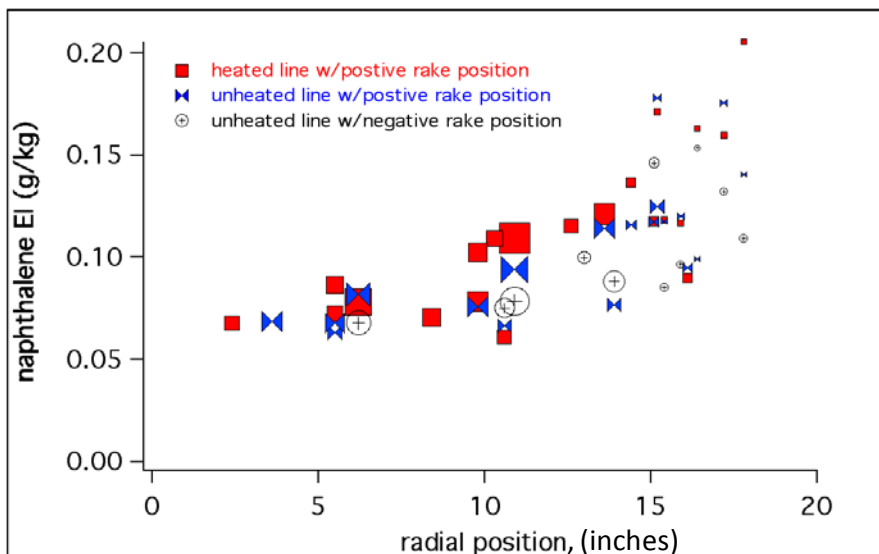


Figure C-4.10 Variation of naphthalene emission with the radial position for engine power (NFF=0.11, idle); the symbol size is scaled to the naphthalene concentration.

C-4.3 THE EFFECT OF ENGINE POWER CONDITION ON THE AMOUNT OF VOLATILE PM PRECURSOR GAS SPECIES VERSUS NON-VOLATILE PM IN THE ENGINE-EXIT-PLANE EXHAUST SAMPLE

Microphysical processing of volatile PM precursor gas species in the sampling system (specifically formation of new particles and condensation on existing non-volatile particles) can lead to measurement errors. Formation of new particles will artificially inflate measurements of the non-volatile PM (EI_{nvPM}), giving instead a measurement composed of non-volatile plus volatile particles. Condensation on existing non-volatile particles will artificially increase their diameter, volume, and mass. Moreover, coatings of condensed materials can influence particle optical properties and, although measurements of optical properties are not specifically part of the IPMTM, this is another type of bias that must be avoided. Therefore, the sampling system must be designed to eliminate formation of new particles and condensation on existing non-volatile particles.

The rates of microphysical processes depend on the sample temperature, sample concentration (or dilution ratio), and the quantity of available non-volatile particle surface area. Increasing sample temperature or dilution ratio decreases the probability that low vapor pressure species will condense and be partitioned to the particle phase. Increasing the available non-volatile particle surface area will tend to increase condensation and – depending on the amount of condensable material available – has no effect on new particle formation. In some instances, condensation and new particle formation compete. In these instances, conditions which favor one tend to suppress the other. Additionally, newly formed particles can collide with existing non-volatile particles and the condensed material contributes to the non-volatile particle's coating. Measurements cannot distinguish between coagulation of newly formed particles with non-volatile particles and direct condensation of gaseous material on the non-volatile particle.

C-4.3.1 Non-volatile PM Emissions

The primary objective of the Validation Test campaign was to assess the validity of the IPMTM sampling methodology to quantify non-volatile PM emissions. The PM size distributions are determined using differential mobility analysis (DMA) coupled with condensation particle counting. Assuming that the particles are spherical, this technique provides not only number density distribution of the engine PM emissions but also surface area and volume distributions. In agreement with our anticipated observations, the non-volatile particle mode dominates the particle size distribution with respect to number density and volume in all the tested conditions (Figure C-4.11). The number based geometric mean diameter of the detected non-volatile particles increases monotonically from 13 nm at NFF = 0.11 to about 35 nm at NFF = 1.00, as shown in Figure C-4.12.

Assuming the particles are spherical, DMA measurements directly yield information on volume per particle. The mass per particle can be determined from these volumes by assuming a particle mass density (e.g., 1 g cm^{-3}) for non-volatile particles. As shown in Figure C-4.13, mass per particle measured from jet engine exhaust increases monotonically with increasing fuel flow rate.

The mean size of a nucleation mode is usually below 10 nm. The observation of only single mode size distributions with mean diameters of 30 to 40 nm (Figure C-4.11) strongly suggest that the nucleation of precursor species, such as sulfuric acid or organic compounds, has been adequately suppressed at the levels of dilution employed in these studies. For purposes of comparison, Figure C-4.2 from previous testing shows the onset of a nucleation mode due to insufficient dilution. Both observations imply that adequate probe-tip dilution of engine exhaust at the engine exit plane may suppress microphysical or even chemical formation of volatile PM.

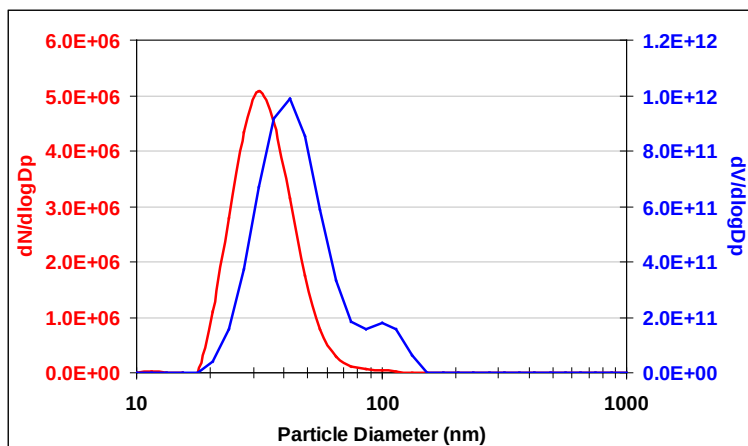


Figure C-4.11 Number and volume size distributions for NFF = 0.11.

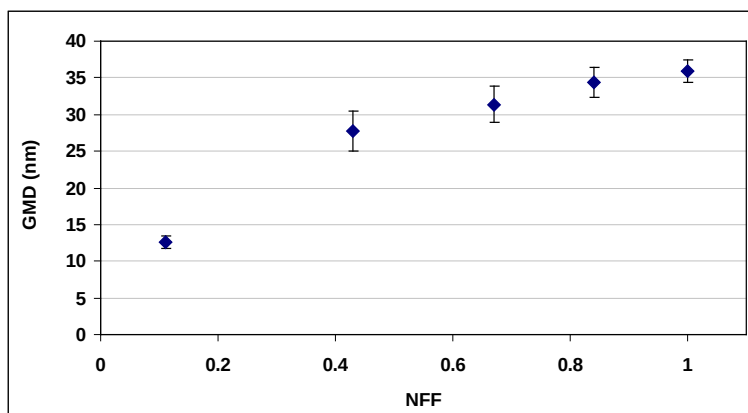


Figure C-4.12 Variation in GMD as a function of NFF.

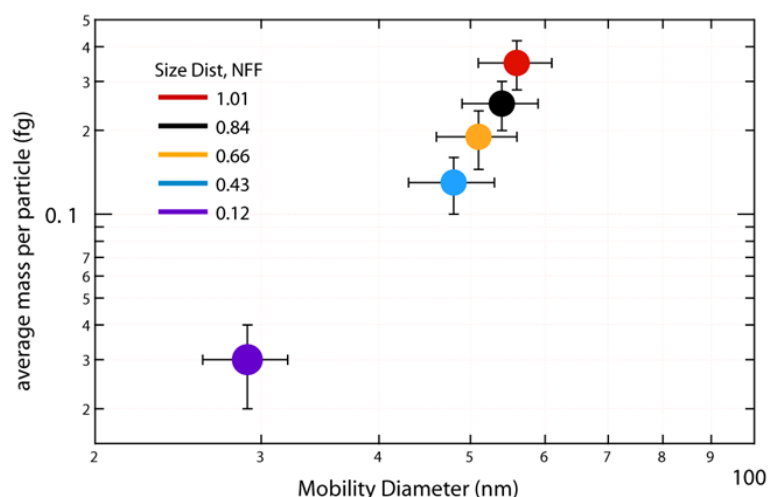


Figure C-4.13 Average mass per particle versus mobility diameter with respect to NFF, where average mass per particle is calculated assuming a particle mass density = 1 g cm^{-3} .

Another important characteristic of non-volatile PM emissions from jet engine exhaust is mass. In the Tinker 2 test, this property is carefully measured by a Multi-Angle Absorption Photometer (MAAP), via simultaneously monitoring the transmitted and the scattered light from a particle loaded filter. As engine power increased, the non-volatile PM mass-based EI (EIm-nvPM) increases to a maximum at NFF~0.8 (Figure C-4.14), which is consistent with our anticipated results based on previous test campaigns. The peak EIm-nvPM for the Validation Test is 200 ± 80 mg/kg fuel and compares favorably with to 300 ± 100 mg/kg fuel measured with the MAAP during the Methodology Development Test.

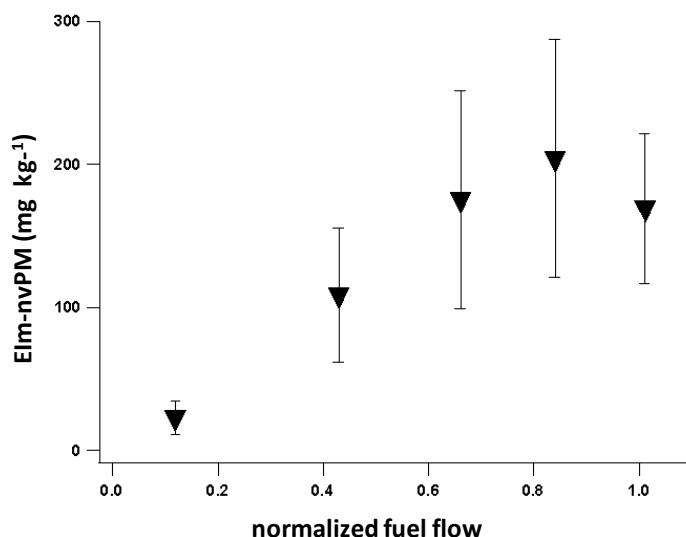


Figure C-4.14 Non-volatile PM mass-based emission index as a function of normalized fuel flow rate.

