SAE INTERNATIONAL

AEROSPACE RECOMMENDED PRACTICE

ARP6320™ **REV. A**

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Superseding ARP6320

Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines

RATIONALE

This ARP6320 document revision provides updated nvPM mass calibration and System Operability information. The nvPM mass calibration data reduction method has been revised, and additional detail supplied on the use of splitters for nvPMmi calibration. Both the Diluter1 temperature control and the Dilution Factor 2 check method 1 have been revised. The “nvPM System Compliance and Operational Checklists” Excel spreadsheet is now presented as two separate checklist documents to simplify use: nvPM System Compliance Checklists v1_4 and nvPM Operations Compliance Checklists v1_4. Additional cross-references to ICAO Annex 16 Volume II[1] are now included in both checklists.

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[1] Actual certification requirements are specified in ICAO Annex 16 as interpreted by the local regulating authority.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) describes recommended sampling conditions, instrumentation, and procedures for the measurement of non-volatile particle number and mass concentrations from the exhaust of aircraft gas turbine engines. Procedures are included to estimate sampling system loss performance. This ARP is not intended for in-flight testing, nor does it apply to engines operating in the afterburning mode.

This ARP is intended as a guide toward standard practice and is subject to change to keep pace with experience and technical advances.

1.1 ARP Section

This document is divided into the following Sections:

2. Reference, Definitions, Terminology, and Units

3. Introduction

4. nvPM System General Description, Measurement and Losses

5. Sampling System Detailed Requirements

6. Particle Mass Measurement Requirements

7. Particle Number Measurement Requirements

8. Calculation of Emission Indices

9. nvPM System Operation

A. Appendix

2. REFERENCES, DEFINITIONS, TERMINOLOGY, AND UNITS

The following publications provide relevant background information for this ARP. The latest issue of the referenced SAE publications shall apply. In the event of a conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document shall supersede applicable laws and regulations unless a specific exemption has been obtained by the appropriate authorities.

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

2.1.1.1 AIR5892 Nonvolatile Exhaust Particle Measurement Techniques

2.1.1.2 AIR6037 Aircraft Exhaust Nonvolatile Particle Matter Measurement Method Development

2.1.1.3 ARP1179 Aircraft Gas Turbine Engine Exhaust Smoke Measurement

2.1.1.4 ARP1256 Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines

2.1.1.5 ARP1533 Procedure for the Analysis and Evaluation of Gaseous Emissions from Aircraft Engines

2.1.1.6 AIR6241 Procedure for the Continuous Sampling and Measurement of Non-Volatile Particle Emissions from Aircraft Turbine Engines

2.1.1.7 AIR6504 Procedure for the Calculation of non-volatile Particulate Matter Sampling and Measurement System Penetration Functions and System Loss Correction Factors

2.1.2 Appended Documents

- Excel spreadsheet – PM_EI_calculator_03-08-2017
- Excel spreadsheet – nvPM System Compliance Checklists v1_4
- Excel spreadsheet – nvPM Operations Compliance Checklists v1_4
- MSS Aviation SOP – AVL Micro Soot Sensor Standard Operating Procedure, AVL, March 2017.
- LII SOP - Laser Induced Incandescence (LII) 300 Standard Operating Procedure, Artium, October 2016.

2.1.3 Other Publications or References

2.1.3.1 Kittelson, D. and Johnson, J., "Variability in Particle Emission Measurements in the Heavy Duty Transient Test," SAE Technical Paper 910738, 1991, https://doi.org/10.4271/910738.

2.1.3.2 Diesel Particulate Emissions: Measurement Techniques, Fuel Effects and Control Technology (PT-42) pp. 137-162, Edited by: J.H. Johnson, T.M. Baines and J.C. Clerc, SAE, Inc., Warrendale, PA, 1991 Transactions of the SAE, Vol. 100, Sec. 3, pp. 1378-1403, 1992.

2.1.3.3 International Standards Organization, Rubber and Plastics Hoses and Hose Assemblies – Determination of Electrical Resistance and Conductivity, ISO 8031, 2009.

2.1.3.4 Hinds, W.C., Aerosol Technology, Second Edition, Wiley & Sons, 1999.

2.1.3.5 International Standards Organization, Air Quality - Definition and Determination of Performance Characteristics of an Automatic Measuring System. International Standard 9169, 2006.

2.1.3.6 National Institute of Occupational Safety and Health (2003). Diesel particulate matter (as elemental carbon). Method 5040: Issue 3, available at: https://www.cdc.gov/niosh/docs/2003-154/pdfs/5040.pdf.

2.1.3.7 ASTM International (2013). Standard Test Method for Monitoring Diesel Particulate Exhaust in the Workplace, D 6877-13.

2.1.3.8 ISO/DIS 27891, Aerosol Particle Number Concentration – Calibration of Condensation Particle Counters, https://www.iso.org/standard/44414.html.

2.1.3.9 ISO/IEC 17025:2005, General Requirements for the Competence of Testing and Calibration Laboratories, https://www.iso.org/standard/39883.html.

2.1.3.10 Dieck, R.H., Measurement Uncertainty: Methods and Applications. The Instrumentation, Systems and Automation Society. 3rd Ed., 2002, pages 106-110.

2.1.3.11 Kline, S. J. and McClintock, F. A. (1953). Describing the uncertainties in single sample experiments. Mechanical Engineering, pages 3-8.

2.1.3.13 Giechaskiel B., Mamakos, A., Anderson, J., Dilara, P., Martini, G., Schindler, W., Bergmann A., “Measurement of Automotive Nonvolatile Particle Number Emissions within the European Legislative Framework: A Review” Aerosol Science and Technology, 46:719–749, 2012.

2.1.3.14 Amanatidis, S., Ntziachristos, L., Giechaskiel B., Katsaounis, D., Samaras, Z., Bergmann, A., “Evaluation of an oxidation catalyst (‘‘catalytic stripper’’) in eliminating volatile material from combustion aerosol”, Journal of Aerosol Science 57 (2013) 144–155.

2.1.3.15 ICAO, Annex 16 to the Convention on International Civil Aviation – Environmental Protection, Volume II – Aircraft Engine Emissions, Third edition July 2008 and latest amendments.