Based on the assumption of mass density = 1 g cm^{-3} , the mass emission index of the non-volatile particles was calculated from DMA data, as shown in Figure C-4.15. The colors of the size distributions are matched to the corresponding integrated mass loading in the inset. Because DMA provides direct information on particle size distribution with respect to number density, surface area, and volume, we are able to evaluate the averaged surface area and volume of the detected non-volatile PM through numerical integration on the DMA measurements. We find that the characteristic non-volatile PM mode increases almost linearly in volume with increasing fuel flow rate as shown in Figure C-4.16 as anticipated.

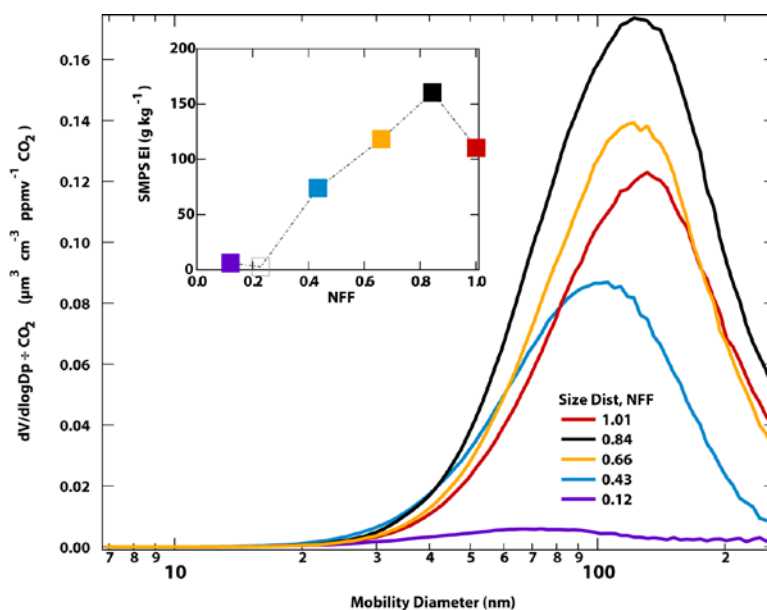


Figure C-4.15 DMA characterized PM volume distributions for five NFF settings on the unheated sampling line. The inset depicts the projected mass based EI assuming a density of 1 g cm^{-3} .

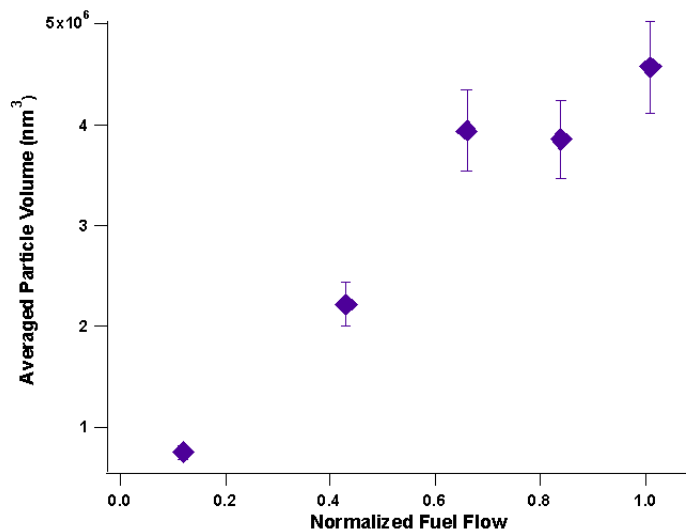


Figure C-4.16 Averaged particle volume as a function of normalized fuel flow rate.

The ratio of the MAAP mass and the integrated volume from the DMA non-volatile size distributions provides an estimate of the measured non-volatile PM mass density. These densities are plotted as a function of normalized fuel flow rate in Figure C-4.17, and are shown to be essentially independent of engine power condition with an average value of $1.46 \pm 0.42 \text{ g cm}^{-3}$.

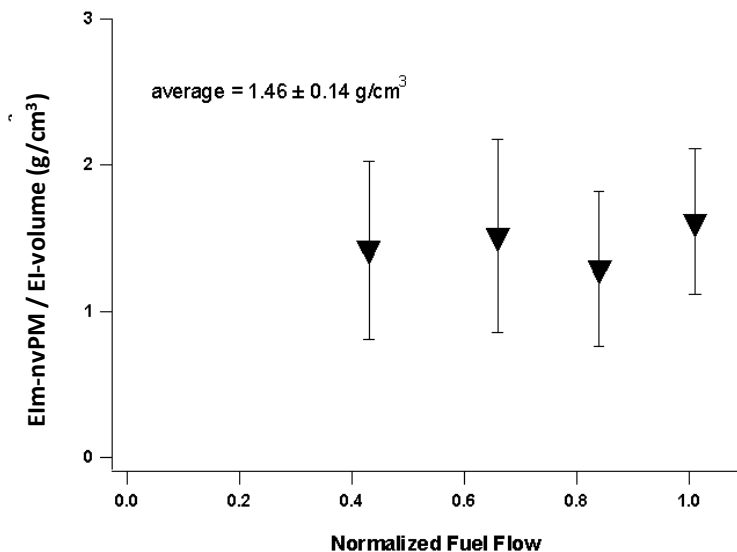


Figure C-4.17 Mass density of non-volatile particles versus NFF.

EIn is measured directly using a CPC. Figure C-4.18 is a plot of EIn versus power for the Validation Test. The large uncertainty in EIn results in no statistically significant variation versus normalized fuel flow rate.

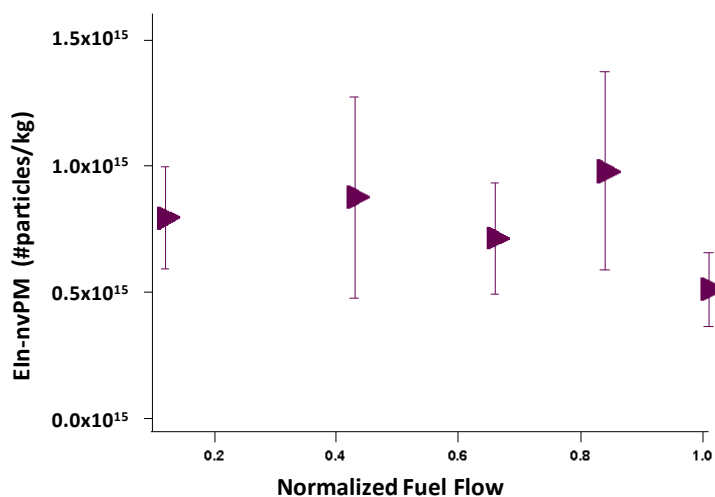


Figure C-4.18 Non-volatile PM number-based emission index, EIn, versus normalized fuel flow rate.

The mass per particle can be calculated from the ratio of the measured mass-based emission index (EIm) using the MAAP to the number-based emission index (EIn) using the CPC. Figure C-4.19 is a plot of mass per particle versus NFF and demonstrates a strong linear correlation. The volume per particle can be calculated from the ratio of the measured volume-base emission index (EIV) using the DMA to the number-based emission index using the CPC. Figure C-4.16 is a plot of volume per particle versus NFF and also reveals a strong linear correlation. Figure C-4.17 plots the ratio EIm/EIV (i.e., particle mass density) versus NFF revealing a constant non-volatile particle mass density over the full range of NFF. These data confirm, using two independent data sets for mass and volume, that the mass density of non-volatile PM from jet engine exhaust is independent of engine power conditions, although both mass and volume per particle increase with normalized fuel flow rate.

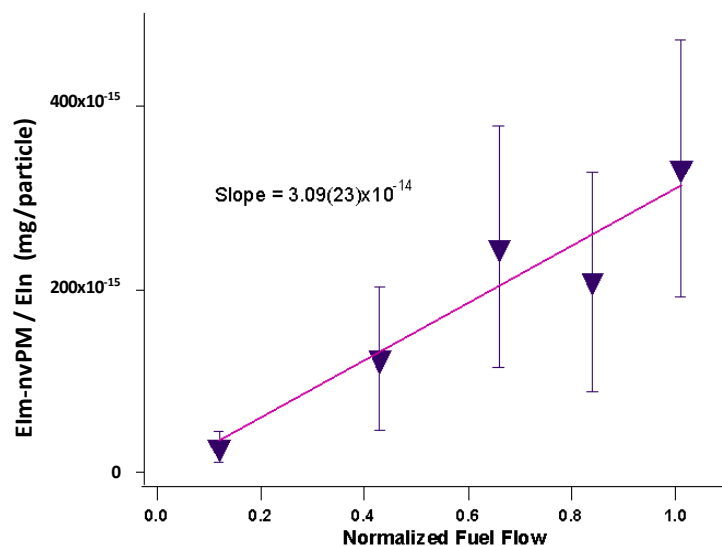


Figure C-4.19 Mass per particle of the non-volatile PM from jet engine exhaust versus normalized fuel flow rate.

C-4.3.2 Volatile PM Emissions – Organics and Sulfates

The Aerodyne Aerosol Mass Spectrometer (AMS) was employed at the Validation Test to determine the extent of nucleation and condensation processes in the sample line by determining the semi-volatile component (organics and sulfates) of measured particles in the size range 40-700 nm diameter. Currently AMS is the only available instrument capable of offering quantitative size and chemically resolved mass loading information for non-refractory sub-micron PM above 40 nm. It couples size-resolved particle sampling and mass spectrometric techniques into a single real-time measurements system.