2.1.3.16 ICAO, Doc 9977, Manual on Civil Aviation Jet Fuel Supply, First edition 2012.

2.1.3.17 ISO 8031:2009 Rubber and plastics hoses and hose assemblies - Determination of electrical resistance and conductivity.

2.2 Definitions and Terminology

2.2.1 Definitions

AIRCRAFT GAS TURBINE ENGINE: Any gas turbine engine used for aircraft propulsion or for power generation on an aircraft, including those commonly called turbojet, turbofan, turboprop, or turboshaft type engines, or auxiliary power units.

AERODYNAMIC PARTICLE DIAMETER: The diameter of an equivalent sphere of unit density (1.0 g/cm^3) with the same settling velocity as the particle in question, also referred to as “aerodynamic diameter”.

CATALYTIC STRIPPER (CS): A catalytic device that removes volatile species through oxidation.

COMPETENT LABORATORY: A testing and calibration laboratory which establishes, implements and maintains a quality system appropriate to the scope of its activities, in compliance with the International Organization for Standardization standard ISO/IEC 17025:2005, as amended from time to time, or equivalent standard and for which the program for calibration of equipment is designed and operated so as to ensure that calibrations and measurements made by the laboratory are traceable to the International System of Units (SI). Formal accreditation of the laboratory to ISO/IEC 17025:2005 is not required.

CYCLONE SEPARATOR: A device that removes particles larger than a prescribed aerodynamic diameter via rotational and gravitational means. The specified cut-point diameter is associated to the percent of particles that penetrate through the cyclone separator [e.g., D_{50} refers to a diameter with a 50% penetration (see D_{xy} below)].

ELECTRICAL MOBILITY DIAMETER: The diameter of an equivalent sphere with the same electrical mobility as the particle in question; also referred to as mobility diameter.

ELEMENTAL CARBON (EC): Light absorbing carbon that is not removed from a filter sample heated to 1143 K in an inert atmosphere during TOT analysis, excluding char.

ERROR: Deviation between measured and true value of a given measurement parameter.

FALL TIME (ISO 9169): The time taken for the output signal to pass from 90 to 10% of the initial output signal produced by a reference material applied to the automatic measuring system, when the application of this reference material is abruptly terminated to put the automatic measuring system in the basic state. (This term is only applicable for an online analyzer.)

FLAME IONIZATION DETECTOR (FID): A hydrogen-air diffusion flame detector that produces a signal nominally proportional to the mass-flow rate of hydrocarbons entering the flame, and generally assumed responsive to the number of carbon ions dissociated from the hydrocarbons entering the flame.

NON-VOLATILE PARTICULATE MATTER (nvPM): Emitted particles that exist at gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to 623 K.

ORGANIC CARBON (OC): Carbon volatilized in He while heating a quartz fiber filter sample to 1143 K during TOT analysis. Includes char formed during pyrolysis of some materials.

PARTICLE LOSS: The loss of particles during transport through the sampling system due to various deposition mechanisms, some of which are size dependent.

PARTICLE SIZE DISTRIBUTION: The probability density function, list of values, or mathematical function that expresses the nvPM (number, mass, surface area, or volume) concentration according to size. Engine exhaust is composed of particles with diameters spread over several orders of magnitude and are typically measured in terms of their electric mobility.

PARTICLE MASS CONCENTRATION: The mass of particles per unit volume of sample.

PARTICLE MASS EMISSION INDEX: The mass of particles emitted per unit of fuel mass used.

PARTICLE NUMBER CONCENTRATION: The number of particles per unit volume of sample.

PARTICLE NUMBER EMISSION INDEX: The number of particles emitted per unit of fuel mass used.

PENETRATION FRACTION: The ratio of particle concentration downstream and upstream of a sampling system element.

PRECISION: The closeness with which a measurement upon a given invariant sample can be reproduced in short-term repetitions of the measurement with no intervening instrument adjustment.

RISE TIME (ISO 9169): The time required for the output signal to pass from 10 to 90% of the final change in the output signal when a reference material is abruptly applied to the automatic measuring system initially in the basic state. (This term is only applicable for an online analyzer.)

STANDARD GAS VOLUME: The volume of gas at 273.15 K (0 °C) and 101.32 kPa (1 Atm).

VOLATILE PARTICLES: Particles formed from condensable gases after the exhaust has been cooled to below engine exit temperatures (e.g., sulfuric acid particles); combustion exhaust material which volatizes at ≤623 K (350 °C).

2.2.2 Symbols, Acronyms, and Terminology

C_mH_n = Formula of hydrocarbon fuel

$[CO_2]$ = Mole fraction concentration of carbon dioxide in the engine exhaust on a wet basis

$[CO_2]_S$ = Mole fraction concentration of carbon dioxide in the engine exhaust as measured on a dry or semi-dry basis

$[CO_2]_b$ = Mole fraction concentration of carbon dioxide in ambient air

$[CO_2]_{dil1}$ = Mole fraction concentration of carbon dioxide after the first dilution stage on a wet basis

$[CO_2]_{dil2}$ = Mole fraction concentration of carbon dioxide after the second dilution stage on a wet basis

$[CO]$ = Mole fraction concentration of carbon monoxide in the engine exhaust on a wet basis

CPC = Condensation Particle Counter

DF = Dilution Factor = (Sample concentration before dilution)÷(Sample concentration after dilution)

DF_1 = First stage dilution factor

DF_{1_s} = First stage dilution factor measured real-time

DF_2 = Second stage dilution factor

D_m = nvPM particle diameter; refers to the electrical mobility diameter except for the cyclone separator where the particle diameter is the aerodynamic diameter, nm

DR = Dilution Ratio, DR = (DF-1):1 (DF = 10 corresponds to a DR of 9:1, 9 parts of diluent mixing with 1 part of sample)

D_{xy}, at zz nm = Aerodynamic diameter at which xy% (detection efficiency) of zz size particles are detected

EI = Emission index, emissions unit per kg of fuel

EI_{mass} = Particle mass emission index, g/kg fuel

EI_{num} = Particle number emission index, particles/kg fuel

F_c = Mass fraction of carbon in fuel = grams of carbon in one gram of fuel, $\frac{g}{g}$

FS = Full Scale of the analyzer working range

GL = Gas Line

HEPA = High efficiency particle air filter, class H13. Removes ≥99.97% of dioctylphthalate particles 0.3 μm in diameter

[HC] = Mole fraction concentration of hydrocarbons (as Methane equivalent) in the engine exhaust (wet)

$[HC]_b$ = Mole fraction concentration of hydrocarbons (as Methane equivalent) in ambient air

$[H_2O]$ = Mole fraction concentration of water in the engine exhaust on a wet basis

ID =Internal diameter

k_{thermo} = Collection Part thermophoretic loss correction factor

LOD = Limit of Detection

m, n = Molar constants for hydrocarbon fuel, C_mH_n

M_C = Atomic weight of carbon = 12.011

M_H = Atomic weight of hydrogen = 1.008

N = (Total) number concentration of particles per unit volume. Typically, particles/cm^3.

$N_{in}(D_m)$ = Upstream particle number concentration for particles of diameter D_i

$N_{out}(D_m)$= Downstream particle number concentration for particles of diameter D_i

nvPM = Non-volatile particulate matter

nvPMmi = Non-volatile particulate matter mass instrument

nvPMni = Non-volatile particulate matter number instrument

NMI = National Measurement Institute (e.g., NIST (National Institute of Standards and Technology), NPL (National Physical Laboratory)

$nvPM_{num\_STP}$ = Diluted nvPM number concentration measured by number instrument at STP condition, particles/cm^3

$nvPM_{mass\_STP}$ = Diluted nvPM mass concentration measured by mass instrument at STP condition, μg/m^3

PTFE = Polytetrafluoroethylene

R_{gas} = Universal gas constant, 0.082 $\frac{\text{L atm}}{\text{mole K}}$

slpm = Standard liters per minute. Volumetric flow at STP condition.

STP = Standard temperature (T_{std}) 273.15 K and pressure (P_{std}) 1 atm (101.325 kPa).

t = Time in seconds, minutes, or hours as noted

T_1 = Sample tube temperature at Diluter1 inlet, K

T_{EGT} = Performance-predicted engine exit exhaust gas temperature (used for thermophoretic loss calculations), K

TOT = Thermal-Optical Transmission

t_{90} =90% response time (Time between change in concentration and the detector reaching 90% of its final signal)

VPR = Volatile Particle Remover

x, y = Molar constants of total hydrocarbon in engine exhaust, expressed as C_xH_y equivalent

Z = Exhaust component, either gaseous or particle

α = Atomic hydrogen-carbon ratio of the fuel = n/m. Typical values are provided in Table 1 of ARP1533

Δt = Time interval

2.2.3 Units

A. PHYSICAL QUANTITIES

atm = 1 atmosphere pressure = 101.325 kPa

cm = centimeter (10^{-2} m)

g = gram

Hz = Hertz (1 per second)

K = Kelvin

kPa = kilopascal (10^3 Pa)

m = meter

nm = nanometer (10^{-9} m)

µm = micrometer (10^{-6} m)

Pa = pascal

s = second

slpm = standard liters per minute

B. PREFIXES

k = kilo, 10^3

c = centi, 10^{-2}

m = milli, 10^{-3}

μ = micro, 10^{-6}

n = nano, 10^{-9}

3. INTRODUCTION

3.1 Background

The Smoke Number (SN) measurement, described in ARP1179, was developed to ensure compliance with an aircraft engine exhaust visibility criterion. However, the SN does not address the current need to quantitatively measure the mass and number of nvPM emitted from the engine. This ARP has been developed based on AIR6241, which implemented techniques pioneered by the turbine engine PM research community [Refs. 2.1.1.1, 2.1.1.2] to measure the mass and number of the emitted non-volatile particles.

The basic concept of the system design incorporates a high degree of standardization, such that systems built to the specifications of this ARP have similar size dependent particle losses. One example of system standardization is the prescription of the particle transfer sampling line length with a maximum but also a minimum value, such that particle penetrations to the instruments will be similar for different systems. The transfer sampling line length has been chosen to accommodate measurements of the largest aircraft gas turbines. There are test facility locations where the use of shorter lines is possible. However, this would change the particle penetration characteristic of the measurement system and reduce the degree of standardization. Therefore, also the minimum line length is specified.

The ARP outlines the requirements for the sampling system, mass, and number measurements in Sections 4 through 7 with additional details provided in the Appendix (Section A). Equations for emission indices calculations for both mass and number are provided in Section 8 and a system operator guide is provided in Section 9 describing how to check, maintain, and operate a nvPM system in compliance to this ARP. Additional technical information and support tools are included in the Appendix and attachments to this ARP.

3.2 Limitations

This ARP addresses the measurement of nvPM delivered to the instruments by the sampling system (corrected for dilution and probe thermophoretic loss). Significant nvPM will be lost in the sampling and measurement system. System losses depend on a number of parameters associated with the nvPM source and the sampling and measurement system. Losses are higher for number than for mass and increase at small particle sizes. When evaluating engine exit plane values, size dependent system loss corrections up to a factor of ~2 for particle mass and up to a factor of ~10 for particle number will be required. System loss correction methodologies are discussed in AIR6504 and will be addressed in future ARPs.

Based on best available technology, but to allow for future improvement of particle system components, only minimum particle penetrations of the diluter and volatile particle remover (VPR), and counting efficiency of the particle instrument have been specified. Using components with better particle penetration characteristics than the minimum, will lead to a higher reported nvPM number concentration.

Note that aircraft engine nvPM emissions will vary with fuel composition, independent of the sampling and measurement system. When evaluating aircraft engine nvPM values, correction factors to account for fuel composition may be required.

Efforts to achieve higher levels of standardization and studies to reduce uncertainty are ongoing.

3.3 Sampling System

The environment behind a gas turbine engine presents significant challenges on the sampling system used to capture the exhaust nvPM sample. The high temperature and velocity exhaust requires a robust probe to collect the sample, followed by a transfer system to transport the sample to the measurement instruments. These requirements are compounded by the need to minimize the influence of the sampling system on the sample properties. Thus, a comprehensively designed system is required.