The AMS measurement of condensed sulfate was found to be below our instrumental detection limit ($0.4 \mu\text{g}/\text{m}^3$). The organic emission indices, $\text{EI}_{\text{m-organic}}$, are presented in Figure C-4.20 and were found to be $\leq 1\%$ of $\text{EI}_{\text{m-nvPM}}$ and insensitive to the variation of engine power level conditions. These results indicate that adequate probe-tip dilution was achieved and sample line production of nucleated and/or condensed volatile material was mitigated.

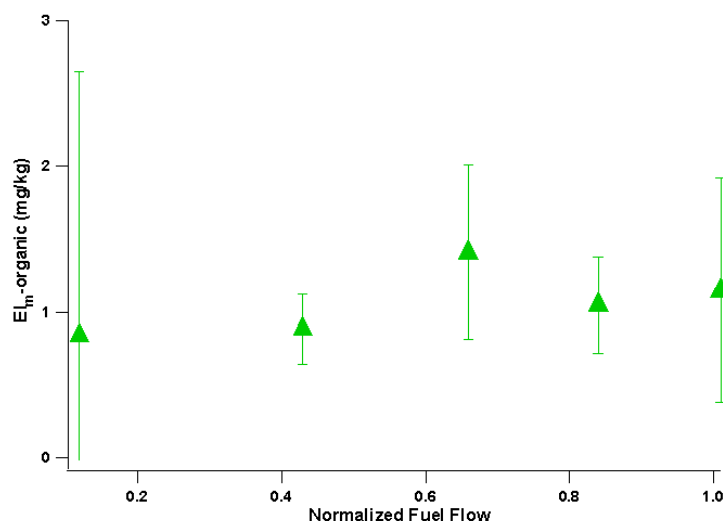


Figure C-4.20 Organic emission index versus NFF.

In contrast to DMA measurements on mobility diameter of the particles (D_p), AMS measures vacuum aerodynamic diameter of the particle, D_{va} . For a spherical particle under vacuum condition, $D_{va} = D_p \cdot \rho$, where ρ is specific gravity of the particle. Table C-4.2 lists the determined specific gravity of non-volatile PM from jet engine exhaust in the Validation Test campaign. Although it shows a slight dependence on normalized fuel flow rate, this variation is still under our experimental uncertainty. The listed values give the averaged mass density of $1.05 \pm 0.21 \text{ g cm}^{-3}$ for non-volatile PM under different engine power level conditions, and within the limits of experimental uncertainty are consistent with the value of $1.46 \pm 0.42 \text{ g cm}^{-3}$ derived from MAAP and DMA measurements.

Table C-4.2 Specific gravity of the non-volatile particles with respect to NFF.

NFF	D_p (nm)	D_{va} (nm)	ρ
0.11	62.8 ± 0.9	50.7 ± 1.5	0.81 ± 0.03
0.43	104.4 ± 0.6	103.7 ± 3.0	0.99 ± 0.03
0.66	112.0 ± 0.9	102.6 ± 9.0	0.92 ± 0.08
0.94	124.2 ± 0.6	162 ± 15	1.30 ± 0.12
1.01	122.1 ± 0.9	149 ± 21	1.22 ± 0.17

C-5.0 FUEL ANALYSIS DATA FOR THE METHODOLOGY DEVELOPMENT TEST

Samples of the fuel were collected after each run of the Validation Test and analyzed by Aerospace Testing Alliance (ATA) in the Chemistry Laboratory at AEDC. The analyses of the samples showed no significant deviations in fuel density, flashpoint, free water, gross heat of combustion, net heat of combustion, hydrogen content, sulfur content and viscosity. The values shown in laboratory report in Figure C-5.1 are representative. One fuel sample was analyzed to determine the solids content of the fuel and the result is shown in Figure C-5.2.

 ATA Aerospace Testing Alliance A Joint Venture of JSC, CSC and GP	ATA Chemistry Laboratory Report of Analysis 445 Von Karman Rd, Arnold Air Force Base, TN 37389-3400	Report # 09-1425 Report Date: 30-Jul-09
Client Name: Robert Howard MS-9013	Phone: (931) 454-7340 Fax: (931) 454-6569	Work Order/ Task: 0500820/01
Chem Lab Sample #: 09-1425-001	Client ID: Tinker-2 Test (11/12/08 End of Day)	Sample Collection Date: 11/13/2008 13:00
Client No: F100-220 Fuel Sample 1		Sample Receipt Date: 7/29/2009 13:48
Site: TECHNOLOGY		Sample Type: Fuel

Test Name	Test Results	Units	Method	Date of Analysis	Analyst
Density (60°F)	0.80868	g/cm3	ASTM D4052	7/30/2009	MH
Density (100°F)	0.79247	g/cm3	ASTM D4052	7/30/2009	MH
Flash Point	148	F	T.O. 42B1-1	7/30/2009	MH
Heat of Combustion, Gross	19844	BTU/lb	ASTM D4809	7/30/2009	MH
Heat of Combustion, Net	18571	BTU/lb	ASTM D4809	7/30/2009	MH
Hydrogen Content of Fuel	13.96	% by wgt.	ASTM D3701	7/30/2009	MH
Sulfur (S)	0.037	% by wgt.	ASTM D4294	7/30/2009	MH
Viscosity (60°F)	2.172	cSt	ASTM D7042	7/30/2009	MH
Viscosity (100°F)	1.497	cSt	ASTM D7042	7/30/2009	MH
Water, Free (AEL)	0	ppm	T.O. 42B1-1	7/30/2009	MH
Water, Total (KF)	85	ppm	ASTM E203-01	7/30/2009	JL

Figure C-5.1 ATA Chemistry Laboratory report showing the fuel properties representative for all engine test runs.

 ATA Chemistry Laboratory Report of Analysis		Report # 09-1425 Report Date: 30-Jul-09			
445 Von Karman Rd, Arnold Air Force Base, TN 37389-3400					
Client Name: Robert Howard MS-9013	Phone: (931) 454-7340 Fax: (931) 454-6569	Work Order/ Task: 0500820/01			
Chem Lab Sample #: 09-1425-005	Client ID: Tinker-2 Test (11/14/08 End of Day)	Sample Collection Date: 11/13/2008 13:00			
Client No: F100-220 Fuel Sample 5	Sample Receipt Date: 7/29/2009 15:45	Sample Type: Fuel			
Site: TECHNOLOGY					
Test Name	Test Results	Units	Method	Date of Analysis	Analyst
Titration Time <i>Filtered using flow-reducer ring</i>	11.9	minutes	T.O. 42B-1-1	7/30/2009	MH
Solids Content of Fuel	1.16	mg/gal	T.O. 42B-1-1	7/30/2009	MH

Figure C-5.2 ATA Chemistry Laboratory report showing the solids content of the fuel.

C-6.0 SUMMARY

- The Validation Test (Tinker 2) campaign demonstrated that emissions measurements following the prescribed IPMTM gave results comparable to the detailed measurements of the Methodology Development Test (Tinker 1).
- EIm-nvPM follows a general trend that has been reported in the previous Methodology Development Test; EIm-nvPM reached a maximum at NFF = 0.6-0.8.
- EIn and EIm-vPMorganic are less sensitive to engine power condition than EIm-nvPM.
- Mass density of non-volatile PM, derived from two different methods of measurements, remains independent of normalized fuel flow rate. These measurements give rise to the average mass density of $1.26 \pm 0.49 \text{ g/cm}^3$.
- The particle number emission index (EIn) is maximum at the center of the engine exit plane and remains statistically unchanged throughout the core region. Outside the core flow EIn is statistically lower.
- Highly volatile gaseous species such as HCHO and C_2H_4 are insensitive to radial location within the core flow.
- The semi-volatile naphthalene increases with radial position.

C-7.0 REFERENCES

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APPENDIX D QUALITY ASSURANCE PROJECT PLAN

for

Testing of the Interim Particulate Matter Test Method Developed for the Joint Strike Fighter (JSF) Program

Revision: 0

October 5, 2008

SERDP Project Number: WP 1538

United States Department of Defense
SERDP and ESTCP
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Arlington, VA 22203

QAPP APPROVAL PAGE

Title: Quality Assurance Project Plan (QAPP) for Testing of Interim Particulate Matter Test Method Developed for the Joint Strike Fighter (JSF) Program, Revision 0, October 5, 2008

Management Approvals:

This QAPP is approved by the following leads for the validation testing of the IPMTM.

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Dr. Richard Miake-Lye Principal Investigator Aerodyne Research, Inc.

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LIST OF ACRONYMS

AEDC	Arnold Engineering Development Center
AESO	Aircraft Environmental Support Office
AFB	Air Force Base
AMS	Aerosol Mass Spectrometer
APEX	Aircraft Particle Emissions eXperiment
ARI	Aerodyne Research Inc.
ATA	Aerospace Testing Alliance
CAA	Clean Air Act
CPC	Condensation Particle Counters
DMA	Differential Mobility Analyzer
DMS	Differential Mobility Spectrometer
DQI	Data Quality Indicator
DQO	Data Quality Objectives
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
GSD	Geometric Standard Deviation
ICAO	International Civil Aviation Organization
IPMTM	Interim PM Test Method
JSF	Joint Strike Fighter
LED	Light Emitting Diode
MAAP	Multi-Angle Absorption Photometer
MASS	Mobile Aerosol Sampling System
Missouri S&T	Missouri University of Science and Technology
MQO	Measurement Quality Objectives
NASA	National Aeronautics and Space Administration

NARATO	North American Research Strategy for Tropospheric Ozone PLA Lever Angle	Power
PM	Particulate Matter	
PTR-MS	Proton-Transfer Reaction Mass Spectrometer	
PTFE	Polytetrafluoroethylene	
QA	Quality Assurance	
QAPP	Quality Assurance Project Plan	
QC	Quality Assurance	
QC-TILDAS	Quantum-Cascade Tunable Infrared Laser Differential Absorption Spectrometer	
QIWP	Quality Integrated Work Plan	
QPM	Quality Project Management	
SAE	Society of Automotive Engineers	
SAE E-31	SAE E-31 Aircraft Exhaust Emissions Measurement Committee	
SIP	State Implementation Plan	
SERDP	Strategic Environmental Research and Development Program	
SMPS	Scanning Mobility Particle Sizer™	
SOP	Standard Operating Procedures	
TILDAS	Tunable Infrared Laser Differential Absorption Spectrometer	

LIST OF TERMS AND SYMBOLS

D_{geomM}	Mass-based Geometric Mean Diameter
D_{geomN}	Number-based Geometric Mean Diameter
D_p	Particle Diameter
EI	Emission Index
EIm	Mass-based Emission Index [g/kg-fuel]
EIm-x	Mass-based Emission Index for species “x” [g/kg-fuel]
EIn	Number-based Emission Index [number/kg-fuel]
EIn-x	Number-based Emission Index for species “x” [number/kg-fuel]
N	(Total) number concentration of the particle size distribution
NFF	Normalized Fuel Flow

D-1.0 INTRODUCTION

This Quality Assurance Project Plan (QAPP) describes the quality elements for validation testing of the interim PM test method (IPMTM) for measuring particulate matter (PM) emissions from jet aircraft engines. The IPMTM is being developed to measure and report PM emission for the engine(s) of the Joint Strike Fighter (JSF), a new multi-mission aircraft that is being designed to replace a wide range of aging military aircraft. This method is being developed by:

- Arnold Engineering Development Center (AEDC)
- Missouri University of Science and Technology (Missouri S&T)
- Aerodyne Research, Incorporated (ARI)

in collaboration with:

- Environmental Protection Agency (EPA)
- National Aeronautics and Space Administration (NASA)
- Federal Aviation Administration (FAA)
- Society of Automotive Engineers (SAE) E-31 Aircraft Exhaust Emissions Measurement Committee
- Jet Engine Manufacturers

This QAPP is developed for the testing of the IPMTM, i.e., application of the IPMTM for PM measurements on a gas turbine engine. It is written for the engine test (Validation Test, Appendix C) of this project designated to demonstrate the IPMTM. However, with proper modification for the differences in the engine and test facility, this QAPP will be applicable to the JSF Program.

This QAPP presents a project overview and descriptions of the quality assurance (QA) and quality control (QC) elements necessary to demonstrate that each component of the test validation is of the quality needed to provide an efficient and effective interim test method that meets all associated goals and objectives. The quality objectives for each critical component of the validation testing are specified herein. This QAPP also provides the framework for implementing project QA activities by addressing topics such as areas of project responsibility; experimental designs and development of test protocols, data integrity, documentation, preventive maintenance, and corrective actions.

The primary objective of the Validation Test is demonstration of the IPMTM on an F100-220 used as a surrogate for the JSF class engine. A key aspect is evaluation of the practicality of implementation and assessment of accuracy with regard to mitigation of new particle formation and condensation of volatile gases in the sample lines that can interfere with the measurement of the non-volatile PM from the engine. The method must prove sufficiently robust to support implementation plans for achieving criteria pollutant attainment. Thus the acceptability and validity of the information and data utilized to support this method depend on rigorous completion of all activities stipulated in the QAPP.

This QAPP delineates the necessary activities to ensure that the delivered IPMTM provided by this project is sufficiently accurate, precise, complete, and representative and meet project data quality objectives. It also provides the framework for implementing QA and QC activities by

addressing topics such as responsible individuals, data integrity, documentation, preventive maintenance, and corrective actions for the Validation Test.

D-1.1 REFERENCES FOR QAPP

This document was prepared in accordance with U.S. Environmental Protection Agency (EPA) QA/R-5 requirements for quality assurance project plans,⁴ the Uniform Federal Policy for Quality Assurance Project Plans,⁵ and with the North American Research Strategy for Tropospheric Ozone (NARSTO) template for quality integrated work plans (QIWP).⁶ This QAPP is generally presented in the NARSTO format, but it contains all the elements required in QA/R-5.

The quality assurance approach utilized by the project team described in this QAPP is based on the national ANSI/ASQC consensus standard.⁷ This standard describes the necessary management and technical elements for developing and implementing a quality system. It recommends a tiered approach to the design of the specific quality system used in each of the organization's efforts. In Part A: Management Systems of this standard, it is recommended that the organization document its quality system in a QMP. It also recommends documenting the applicability of the quality system to activity-specific efforts in a Quality Assurance Project Plan (QAPP) or similar document to address the requirements of the standard's Part B: Collection and Evaluation of Environmental Data. The development of this QAPP and the quality system described herein is largely based on Part B of this consensus standard, although critical elements in Part A are also addressed.

Since a significant portion of the work performed by the Project Team described herein involves non-routine measurements and research and development, it is not always practical to employ a formalized quality system as would be delivered by a QAPP. In these cases the quality system may be based on guidance presented by EURACHEM.⁸ In this document the guidance is directed towards sound practices rather than compliance with formal standards. The two approaches are not necessarily at odds with one another, but compliance may occasionally place requirements that are considered to be over and above what is considered to be best practice. Conversely no single quality standard necessarily covers all the elements of activity, which might be considered relevant as best practice. The goal is to provide a quality system that provides the necessary flexibility in research projects.

⁴ U.S. EPA, Requirements for Quality Assurance Project Plans, QA/R-5, EPA/240B-01/003, March 2001. Reissued by Memorandum, May 31, 2006.

⁵ U.S. EPA and U.S. DoD, "Uniform Federal Policy for Quality Assurance Project Plans, Part One: UFP-QAPP Manual," Version 1, March 2005

⁶ NARSTO, "NARSTO Quality Planning Handbook," ORNL/CDIAC-111, November 1999, available at: <http://cdiac.esd.ornl.gov/programs/NARSTO/qadocumentation.html>

⁷ ANSI/ASQC E4-1994, "Specifications and Guidelines for Environmental Data Collection and Environmental Technology Programs," 1994

⁸ EURACHEM/CITAC, "Quality Assurance for Research and Development and Non-routine Analysis," Guide CG2, November 1998

D-1.2 QUALITY ASSURANCE POLICY

Data collection or characterization studies may be used to support technical, economic, regulatory, and enforcement decisions and must therefore be of known and characterized quality. Thus, at a minimum, all projects and/or activities that involve the generation of measurement or characterization data shall have an appropriate quality system in place to ensure that the generated data are of adequate, known and documented quality.

The IPMTM project team recognizes the need to provide an IPMTM of optimum and fully characterized quality. A comprehensive program of quality management has therefore been established to identify requirements and provide procedural guidance for achieving quality objectives. It is the goal of this project team to execute the project through proper planning, guidance, control, review, communication, assessments, reporting, and corrective action.

The quality system described herein emphasizes rigorous planning for and the incorporation of quality components at all critical junctures of the project. This approach reduces errors, improves efficiency, and provides the highest quality product in the most cost-effective manner. Further, it requires that the data acquisition planning process (field testing) be coordinated, communicated, reviewed and documented during the project planning stages. A critical component of the planning stage is the development of specific technical objectives. The goal is to assure that all information and work produced meets defined and documented quality elements such as accuracy, precision, completeness, comparability, and representativeness.

The quality assurance objectives for this project involve data collection, evaluation, and related support functions including the following:

- Development and implementation of a QAPP or similar quality document and of a subsequent quality system for all tasks that involve data collection or characterization activities.
- Assurance that QAPPs are followed, reviewed regularly and updated as needed.
- Production of validated and reviewed data that meet project data quality objectives (DQOs) and/or measurement quality objectives (MQOs).
- Maintenance of regular communications within the project team and advisory groups to periodically apprise them of the status of project product quality.
- Assurance that all personnel have the necessary training and resources to meet project objectives and standards for product quality.
- Development of software and system acceptance tests to ensure that such items meet project requirements for functionality and system performance.
- Application of standard operating procedures (SOPs) for all critical portions of field tests, and review procedures to data transfer, security, and storage to ensure the integrity of the characterization data.

D-1.3 BACKGROUND

The 1997 changes to the Clean Air Act (CAA) resulted in the requirement for accurate estimates of size, distribution, and chemical species of particulate matter less than 2.5 microns in diameter (PM_{2.5}) emitted from military aircraft. These estimates will be used for emission inventory

purposes in some areas in the U.S. that are non-attainment for PM_{2.5}, in conjunction with State Implementation Plan (SIP) activities.

The EPA has provided guidance on developing an interim PM test method for the Joint Strike Fighter (JSF) that is more accurate, less expensive and less time consuming than the current methods. A project was established that enabled the Arnold Engineering Development Center (AEDC), Missouri University Science and Technology (Missouri S&T) and Aerodyne Research, Incorporated (ARI) in collaboration with the EPA, Air Force, Navy, FAA, NASA, SAE E-31, jet engine manufacturers, and academia to develop an interim PM testing method for the JSF. Development of this new interim test method will allow prompt basing of the JSF, reduce the cost of testing through reduced engine test time, and further the science of PM testing. It is anticipated that the EPA-approved interim PM test method developed for the JSF will eventually be applied to other emerging and possibly legacy military aircraft programs.

The JSF Office requested a briefing from the investigators principally involved in conducting the series of NASA APEX research studies and representatives of the SAE E-31 Committee on the status of modern PM measurement techniques with potential for satisfying EPA requirements for the JSF F-135 Program. The briefing and follow on meetings were also attended by representatives from the EPA, which followed up with a letter granting the use of modern PM measurement techniques for meeting the JSF F-135 Program PM emissions reporting requirements. The JSF Program Office and EPA agreed that more modern techniques should be implemented for PM characterization of military engines. AEDC formed a project team from this group of investigators to develop the Interim PM Test Method for the JSF Program.

D-1.4 PROBLEM DEFINITION

The exhaust exiting the engine contains non-volatile PM and volatile gas constituents (precursors) that have a propensity, as the gas cools, to nucleate and form volatile particles (new particle formation) and/or condense and coat non-volatile particles (condensation). There are no volatile particles in the exhaust at the engine exit plane, only their gas phase precursors. The new particle formation and condensation occur naturally in the downstream exhaust plume as the exhaust gases cool through mixing with engine bypass and ambient air. But, new particle formation and condensation can also occur in the sampling lines as the sample gas temperature is lowered through interaction with the cooler sample line walls. The objective of the IPMTM is to define a sampling process by which non-volatile PM can be measured accurately by eliminating or accounting for the interference of new particle formation and condensation. The IPMTM approach is addition of a dilution gas as the sample enters the sampling probe (probe-tip dilution) to eliminate, or mitigate, new particle formation and condensation in the sampling line over all engine power level conditions.