The sampling system, discussed in detail in Section 5, is designed to control the sample temperature, dilution, and pressure to minimize perturbations to the PM prior to measurement. The Transfer Part, which constitutes a significant portion of the system, has been standardized to minimize variability between test facilities and operators. The exhaust sample is diluted and maintained at prescribed temperatures and flow rates to prevent condensation, minimize coagulation of particles to be measured, and to minimize particle transport loss. Once the exhaust sample has been transported to the measurement instruments, nvPM mass and number concentrations are measured.

Understanding the sampling system particle transport loss is important for accurate nvPM measurements. The parameters needed to enable an estimation of size-dependent particle loss are discussed in AIR6504. The largest source of particle size-independent transport loss, the thermophoretic loss, is assessed and used to correct the measured nvPM mass and number. Except where noted, all particle sizes mentioned throughout this document refer to particle electrical mobility diameter as defined in 2.2.

3.4 Measurement of nvPM Emissions

Once the sample has been transported to the instruments, nvPM mass and number emissions are quantified as described in Sections 6 and 7. The nvPM mass and number emissions indices (EI) are then determined based on the quantity of fuel consumed, as described in Section 8. Ambient nvPM concentrations shall also be measured and reported. Determination of uncertainties in the calculated particle number and mass EI are described in the Appendix (A.7.2).

4. nvPM SAMPLING AND MEASUREMENT SYSTEM GENERAL DESCRIPTION

The nvPM sampling and measurement system shall consist of three parts, divided into five sections:

a. Collection Part (Section 1)

b. Transfer Part (Sections 2, 3, and 4)

c. Measurement Part (Section 5)

A flow diagram of the nvPM sampling and measurement system is provided in Figure 1, with the terminology described in Table 1. More details and examples of the requirements and recommendations for each section of the system are provided in Appendix A.