The problem is to design, develop, characterize, and implement an EPA-approved, modern, real-time measurement technique that will be used at the exit plane of aircraft gas turbine engines to characterize PM in a manner similar to gaseous measurements for regulatory purposes on commercial engines. This method must provide measurements of non-volatile PM mass and

particle size distribution. Size information is not provided by the EPA Method 5⁹ that is currently used for military engine PM characterization measurements.

Recent findings have indicated that adverse human health effects are associated with fine particulate matter (≤ 2.5 microns in aerodynamic diameter), and are perhaps even more strongly associated with ultrafine particulate matter (≤ 1.0 microns in aerodynamic diameter).¹⁰ Therefore there is a health effects need for more detailed measurement of the mass, size, and quantity of these particle emissions than provided by Method 5.

D-1.5 PROJECT SCOPE

EPA is interested in both non-volatile and volatile PM. But only non-volatile PM exists at the exit plane while volatile PM forms far downstream as the exhaust plume cools as it mixes with engine bypass and ambient air. Therefore, this project addresses only the measurement of non-volatile particulate matter within a distance of one nozzle diameter from the exit plane of the aircraft gas turbine engine. Volatile PM will be estimated from gaseous precursors measured or estimated at the exit plane and analysis of the fuel. Future studies will address the possibility of direct measurements of the volatile PM component of aircraft gas turbine exhaust.

D-1.6 OVERALL PROJECT OBJECTIVES

The objectives of this project are:

- Development of a method for characterization of non-volatile particulate emissions from the JSF aircraft gas turbine engine using modern particulate emissions measurement instrumentation.
- Add to a growing body of knowledge to advance the scientific basis of environmental decision-making.
- Improvements in the accuracy of estimating particulate emissions from aircraft gas turbine engines.
- Provide the necessary assurance that the ensuing recommended control strategies employed to achieve attainment for PM_{2.5} and other pollutants will be efficient and cost effective.
- Reductions in the engine test time and expense for PM emissions reporting requirements.
- Providing useful information to the Society of Automotive Engineers E-31 Aviation Emissions Measurement Technical Committee that is developing long-range protocols for PM emissions measurements from aircraft engines for adoption by the United Nations International Civil Aviation Authority as standards and recommended practices contained in Annex 16, volume II.

D-1.7 VALIDATION TEST OBJECTIVES

The objectives of the Validation Test phase are:

- Demonstration of the IPMTM on a surrogate (F100-220) for the JSF class engine.

⁹ California Air Resources Board, "Method 5: Determination of Particulate Matter Emissions from Stationary Sources," Amended July 28, 1997.

¹⁰ National Research Council, "Research Priorities for Airborne Particle Matter, 1. Immediate Priorities and a Long-Range Research Portfolio," 1998

- Evaluation of the implementation process.
- Assessment of accuracy with regard to mitigation of new particle formation and condensation of volatile gases in the sample lines.
- To provide experimental information to the SAE E-31 for advancement of the PM sampling methodology and measurement techniques for gas turbine engine.

D-2.0 PROJECT MANAGEMENT

D-2.1 PROJECT ORGANIZATION AND RESPONSIBILITIES

Quality assurance is an interdisciplinary responsibility involving all project personnel and ultimately each Principal Investigator, researcher, contractor, staff member, and technician. A general organizational chart for this research project is presented in Figure D-2.1. Following is a list of positions or organizations, along with their corresponding names and responsibilities for the implementation of this project.

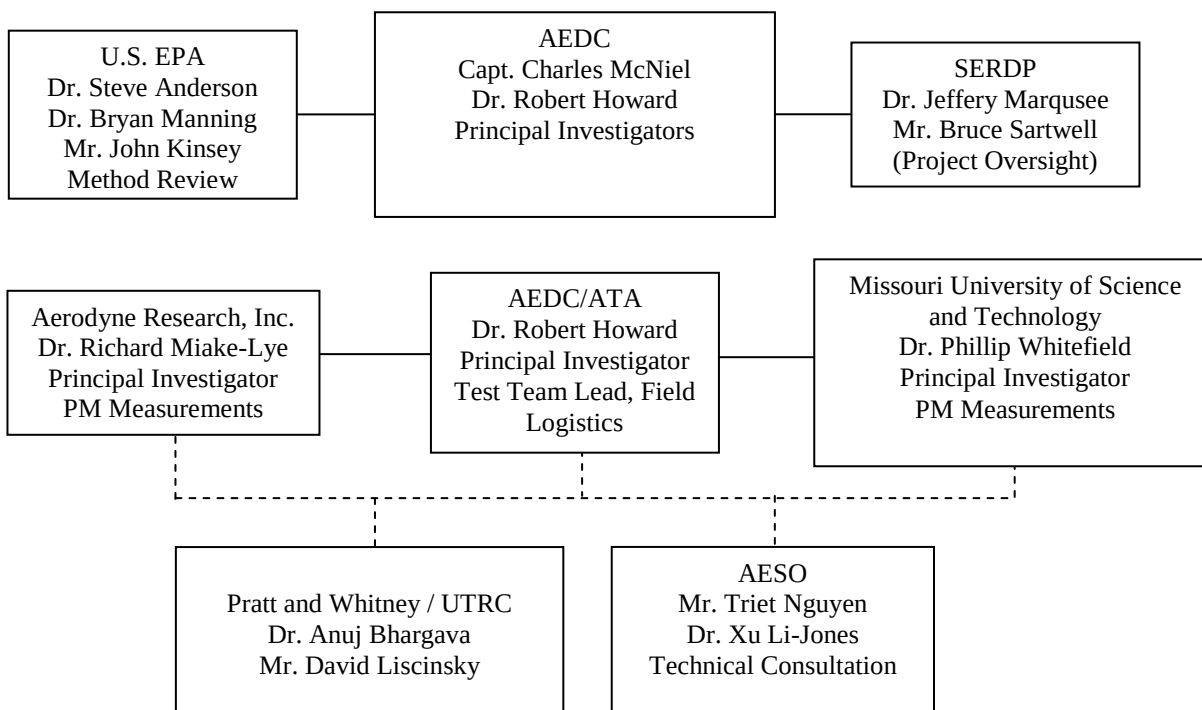


Figure D-2.1 IPMTM Research Project Overall Organization Chart

AEDC Principal Investigator

Capt. Charles McNiel, USAF, Arnold Engineering Development Center, Arnold AFB, Tullahoma, TN.

- Directs and integrates activities of Project staff
- Interacts with SERDP and the EPA and reports project progress

- Ensures that the project operations conform to all applicable federal regulations, contracts, AEDC policies, and prudent government practices.
- Primary responsibility for conducting the project within available budget and approving major expenditures.
- Keeps current on project status and issues periodic progress reports to SERDP.

AEDC Principal Investigator, Test Team Lead, Field Logistics

Dr. Robert Howard, ATA, Arnold Engineering Development Center, Arnold AFB, Tullahoma, TN

- Manages the day-to-day project efforts.
- Ensures close cooperation and coordination of the project participants.
- Interacts with the EPA and reports project progress.
- Responsible for the design, fabrication, and testing of sample probes, rake system and traverse system for validation testing of the IPMTM
- Co-responsible for establishing test matrices for specific IPMTM field tests.
- Co-responsible for the design, fabrication, and operation of the dilution sample extraction system for the IPMTM validation test.
- Schedules, plans, and manages IPMTM Method field testing events through collaboration with all project participants and test facility personnel, equipment, expendables and facilities.
- Develops provisional overall Test Plans for IPMTM Method field test events.
- Field Manager for project participants during IPMTM Method field testing.
- Responsible for interfacing between project participants and test facility personnel.
- Plans, schedules and coordinates each individual field test event.
- Collaborates in data validation, analysis and final report preparation.
- Oversees all organizations involved in the field tests.
- Obtains and reviews fuel test results associated with gas turbine engine field tests.
- Provides technical leadership for the project.
- Responsible for implementation of this QAPP.
- Facilitates coordination with other related projects and technical experts.
- Provides additional managerial support as required.
- Communicates the knowledge gained and lessons learned during the IPMTM field tests to the aviation PM testing community.

Missouri University of Science and Technology, Principal Investigator

Dr. Philip Whitefield, Director of Missouri University of Science and Technology (Missouri S&T), Center of Excellence for Aerospace Particulate Emissions Research

- Co-responsible for the technical approach and development of the IPMTM
- Responsible for the design, fabrication, and operation of the Missouri S&T PM measurement system.
- Responsible for the setup, calibration and operation of the Missouri S&T PM measurement system during IPMTM field tests.

- In collaboration with the other organizations, guides the overall approach for performing the experiments and reviewing their results.
- Provides consultation to other organizations performing IPMTM field tests.
- Co-responsible for establishing test matrices for specific IPMTM field tests.
- Co-responsible for the design, fabrication, and operation of the dilution sample extraction system for the IPMTM validation test.
- Provides calibrated test aerosols for conducting the PM sample penetration tests for the sample extraction system.
- Performs data validation, reporting, and data interpretation from the Missouri S&T PM measurement system after the IPMTM field tests.
- Evaluates overall data quality, characterization results, and overall system performance for suitability to meet project objectives.
- Interprets the experimental results, uses the results for development of the IPMTM and to address other project objectives.
- Communicates the knowledge gained and lessons learned during the IPMTM field tests to the aviation PM testing community.

Aerodyne Research, Inc.

Dr. Richard Miake-Lye, Principal Investigator, Aerodyne Center for Aero-Thermodynamics

- Co-responsible for technical approach and development of the IPMTM.
- Responsible for the setup, calibration and operation of the Aerodyne PM Measurement System during IPMTM field tests.
- Co-responsible for establishing test matrices for specific IPMTM field tests.
- Performs data validation, reporting, and data interpretation from the Aerodyne PM Measurement System after the IPMTM field tests.
- Interacts with advisory committees, external scientific reviewers, collaborators, and co-investigators in the development and periodic re-evaluation of study priorities, reporting of results, and obtaining external input for project.
- Communicates the knowledge gained and lessons learned during the IPMTM field tests to the aviation PM testing community.

US EPA - Method Review and Collaboration

The U.S. EPA has the ultimate authority to approve or disapprove the proposed interim PM testing method. Several organizations within the EPA provide oversight for this project:

Dr. Stephen O. Andersen, Director of Strategic Climate Projects, Office of Air and Radiation, Climate Protection Partnership Division, Washington D.C.

- Oversees the project on behalf of the U.S. EPA.
- Works with the Project Managers, oversight groups, collaborators, etc. in assuring that the interests and concerns of the EPA are appropriately represented as project priorities are developed or modified due to external input.
- Mr. Bryan Manning, Assessment and Standards Division, National Vehicle and Fuel Emissions Lab, Office of Transportation and Air Quality, Ann Arbor, Michigan

- Develops and approves EPA policy associated with PM testing of aircraft gas turbine engines.
- Assures that the results and issues in the project are communicated within the appropriate groups and offices within the EPA and that their appropriate input is communicated back to the Project Managers and investigators.
- Assures that the technical requirements of the EPA for this project are met, and communicates with the Project Managers and investigators in a timely manner when action is needed to meet these requirements.
- Responsible for approval of the IPMTM before implementation to the JSF.
- Mr. John Kinsey, National Risk Management Research Laboratory, Research Triangle Park, North Carolina
- Participates in key portions of the development and testing of the IPMTM.
- Provides technical input and oversight.
- Provides input as needed to assure that the project has effective and appropriate peer review.
- Provides filter-based measurements during field tests, collocated with the automated methods conducted by other organizations.
- Provides review of the QAPP and Test Method.

Aircraft Environmental Support Office (AESO)

AESO conducted an independent experimental study, in “piggy-backed” mode, during the Validation Test. The results of their study were beneficial and transitioned to this project through collaboration at planning meetings and post-test workshops. Aspects of their direct interaction with this project are noted below.

Mr. Triet Nguyen, Deputy Program Director, AESO
Dr. Xu Li-Jones, CTR FRC-SW, 08212, AESO

- Provides technical collaboration during planning, testing and post-test data review.
- Provides general project assessment oversight.
- Reviews test plans.
- Reviews the overall performance of the project and provides input to Project Managers on problem areas.

UTRC/ Pratt and Whitney

Dr. Anuj Bhargava, Pratt and Whitney
Mr. David Liscinsky, UTRC

- Provides technical collaboration during planning, testing and post-test data review.
- Provides measurement support.
- Represent the manufacturers of aircraft gas turbine engines.
- Provides information concerning engine characteristics, fuel consumption, and operating parameters.
- Evaluates PM data at field test events.
- Provides detailed collaborative data analysis.
- Reviews data for the sample line PM penetration tests.

D-2.2 PROJECT ASSESSMENTS

The project team is committed to achieving and maintaining the highest level of quality possible throughout the performance of this project. The goal is to generate technically sound and defensible data and information. The former is an obvious requirement but is not, in and of itself, sufficient to defend the data against an adversarial inquiry. The latter requires rigorous and systematic documentation of the level of quality achieved.

The quality of the project data are evaluated by the use of routine quality control checks incorporated by each participating organization shown in Figure D-2.1. In addition, the project has been designed with and includes a relatively large number of experts and authorities on particulate measurements of aircraft gas turbine engines from different organizations. This project design enables and encourages a strong internal project assessment process. These assessments are described in Section D-6.0. The development and use of data quality objectives, described in Section D-4.1, formalizes and expedites the assessment process.

D-2.3 PERSONNEL QUALIFICATIONS AND TRAINING

The project team has extensive experience and has internationally recognized experts in making measurements of gaseous and particulate air pollutants in a research environment and in managing research projects. Some of the project team members have over fifteen years of experience in the development of PM methods and characterization of PM from aircraft gas turbine engines.

Sufficient specialized and general education lays the foundation for implementing a successful research project. It is not intended to provide detailed and specific knowledge in each area, but it promotes an understanding of the nature of the overall research effort and the ultimate objective of the project. Therefore, general and specialized training is required for all project personnel.

All project personnel must be familiar with the content of this QAPP and its references, thus obtaining a project overview, including information on all functions of the measurement systems, from experimental design, objectives, sampling, and data validation and reporting. If revisions are made to the QAPP, all affected individuals must review those revisions at that time.

All project personnel must read the detailed Standard Operating Procedures (SOPs) and instrument manuals applicable to their area of responsibility. In addition, if revisions are made to the SOPs, all affected individuals must review those revisions. Each individual must have thorough training and experience specific to their project responsibilities.

New project personnel must receive thorough training and project indoctrination by experienced personnel. They must be provided with the SOPs, and other relevant documentation pertinent to their task. Training will be based on these documents and will include research project objectives and goals, sampling systems, instrument operation and calibration, quality assurance and quality control activities, data collection and validation, troubleshooting, communication, and documentation.

D-2.4 COMMUNICATIONS PLAN

The project team members are linked by e-mail correspondence, and also use this as a means to communicate and exchange data, either as e-mail attachments or by network-accessible files. This is the primary means for the team members to be kept abreast of all project developments and information. A considerable amount of information is exchanged by e-mail within this project. Secure web sites have been established to post data and information. Each key member of the IPMTM team maintains dedicated hard copy and/or electronic files of all e-mail correspondence.

Conferences are periodically scheduled to present the detailed field test results, to discuss data intercomparisons and interpretation, and to perform the internal assessment process described in Section D-6.0. In addition, periodic project meetings and weekly conference calls are held. In these meetings detailed technical information is presented, project status is discussed, and project direction is assessed.

The team members are world-class experts in the development of particulate matter measurements from aircraft gas turbine engines. Their expertise also includes instrument operation and repair, calibration systems, electronics, control systems, sampling systems, hardware fabrication, and software operation. The team is also linked to national and international specialists and experts in all critical areas to support the project, including representatives of instrument manufacturers, SAE-31 Committee members, and academia.

D-3.0 EXPERIMENTAL APPROACH

D-3.1 INTRODUCTION

The development plan for the IPMTM called for two ground-level engine test campaigns on military turbine engines. The first, called the Methodology Development Test (Appendix B) was conducted in 2007 to experimentally address unresolved measurement issues identified as a result of prior NASA PM characterization studies (APEX test series, and etc.). The second test, called the Validation Test, was conducted to demonstrate and evaluate the IPMTM on a military engine using the probe-rake and sampling system hardware developed for the JSF F135 particle characterization measurements. This QAPP is developed for the Validation Test to assure the quality in the measurements and sampling integrity. With modifications that incorporate the differences in the engine and test facility, this QAPP will be applicable to the JSF engine PM characterization testing.

The primary objectives of the Validation Test are to (1) evaluate and demonstrate a new interim PM test method for PM measurements and, (2) use the demonstration testing opportunity to address certain sampling issues that were identified as research needs by the SAE E31 committee.

D-3.2 TEST LOCATION

The test was conducted November 2008 on an F100-220 engine in an engine test facility at the Tinker Air Force Base, OK. Figure D-3.1 illustrates the layout for the test. The sampling probes were mounted between the engine exit and the exhaust diffuser duct. Sample lines were routed

from the probes in the test cell, though wall feed-through ports into the machine room, and down the hallway to the particle and gas analyzer instruments located in the trailers and vans parked outside wall of the building. The Missouri S&T, ARI, AEDC and AESO trailers and vans were parked along the wall.

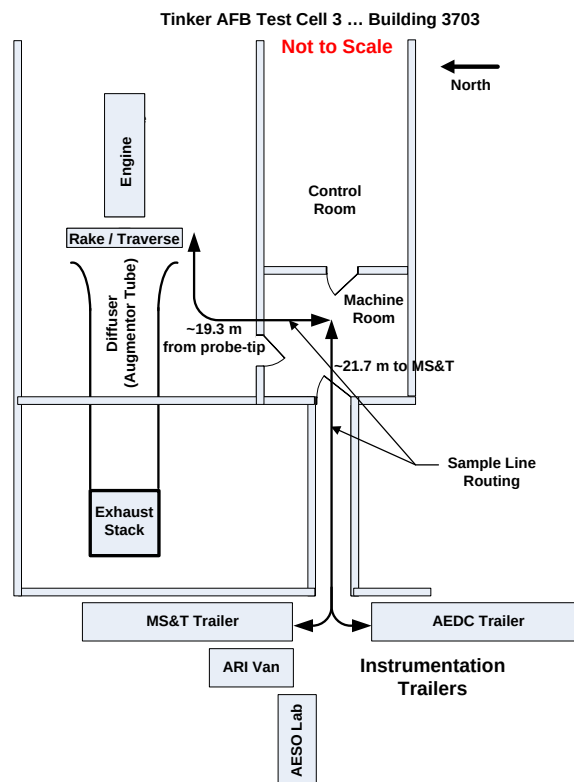


Figure D-3.1 Illustration of the Test Facility and Measurement Layout.

Figure D-3.2 illustrates the sampling system approach consisting of a probe-rake mounted to a traverse stand that would be installed behind the nozzle exit of a gas turbine engine. Exhaust gas enters the tip of a particle probe designed to preserve sampled-particle integrity by affording sample dilution at the probe tip as illustrated in Figure D-3.2.

D-3.3 SAMPLING EQUIPMENT

Figure D-3.2 shows the major components of the sampling system. Exhaust gas enters the tip of a particle probe designed to preserve sampled-particle integrity by affording sample dilution at the probe tip. Diluting the sample suppresses modification of the PM that might occur through gas to particle conversion, agglomeration and condensation of volatile gases, and reduces sample system particle losses.