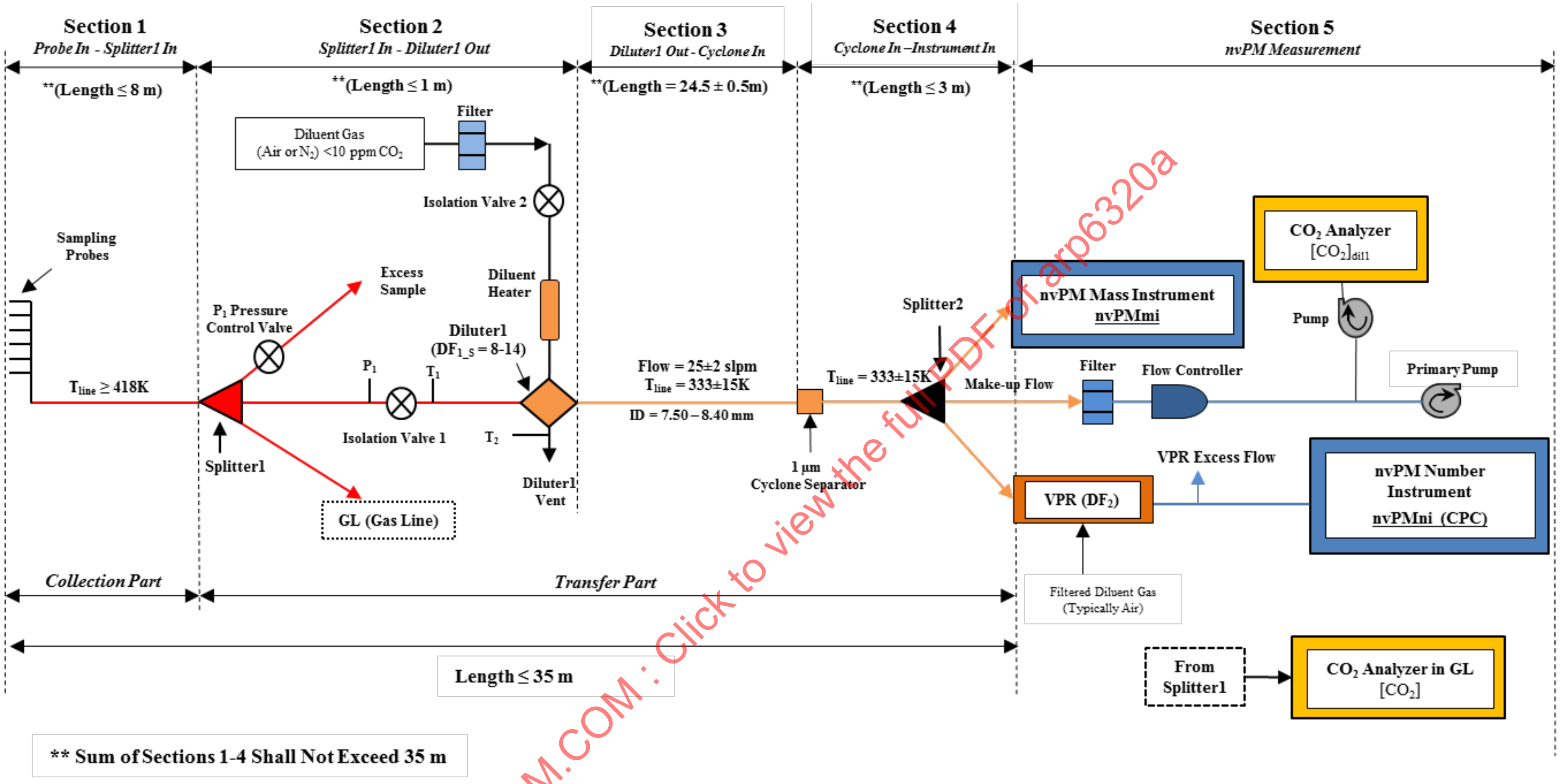


Figure 1 - Flow schematic of nvPM sampling and measurement system

Table 1 - nvPM sampling and measurement system flow schematic terminology

Terminology		Description
Section 1	**Sampling Probes**	Single or multi-point hardware used to sample exhaust from the aircraft engine exit.
	Heated Sample Line	Heated length of tubing to transport sample from Probe to Splitter1 inlet.
Section 2	**Splitter1**	Flow splitter assembly to provide samples to gaseous and nvPM sampling systems. Also provides a flow path to relieve and control the sample line pressure.
	P_1 Pressure Control Valve	Valve used to control pressure at Diluter1 inlet.
	P_1	Pressure at Diluter1 inlet regulated with the pressure control valve.
	Excess Sample Flow	Sample vent from P_1 pressure control valve.
	T_1	Sample tube temperature at Diluter1 inlet. Used to calculate Section 1 thermophoretic losses.
	Isolation Valve 1	Isolates the collection part and gas line (GL) from the transfer part to facilitate the system leakage checks described in A.4.
	Isolation Valve 2	Diluent 1 shut off valve.
	Diluter1	Ejector-type diluter which provides near ambient pressure to inlet of Section 3. Dilutes the nvPM sample early in the system to minimize PM coagulation and thermophoretic losses.
	Diluent Gas	Compressed gas (Nitrogen or Air) for Diluter1. CO_2 impurity shall be low (<10ppm CO_2) to allow accurate online validation of Dilution Factor 1.
	Filter	High efficiency particle filter required to prevent particle contamination from diluent gas.
	Diluent Heater	Heats diluent gas to Diluter1.
	Diluter1 Vent	Allows venting of excess diluted sample to atmosphere to maintain constant ambient pressure at diluter exhaust and prevent Transfer Part overpressure.
	T_2	Temperature at vent flow to monitor Diluter1 outlet sample temperature.
GL	**Gas Line**	Heated section to transport raw gas sample to instruments for obtaining ARP 1256 and/or ARP1179 gas and/or smoke number measurements, respectively.
Section 3	**Heated Sample Line**	Standardized sampling section. Allows measurements at a safe distance from the engine.
Section 4	**1 µm Cyclone Separator**	Removes non-combustion particles (≥1µm dia.) and helps prevent instrument blockage.
	Splitter2	Flow splitter to provide sample for nvPM mass and number concentration measurements and a flow path to ensure that the system flow rate is maintained within 25 slpm ± 2 slpm.
	Instrument Inlet Lines	Heated tubing to transport sample from Splitter2 outlets to nvPMmi and VPR inlets.
Section 5	**Filter**	High efficiency filter to remove sample particles and prevent damage of flow controller.
	Flow Controller	Maintains constant flow rate in Section 3 by controlling a make-up flow.
	Pump(s)	Draws make-up flow from Splitter2 and provides samples to CO_2 analyzer(s)
	CO_2 Analyzer	Measures CO_2 concentration in the diluted sample to nvPMmi ($CO2_{\_dil1}$).
	nvPMmi	nvPM mass instrument.
	VPR	Volatile Particle Remover - device that removes volatile species and further dilutes the sample (second stage dilution, DF_2) prior to entering the nvPMni.
	VPR Excess Flow	Allows venting excess diluted sample from VPR to prevent CPC overpressure.
	Filtered Diluent Gas	Compressed diluent gas (Air) for Diluter2. The required low impurity (<0.1ppm CO_2) shall allow online validation of Dilution Factor 2 (if required).
	nvPMni	nvPM number instrument (CPC).

4.1 Collection Part (Section 1)

Section 1 is composed of the probe/rake hardware and a sample connection line. Section 1 complies with ARP1179 and ARP1256 for smoke number and gaseous emission measurements, respectively.

4.2 Transfer Part

At the inlet to Section 2, the Splitter1 assembly shall split the sample into the Transfer Part line, the Gas Line (GL) for the measurement of undiluted gas emissions, and the excess sample line. The gaseous emission species to be measured depend on which nvPM EI calculation method is implemented by the user, either CO_2 only or full gas emissions (CO_2, CO, and HC).

This arrangement also allows the GL to be used to measure Smoke Number, if required, as specified in ARP1179.

The Transfer Part is standardized to minimize hardware variation in order to provide comparable particle transport characteristics across multiple facilities and engine types.

The Transfer Part line shall be arranged such that the nvPM sample:

a. Passes through Diluter1, an ejector-type diluter which draws, dilutes, and cools the sample;

b. Passes through Section 3;

c. Passes through a Cyclone Separator and Splitter2 in Section 4 before entering the Measurement Part in Section 5.

4.3 Measurement Part

4.3.1 nvPM Mass Measurement

The nvPMmi shall meet the requirements in Section 6. Each make and model of the nvPMmi shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that the make and model of the nvPMmi meets the performance specifications listed in Table 3 in 6.2.

4.3.2 nvPM Number Measurement

The nvPM number concentration shall be determined using a system consisting of a Volatile Particle Remover (VPR) and a Condensation Particle Counter (CPC) (nvPMni) in series. The VPR includes a device for the removal of volatile species and a dilution system (DF_2) to reduce the nvPM concentration to the single count mode of the CPC (discussed in Section 7).

Each make and model of the VPR and CPC shall receive a certificate from the instrument manufacturer or from another competent testing and calibration laboratory confirming that the make and model of each device meets the performance specifications listed in Tables 6 and 7, and in 7.1 and 7.2.

4.3.3 Make-Up Flow Path

The Make-up flow path shall be used to maintain a constant sample flow rate through Section 3 and provide a diluted (DF_1) sample for CO_2 concentration measurement. The Make-up flow path shall contain a pump, flow controller, and CO_2 analyzer.

4.4 Sampling System Particle Transport Loss

Generally, significant particle transport losses occur in sampling systems by thermophoresis, diffusion, and inertial mechanisms. In the aircraft engine exhaust nvPM sampling system, these occur throughout the Collection and Transfer Parts. Thermophoretic losses are independent of particle size, while diffusion and inertial losses are highly size-dependent.

4.4.1 Collection Part Thermophoretic Loss

Collection Part thermophoretic loss is the largest size-independent particle loss for particle number and mass. Thermophoretic losses are dependent on the temperature gradient between the sample and the sampling line wall. The largest (>95%) source of thermophoretic loss occurs in the Collection Part (Section 1) as the sample cools from engine exhaust temperature to the sample line temperature.

Per Reference 2.1.3.1 and as discussed in AIR6504 for sampling aircraft exhaust emissions, at exhaust temperatures up to 973 K (700 °C) the particle penetration fraction due to thermophoresis relates to the sampling tube inlet and outlet temperatures (in K) by the relation in Equation 1.

$$\text{Thermophoretic penetration fraction } (\eta_{\text{thermo}}) = \left(\frac{T_{\text{outlet}}}{T_{\text{inlet}}}\right)^{0.38} \quad \text{(Eq. 1)}$$

The correction factor for nvPM thermophoretic particle loss in the Collection Part, k_{thermo}, shall be calculated using the engine performance-derived average exhaust exit gas temperature (T_{EGT}) and Diluter1 inlet wall temperature (T_1) in the inverse of Equation 1:

$$k_{\text{thermo}} = 1/\left(\frac{T_1}{T_{\text{EGT}}}\right)^{0.38} \quad \text{(Eq. 2)}$$

If $T_{\text{EGT}} < T_1$, then $k_{\text{thermo}} = 1$

This correction factor shall be used to correct the nvPM mass and number concentrations and EIs as discussed in 8.1.

4.4.2 Diffusion and Inertial Losses

To correct for diffusion and inertial losses, a particle size distribution would be required. Measurement of a traceable particle size distribution is a complex activity, and beyond the scope of this ARP. However, theoretical particle size distributions may be used to estimate size-dependent transport losses. The parameters required to calculate particle size-dependent transport losses and theoretical particle size distributions (listed in Table A2) shall be recorded to enable an estimation of size-dependent loss mechanism correction factors.

AIR6504 provides detailed explanations of particle loss mechanisms and an estimation procedure for correcting size-dependent particle losses in the nvPM measurement system. The procedure is based on a theoretical particle size distribution calculation, assumptions and parameters generated using this ARP.

5. nvPM SAMPLING SYSTEM DETAILED REQUIREMENTS AND RECOMMENDATIONS

5.1 General Sampling System Requirements

The sampling system shall be constructed adhering to the following requirement:

The total sample line length from probe tip to the instrument inlet shall not exceed 35 m (note that this is not equal to the sum of the maximum individual section lengths). Detailed length requirements are provided in Figure 1.

The sampling system, excluding Section 1, shall be constructed adhering to the following general requirements:

a. Sample lines shall be as straight-through (i.e., minimize number of bends) as practical.

b. The number of fittings shall be minimized. Fittings shall be manufactured from stainless steel (304SS or 316SS preferable) with an internal smooth bore (unless otherwise specified). The number of bulkhead union fittings shall be minimized and thermally insulated to prevent thermal gradients. Details on best practices for use of unions and other fittings are provided in A.2.2 of the Appendix.

c. The sampling line should be actively heated across fittings. If not practical, the sample line should be heated as close as possible to the next heated element and thermally insulated across the fitting.

d. Any necessary bends shall have radii greater than 10X the internal diameter (ID) of the lines.

e. There shall be no forward-facing step-shoulders greater than 15% of the ID and changes in line ID greater than 15% may only occur at a splitter flow path interface. Differences in ID of less than or equal to 15% shall be considered as no change in sampling line ID.

Where carbon loaded polytetrafluoroethylene (PTFE) is used as the sampling line material, it should meet the recommended anti-static resistance limits in Reference 2.1.3.16.

5.2 Section 1: Probe/Rake Inlet to Splitter1 Inlet

The probe shall adhere to following requirements and provide compatibility with ARP1179 and ARP1256:

a. The sampling probe material shall be stainless steel (e.g., 304 or 316) or any other non-reactive high temperature material such as Inconel 625 or Nimonic 75 alloys which may be more suitable for exhaust temperatures which exceed the specification limits of stainless steel.

b. If a sampling probe with multiple sample orifices is used, all sampling orifices shall be of equal diameter. The sampling probe design shall be such that at least 80% of the dynamic head pressure drop through the sampling probe assembly (from free stream to probe exit) is taken at the orifices. If active cooling of the probe is employed, the exhaust sample shall be maintained at a minimum temperature of 418 K (145 °C).

c. The number of locations sampled shall not be less than twelve (12). The sampling locations shall be arranged over the exhaust nozzle exit area for straight turbojet, turboprop, turboshaft, and mixed flow (or confluent flow) fan engines, and over the core nozzle exit area for non-mixed fan engines. Probes with multiple sampling orifices or individual probes ganged together are acceptable. Cruciform type sampling probe are in common use with a minimum of three sampling orifices per arm. The radial locations of the orifices are usually at centers of equal area to obtain an area weighted average sample.

d. The axial location of the exhaust sampling plane shall be perpendicular to the nozzle axis and as close to the plane of the exit nozzle as engine performance parameters permit. The angular position of the probe arm is free and may be varied, as long as the sampling requirements of ARP1256 are met. The position of the probe shall not exceed 0.5 exit nozzle diameters from the exit plane.

e. Probe placement and configuration shall be determined by representative gaseous or smoke demonstrations as stated by ARP1256 or ARP1179 guidelines. In order to promote consistency, a specific probe design should be standardized for use within a given type or series of engines.

The sample shall be transferred from the probe exit to Section 2 via a connection line of 4.0 to 8.5 mm inside diameter, taking the shortest route practical. In order to minimize particle losses, the length from probe inlet to the Splitter1 inlet shall be less than or equal to 8 m.

To conform to ARP1179 and ARP1256, the sample connection line temperature shall be maintained at 433 K ± 15 K (160 °C ± 15 °C), except for the section needed to cool the gas from the engine exhaust temperature to that of the sample line. The sample temperature reduction within Section 1 is required for the calculation of Collection Part thermophoretic particle loss.

The sample connection line from the probe/rake exit to Section 2 shall be constructed of Stainless Steel or carbon-loaded electrically grounded polytetrafluoroethylene (PTFE).