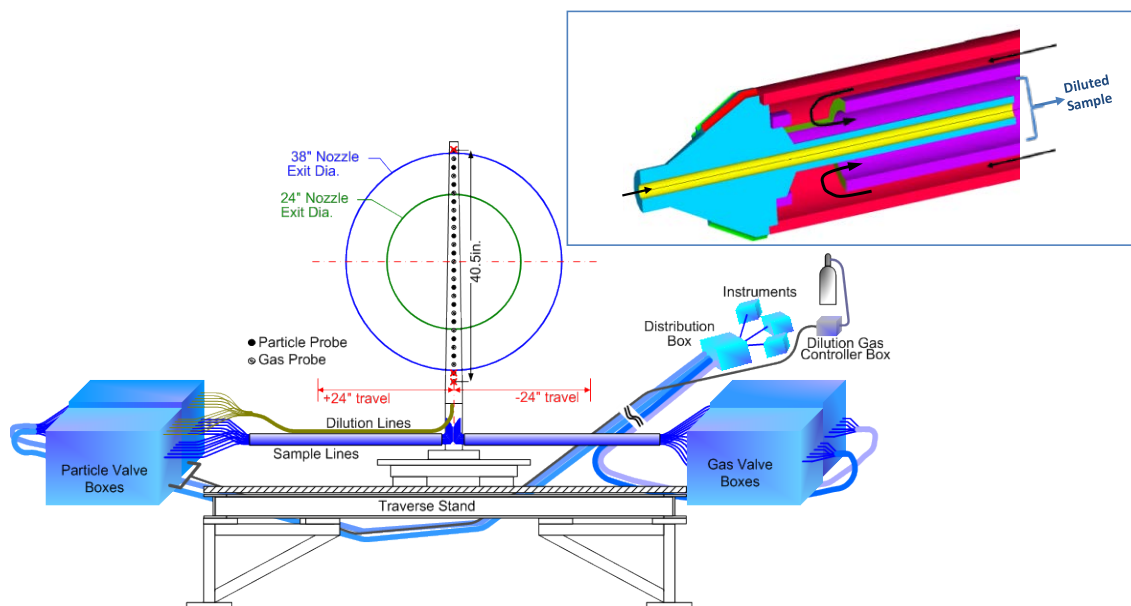


Figure D-3.2 Schematic showing the major elements of the sampling system.

The diluted sample is transported to a Particle Valve Box used to remotely select the probe to be sampled. Diluted sample from the selected probe travels to Distribution Box used to disperse the sample to multiple diagnostic instruments. The diagnostic instruments are located at a safe distance (up to 30 meters) from the engine. The Particle Valve Box automatically back-purges the PM sample line segments for probes that are not selected for sampling. Particle probes are dispersed along the rake. The rake is traversed horizontally to fixed locations and particle probes systematically sampled vertically along the rake in order to spatially map PM emission over the nozzle exit plane.

The IPMTM document (Appendix A) has the sample system and dilution system attributes and operation procedures. Also, sample line penetration measurement procedures are given.

D-3.4 INSTRUMENTATION AND DATA ACQUISITION

Diagnostic needs for the IPMTM include characterization of non-volatile PM number density, non-volatile PM size distribution and non-volatile PM mass density. Other diagnostic instruments for PM and gases are used to assure data quality through real-time monitoring of the sampling system operation and assessment of gaseous emissions for assurance the engine performance is on par with historical manufacturer's data for that engine.

A more detailed description of the instruments can be found in Appendix A.

D-3.4.1 Particulate Matter Species

The primary instruments for the IPMTM are the Condensation Particle Counter (CPC) and Differential Mobility Analyzer (DMA) instruments, PM size and number characterization, and the Multi-angle Absorption Photometer (MAAP) for PM mass characterization. The specific instruments to be used for the Validation Test are:

- CPC: Saturator-condenser type Condensation Particle Counters (CPCs): TSI 3022A and 3025A (Section A-5.1).

- DMA: Commercial Differential Mobility Analyzers (DMAs): TSI 3071 or 3081 (Long), TSI (short), TSI 3085 (nano), used in the scanning mode (Section A-5.2).
- MAAP: Thermo Electron Multi-Angle Absorption Photometer (MAAP) [Petzold and Schonlinner, 2004; Petzold et al., 2005]. The MAAP measures particulate black carbon by collecting aerosol onto a 2 cm² quartz fiber filter tape. The transmission and scattering of 630 nm wavelength LED light are monitored by multiple photodetectors. A two-stream radiative transfer calculation separates the scattering from the absorption component for the total particle loading on the filter tape. The instantaneous loading is computed by the derivative of the total.
- AMS: The Aerosol Mass Spectrometer (AMS) is a unique instrument that is used for measuring the amount of volatile gas condensation on non-volatile particles versus particle size. This is an excellent instrument for real-time assessment of the quality of the exhaust sampling system.

The instruments listed in Table D-3.1 are gas species analyzers used in the Methodology Development Test and the Validation Test. Measurements from instruments of these types complement the PM measurement and lend quality to the data set. Of course, CO₂ measurements, as discussed elsewhere, are required to assess and/or validate the sample dilution ratio.

The data stream produced by each analyzer will be logged using a multicomputer network operating the specialized software provided with the instrument. The computers will be time synchronized using a clock card which is set on a daily basis using a portable atomic clock. The data files obtained during testing will be stored both on the hard drive of each individual computer as well as archived daily on removable media.

Table D-3.1 Trace gas instruments for assessing the quality of exhaust sampling for PM.

Instrument	Species Detected	Detection Limit ^a	Time Resolution
Licor 6262 Licor 820	CO ₂ CO ₂ (high range)	300 ppb 2 ppm	1 sec
NO _x Chemiluminescence Analyzer ThermoElectron (model 42C)	NO NO _x ^b	0.5 ppb 0.5 ppb	1 sec/20 sec 20 sec
QC-TILDAS ^{c,d}	NO ₂	0.5 ppb	1 sec
	C ₂ H ₄	2 ppb	1 sec
	CO	2 ppb	1 sec
	HCHO	1 ppb	1 sec
	HONO	2 ppb	1 sec
PTR-MS ^e	acetaldehyde, propene, benzene, toluene, styrene, C ₂ -benzene ^f , phenol, naphthalene, methylnaphthalene, dimethylnaphthalene	2-5 ppb	8 sec

^a Detection limits are quoted as 2 times instrument noise level.

^b The measurement of NO_x using catalytic reduction of NO₂ to NO (most chemiluminescence analyzers) also measures higher nitrogen oxides such as HNO₃, HONO, and organic nitrates.

^c quantum-cascade tunable infrared laser differential absorption spectrometer (Aerodyne Research, Inc.).

^d tunable infrared laser absorption spectrometer (Aerodyne Research, Inc.).

^e proton-transfer reaction mass spectrometer.

^f C₂-benzene includes *o*-xylene, *m*-xylene, *p*-xylene, and ethylbenzene.

D-3.4.2 Instrument Calibration

Both PM and gaseous emissions will be monitored during the experimental program. The types of calibration performed on the PM instruments are generally limited to air flow rate and similar parameters as outlined in the applicable operating manual. For the gas analyzers a pre-test multi-point calibration will be performed using certified gas standards in addition to daily zero and span checks. Calibrations will be performed before each run, but no less than once daily.

Other pre-test preparations will include check-out of each analyzer for proper operation, assembly of operating manuals and back-up software, and preparation of a detail packing list for installation and removal of the sampling system.

D-3.4.3 Pre-Test Preparations

The main pre-test preparation will be to thoroughly clean the sampling probes, lines, and tunnel. This will be accomplished by power washing all system components using a dilute solution of Alconox in deionized (DI) water followed by a DI water rinse. After power washing, all system components are allowed to air dry and then capped prior to transport to the field. After cleaning, all port plugs are removed from the sampling tunnel to remove any foreign material that may have fallen into the cavities.

Other pre-test preparations will include check-out of each analyzer for proper operation, assembly of operating manuals and back-up software, and preparation of a detail packing list for installation and removal of the sampling system.

D-3.4.4 Test Matrix

The primary objective this test is to demonstrate and evaluate the application of the IPMTM to the F100-220 engine. A secondary objective is to obtain data to support PM sampling issues in support of SAE E-31 research needs. Four engine runs are envisioned to accomplish the objectives of the Validation Test: (1) an initial equipment shakedown followed by a spatial mapping at a medium low engine power level (PLA=35 degrees); (2) exhaust mappings at PLA=16.5 (idle) and PLA=75; (3) exhaust mappings at PLA=85 (takeoff, non-afterburning) and PLA=65; and (4) research with the PM sample line unheated and actively heated. Data will be acquired only at steady-state engine power conditions. Table D-3.2 gives estimates of the approximate run time required to accomplish the test.

Table D-3.2 Test Matrix

Test Run #	Duration (min)	Test Objective (Power Lever Angle (PLA) in degrees)
1	60	Checkout/Rake fixed/Data on one probe versus engine power (PLA=16.5, 30, 50, 65, 75, 85)
1	120	Map flow at PLA=35
2	240	Map flow at PLA=16.5 (idle)
2	240	Map flow at PLA=75 (idle)
3	180	Map flow at PLA=85 (maximum non-AB)
3	240	Map flow at PLA=65
4	240	Power (PLA=16.5, 30, 50, 65, 75, 85; repeat down) PM sample-lines not heated
4	120	Power PLA=35 Heating PM Sample Line

The spatial mapping measurements will be performed by first locating the rake at the centerline of the engine (x=0 inches) and sampling particle probes vertically along the rake. Then the rake will be stepped 3.0 inches from centerline and vertical positioned probes sampled again. This process will be repeated until the rake has been stepped to the physical edge of the physical edge of the nozzle and then repeated on the opposite side of engine centerline. Only probes within the physical extent of the nozzle will be sampled.

D-4.0 MEASUREMENT PROTOCOLS, QUALITY ASSURANCE, AND QUALITY CONTROL CHECKS

D-4.1 DATA QUALITY INDICATORS

The data quality indicator (DQI) goals for the monitoring to be conducted are shown in

Table D-4.1 for precision, accuracy, completeness, and detection limit. Since a certified reference standard is not available for the PM measurements themselves (e.g., number concentration), the manufacturer's calibration will be used.