5.3 Section 2: Splitter1 Inlet to Diluter1 Outlet

Section 2 shall contain a sample splitter (Splitter1), a diluter (Diluter1) and a valve (Isolation Valve 1). The isolation valve is needed in order to perform the leakage check on the gas sample line (GL).

The sample line material shall be such as to minimize build-up of particulate matter or static electricity, for example, stainless steel or carbon-loaded electrically grounded polytetrafluoroethylene (PTFE).

The length of Section 2 from the Splitter1 inlet to the Diluter1 outlet shall not exceed 1 m.

5.3.1 Splitter1

Splitter1 shall be constructed of stainless steel, and the body temperature maintained at greater than or equal to 418 K (145 °C).

The number of Splitter1 flow paths depends on the number of undiluted sample measurement lines and/or the need to relieve large excess sample pressure. Single or multiple sequential splitters can be used.

The splitter angle relative to the incoming flow shall be as acute as practical and not exceed 35 degrees, and the nvPM sample flow path shall be as straight-through and as short as practical.

The Splitter1 geometry shall meet the following requirements:

a. No forward-facing step-shoulders on the inner wall.

b. No change in ID from Splitter1 outlet to Diluter1 inlet.

c. Flowpath to GL ID = 4 to 8.5 mm

d. Excess sample line internal cross-sectional area shall be greater than or equal to the total inlet area of the probe tips.

e. There shall be no reduction of Excess Sample line ID from Splitter1 outlet.

Examples of best practice splitter geometry are provided in A.2.1.

5.3.2 Isolation Valve 1

The Isolation Valve 1 shall be placed between Splitter1 outlet and Diluter1 inlet. The valve shall be full bore with no forward facing step-shoulders greater than 15% of the ID and the seals shall be dry and heat resistant to at least 448 K (175 °C).

5.3.3 Diluter1 Inlet Interface

In order to minimize thermophoretic losses within Diluter1 and provide an interface between two different active heating sections, Diluter1 nvPM Section 2-line wall temperature (T_1) (Figure 2), shall be maintained at greater than or equal to 418 K (145 °C). Note that T_1 (used for Collection Part thermophoretic loss calculations) does not have to be located directly at the active heating interface.

5.3.4 Diluter1

Diluter1 shall be an ejector-type diluter with an inlet ID greater than or equal to 7.59 mm.

The diluent shall be nitrogen or air, be HEPA filtered and contain less than 10 ppm CO_2. The diluent flow shall be controlled as specified by the Diluter1 manufacturer. Typically the diluent flow is controlled via a critical orifice at the diluent inlet connector with the diluent pressure maintained to keep critical flow through the orifice.

The dilution factor, DF_1, shall be measured in real-time during nvPM concentration measurements. A minimum dilution factor of 8 is required to minimize nvPM coagulation, while the maximum of 14 is needed to maintain the diluted sample within the measurement range of the nvPM mass instrument.

For sampling unmixed flow engine exhaust, a Diluter1 inlet pressure range is typically -5500 to +5500 Pa (-55 to +55 mbar) relative to ambient, DF_1 shall be controlled to within the range of 8 to 14. This may not be achievable at low power engine conditions if the Diluter1 inlet pressure drops below -5500 Pa, which could cause DF_1 to increase above the maximum value of 14. Note that a blockage in the diluter inlet can also cause a low inlet pressure and thus high DF_1.

For sampling mixed flow engine exhaust, the sample at probe inlet is already diluted via the bypass air flow. With a high (>14) primary dilution factor (from engine bypass and DF_1), it is more likely that the nvPM mass instrument will be close to or below its limit of detection. Thus, DF_1 may be controlled at a value of less than 8, such that the total sample primary dilution (engine bypass and DF_1) is maintained at a minimum value of 8. The maximum value of DF_1 (not including engine bypass) shall still be 14.

DF_1 may be adjusted by controlling P_1 with the pressure control valve on the excess sample flow path or by adjusting the diluent gas flow.

The Diluter1 vent shall be open to ambient (equal to engine inlet pressure). To minimize impact on the operable DF_1 range, the Diluter1 vent line pressure drop should be kept to a minimum.

The Diluter1 body shall be heated to 333 K ± 15 K (60 °C ± 15 °C), as shown in Figure 2. The diluent shall be heated as needed to maintain a diluted nvPM sample temperature of 333 K ± 15 K (60 °C ± 15 °C), which shall be monitored at the Diluter1 vent (T_2). A safety feature should be implemented to prevent the diluent heater from over-heating when the diluent gas is not flowing.

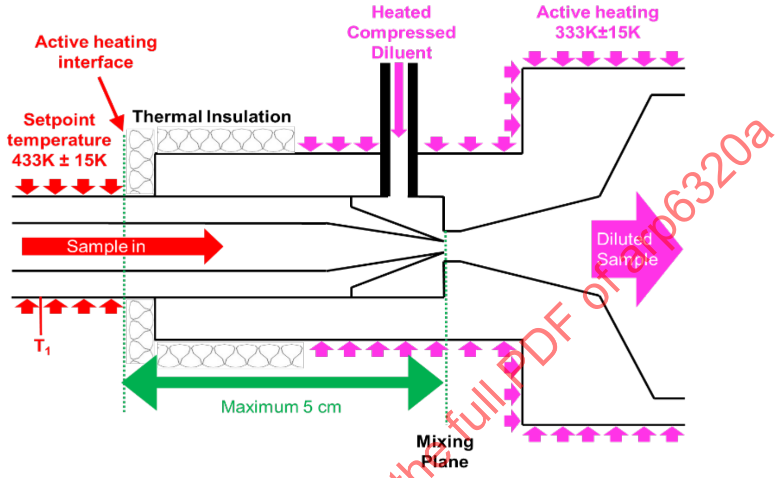


Figure 2 - Cross-section of example ejector-type Diluter1 inlet with heating interface

The particle penetration of Diluter1 (with diluter unheated under ambient laboratory conditions) shall meet the minimum requirements as shown in Table 2. The Diluter1 penetration validation methodology shall be the same as utilized for the VPR in A6.1.3.