Table D-4.1 DQI Goals for Instrumentation

Experimental Parameter	Measurement Method	Precision^a	Accuracy^b	Completeness	Detection Limit or Range
Carbon Dioxide	Infrared analyzer	± 5%	± 5%	95%	0 to 1000 ppmv
Carbon Dioxide	FTIR ^c analyzer	± 5%	± 5%	95%	0 to 25%
Volumetric air flow	Mass flow controllers ^d	5%	+ 10%	95%	0 to 10 lpm depending on instrument

^a Calculated as the RSD of the reference measurements obtained at a constant instrument set point.

^b Average variation between the reference measurements and instrument readings as determined over the entire operating range.

^c Fourier Transform Infrared

^d Includes all PM analyzers

D-4.2 QUALITY CONTROL

A number of quality control (QC) checks have been established for the instrumentation to be used in the study. These checks are listed in

Table D-4.2 by experimental parameter. As shown, the QC checks range from simple indicator lights to a complete leak check of the sampling system.

Table D-4.2 Quality Control Checks

Experimental Parameter	Instrument	QC Check(s)	Frequency	Acceptance Criterion
Sample Extraction / Collection System	Sample lines	Leak check sampling tunnel and instrument sample lines	Upon initial setup and daily	No indicated leak
	Sample lines	Electrical ground continuity check	Upon initial setup	“Circuit” not open
	All continuous PM analyzers	Establish “system blank” using HEPA filter on probe inlets	After sampling	Record and store files for later evaluation
Data Acquisition (DA) Software	All instruments with digital outputs	All software running and communication with each instrument	Before each test run	No indication of faults
	All instruments with analog outputs	DA software running and instruments responding	Before each test run	No “dead” signal inputs
PM number concentration and particle size	SMPS including CPC	Check polydisperse aerosol, monodisperse aerosol, and sheath air flow set points	Before each test run	± 10% of set point
		Check CPC reading without voltage scanning	Before each test run	< 0.5 particle/cm ³
		Check inlet impactor and clean/grease, if necessary	Daily	Document
Non-volatile PM Mass	Model 5012 MAAP	Check “Error” light on front panel	Before and during each test run	Light off

D-5.0 DATA REDUCTION AND REPORTING

D-5.1 DATA PROCESSING

The following data will be generated in the course of this program:

- Electronic data from the field computers
- Laboratory notebooks used to document experimental observations and modifications to sampling procedures
- Data sheets for QC checks and engine operation
- For the electronic data, individual data files are generated for each day of sampling. At the completion of each test, the data files will be stored appropriately in the field computer. At the end of each day’s testing, all files generated will be copied to a compact disk and identified appropriately. Extreme care will also be exercised to ensure that hand-recorded

data (i.e., in bound laboratory notebooks and on data sheets) are written accurately and legibly. Errors and discrepancies will be noted in the bound laboratory notebook.

All applicable calculations will be performed in an Excel spreadsheet. The calculation procedure will be checked by hand to ensure accuracy. Any assumptions used will be noted as comments in the spreadsheet calculations.

D-5.2 DATA REDUCTION

As discussed previously, most of the instruments to be used in the study have a direct readout in terms of concentration (mass of pollutant/unit volume of sample gas). The pollutant concentration is then used to calculate the emissions index (mass of pollutant/unit mass of fuel burned) using a carbon balance. In addition, individual SMPS scans are also combined into a composite particle size distribution for a particular test condition (e.g., 7% rated thrust for FT blend 1). The calculation scheme used for data reduction is described in the following sections.

D-5.2.1 Emission Index Calculations

Fuel-specific emission indices (factors) will be calculated from the data collected. For example, the PM mass emission index, expressed in particulate mass per kg of fuel burned, EIm, is calculated from the particle mass concentration using:

$$EIm(mg/kg) = \frac{200.3 C_{PM}(mg/m^3) f_c}{C_{CO_2}(\%)} \quad (\text{Eq. D-5.1})$$

where: C_{PM} = background corrected particle mass concentration (mg/m³)
 C_{CO_2} = background corrected CO₂ concentration at sampling point (%)
 f_c = fraction of carbon in fuel (g/g fuel)
200.3 = a combined constant for unit volume and weight corrections

A similar calculation will also be performed by substituting the concentration of the other pollutants measured for the value of C_{PM} in Eq. D-5.1.

D-5.2.2 Determination of Particle Size Distribution

Particle size distributions are determined in this project from either the SMPS or the Nano-SMPS measurements. For the SMPS and Nano-SMPS measurements, the manufacturer provided software can generate a time-series data spreadsheet with particle number concentrations and distribution density (dN/dlogD_p) data for individual particle size ranges (bin). To obtain the average particle size distribution for a particular test period, the dN/dlogD_p readings for each individual size bin are first averaged over the sampling time and the average particle size distribution obtained by plotting the bin-averaged dN/dlogD_p against the bin mean diameter. If necessary, the particle size distribution curve thus obtained can be smoothed with an in-house computer program using a symmetric k-nearest neighbor linear least squares fitting procedure. The instantaneous total particle number concentration (N), geometric mean diameter (GMD), and geometric standard deviation (GSD) are then calculated for each data acquisition period (e.g., engine thrust level) using the following procedure.

First is to determine the $(d\log D_p)_i$ for each instrument bin. The $(d\log D_p)_i$ for the i -th bin is the logarithm difference of mean diameters between the i -th bin and the $(i+1)$ -th bin and is given by the Eq. (D-5.2) as:

$$(d\log D_p)_i = \log(D_{p_{i+1}}) - \log(D_{p_i}) \quad (\text{Eq. D-5.2})$$

The D_{p_i} and $D_{p_{i+1}}$ in the Equation (D-5.2) represents the mean diameter of the i -th and $(i+1)$ -th bin, respectively. The N , GMD, and GSD at time t are then calculated by Eqs. (D-5.3) to (D-5.5) as:

$$N = \sum_{i=1}^M (dN/d\log D_p)_i \times (d\log D_p)_i \quad (\text{Eq. D-5.3})$$

$$\text{GMD} = 10^{\left[\frac{\sum_{i=1}^M (dN/d\log D_p)_i \times (d\log D_p)_i}{N} \right]^{0.5}} \quad (\text{Eq. D-5.4})$$

$$\text{GSD} = 10^{\left[\frac{\sum_{i=1}^M (dN/d\log D_p)_i \times (d\log D_p)_i \times (\log D_{p_i} - \text{GMD})^2}{N} \right]^{0.5}} \quad (\text{Eq. D-5.5})$$

M in Eqs. (D-5.3) to (D-5.5) is the total number of bins that an instrument contains. $M = 105$ for the SMPS and $M = 98$ for the Nano-SMPS. The instantaneous data are then averaged over the entire sampling time to obtain the test-averaged N , GMD, and GSD.

D-5.2.3 Calculation of DQI Goals

The DQI goals are specific criteria used to quantify how well the collected data meet the appropriate data quality objectives. The definitions and calculations for precision, accuracy and completeness are:

Precision—Precision is the agreement between a set of replicate measurements without assumption of knowledge of the true value. Precision is expressed as percent RSD and can be determined using the following formula:

$$\text{RSD} = \left(\frac{\text{Standard Deviation of Replicate Measurements}}{\text{Average of Replicate Measurements}} \right) \times 100 \quad (\text{Eq. D-5.6})$$

Accuracy—Accuracy is the degree of agreement between an average measurement and an accepted reference or true value, expressed as a percentage of the reference or true value. Accuracy DQI must include systematic errors associated with the sampling process.

$$\% \text{ Bias} = \left(\frac{(\text{Averaged Measured Values}) - (\text{Known Value})}{\text{Known Value}} \right) \times 100 \quad (\text{Eq. D-5.7})$$

Completeness—Completeness expresses the percent of acceptable data collected, using the following expression:

$$\% \text{ Completeness} = \left(\frac{\text{Amount of Valid Data Collected}}{\text{Intended Collectable Data}} \right) \times 100 \quad (\text{Eq. D-5.8})$$

D-6.0 ASSESSMENTS AND CORRECTIVE ACTION

D-6.1 READINESS REVIEW, AUDITS, AND DATA QUALITY ASSESSMENT

Prior to initiation of sampling activities, a readiness review will be performed. The equipment will be inspected visually and checked to ensure complete assembly of the sampling systems and their proper operation.

For this project, no systems or performance audits are planned. However, audits may be initiated by EPA Quality Assurance staff, as appropriate. In that event, project personnel will cooperate fully. Any on-site audit will be conducted after work has commenced but before the first sampling period, giving an opportunity for corrective action.

An assessment will be made of the quality of the data relative to the guidelines for accuracy and precision in the project DQOs. This assessment will use the data quality process that begins with the review of the planning documentation and ends with an answer to the questions posed at the beginning of the project. The five steps of the data quality assessment are:

1. Review the sampling design and the requirements for an acceptable performance evaluation sample;
2. Conduct a preliminary data review;
3. Select the appropriate statistical test for the method activity;
4. Verify the assumptions of the statistical test; and
5. Draw conclusions from the data.

The statistical tests used for this project will be limited to small sample-sized statistics that are valid for a replicate data set.

D-6.2 CORRECTIVE ACTION

Corrective action is required when:

1. An individual measurement DQI is not met;
2. A monitor's response changes suddenly or dramatically for no apparent reason; or
3. If the error in the monitor's response changes beyond ± 5 percent over the course of a test run, even if the change is within the DQI range. Instrument error drift over the course of a test run is the difference in the measurement error from the start of the test to the end of the test as determined by a pre-test and post-test QC check. The PI will determine the importance of the parameter of poor quality. From this determination, a decision will be made to:
 - Document the problem, arrange for calibration when convenient, and correct the data later in accordance with the recalibration; or
 - Discard the data, immediately correct the problem by recalibration and/or repairs, and repeat the test(s).

Corrective action will be taken as quickly as possible while adhering to safety protocols. All corrective actions taken and the events leading up to corrective action will be recorded in the project notebook.

If a data audit indicates that DQIs are not being achieved, efforts will be made to locate and correct the problem before further experiments are performed. Possible sources of error include changes in monitoring system operating parameters that occurred during sampling and were undetected at the time, contamination errors, instrument errors or malfunctions, and sampling errors such as overloading sampling substrates. If the error is such that the post run data cannot be corrected, the sampling effort will be repeated as resources permit. Otherwise, the data will be considered unusable and discarded.