Table 2 - Minimum requirements for particle penetration fractions (transmission efficiencies) of Diluter1

Particle Size (Diameter)	15 nm	30 nm	50 nm	100 nm
Minimum particle penetration fraction	80%	90%	90%	90%

5.3.5 Gas Line (GL)

Engine exhaust gaseous emissions are needed for nvPM EI calculation. The GL provides an exhaust sample for the measurement of raw gas concentrations. The GL and gaseous emissions analyzers shall follow the guidelines in ARP1256. Note the Collection Part (Section 1) of the nvPM sampling and measurement system meets the specifications in ARP 1256. The Isolation Valve 1, between Splitter1 and Diluter1 (Figure 1), facilitates the ARP1256 leak check in the GL.

If the full nvPM EI calculation method is utilized, $[CO_2]$, [CO], and [HC] measurements are needed, and shall be performed simultaneously. While the engine is at a stable operating condition, sequential switching can occur between [CO], [HC], and $[NO_x]$ measurements and nvPM measurement.

NOTE: If [CO], [HC], and [NOx] are not measured, the simplified case in Table 9 for nvPM EI calculation could be used.

If the simple nvPM EI calculation method is utilized, only CO_2 (wet, semi-dry or dry) measurement is needed.

SN measurements may be obtained using the GL and follow ARP1179.

For determination of DF_{1_S}, a raw measurement of CO_2 concentration (dry, semi-dry, or wet) shall be performed simultaneously with the nvPM measurements to determine DF_1 to maintain it within the specified range.

5.3.6 Excess Sample Line

The probe inlet pressure will vary according to engine thrust. The sample line pressure at Diluter1 inlet (P_1) shall be maintained near local ambient air pressure using a suitable Pressure Control Valve with sufficient internal area. When fully closed, the valve shall be capable of holding a vacuum pressure of -75 kPa relative to ambient.

An optional shut-off valve, with sufficient internal area to avoid system backpressure, should be added downstream of the Pressure Control Valve to prevent leakage at sub-atmospheric conditions inside Splitter1.

5.4 Section 3: Diluter1 Outlet to Cyclone Separator Inlet

The requirements of Section 3 sampling system are tightly specified in order to standardize the particle loss in this part, which is the longest in the nvPM sampling system and a large component of size-dependent particle loss.

The sampling line material shall be carbon-loaded electrically grounded PTFE.

The sampling line ID shall be between 7.50 mm and 8.40 mm. Note, the sampling line ID specification corresponds to commercially available line outer diameter nominal dimensions of 3/8 inch with 0.035-inch wall thickness; and 10 mm with a 1 mm wall thickness.

The sampling line shall be of length 24.5 m ± 0.5 m, have no unnecessary fittings and consist of a maximum of three segments. The coiled sample line bend radii shall be greater than 0.5 m.

The sampling line temperature shall be maintained at 333 K ± 15 K (60 °C ± 15 °C) through active heating and the sample flow shall be maintained at 25 slpm ± 2 slpm. This flow rate is monitored via three measurements downstream of Splitter2 (i.e., nvPMmi, volatile removal device and make-up flow). Optionally, the flow rate may be monitored via a differential pressure measurement between Diluter1 and Splitter2.

5.5 Section 4: Cyclone Separator Inlet to Instrument Inlets

The sampling lines to the nvPMmi and VPR inlets shall be constructed of stainless steel or carbon loaded electrically grounded PTFE.

The sampling lines shall be heated to 333 K ± 15 K (60 °C ± 15 °C) and each total line length from Cyclone Separator inlet to the inlet of the nvPMmi and VPR shall be kept as short as practical and shall not exceed 3m.

5.5.1 Cyclone Separator

An in-line cyclone separator prevents large non-combustion PM from particle-shedding to affect mass and number measurements. The cyclone separator material shall be stainless steel and heated to 333 K ± 15 K (60 °C ± 15 °C), and its inlet and outlet IDs shall be within 15% of the sample line ID.

The performance of the cyclone separator at a sample flow rate of 25 slpm shall meet the following specifications in order to provide an optimal, >99%, transmission efficiency for 0.5 μm particles:

a. Cut-point: D_{50} = 1.0 μm ± 0.1 μm

b. Sharpness: $(D_{16}/D_{84})^{0.5}$ less than or equal to 1.25

c. Pressure-drop: ΔP less than or equal to 2 kPa

5.5.2 Splitter2

Splitter2 separates the sample into three flow paths to deliver the diluted nvPM sample to:

a. nvPM mass instrument (nvPMmi)

b. Volatile particle remover (VPR) for nvPM number instrument

c. Make-up flow, which includes diluted CO_2 concentration measurement

Single or multiple sequential splitters can be used. Splitter2 shall be constructed of stainless steel and heated to 333 K ± 15 K (60 °C ± 15 °C). The split angles relative to the incoming flow shall be as acute as practical not exceeding 35 degrees and all nvPM flow paths shall be as short as practical.

The Splitter2 geometry shall meet the following requirements:

a. No forward-facing shoulders on the inner wall

b. No change in ID from Splitter2 outlet to nvPMmi inlet

c. No change in ID from Splitter2 outlet to VPR inlet

Examples of best practice splitter geometry are given in A.2.1 in the Appendix.

5.5.3 Instrument Inlet Lines

There shall be no change in ID between the sampling line and the instrument inlets.

Additional emissions diagnostic instrumentation may be placed in the Make-up flow path downstream of Splitter2.

5.6 Section 5: nvPM Measurement

The sampling system of Section 5 includes only the Make-up flow path requirements. The instrument requirements are described in Sections 6 and 7.

5.6.1 Make-Up Flow

The Make-up flow path shall contain a primary pump and flow controller to maintain a constant total sample flow rate, (sum of Make-up flow, nvPMmi, and VPR) of 25 slpm ±2 slpm up to 10 kPa below ambient, through Section 3.

The Make-up flow path shall also contain a CO_2 gaseous analyzer (located after a flow controller) to continuously measure CO_2 concentration downstream of Diluter1 $[CO_2]_{dil1}$ during the nvPM concentration measurement.

The CO_2 analyzer shall meet the performance specifications given in ARP1256 noting that its total range should be approximately ten times lower than the CO_2 analyzer used on the raw gaseous sample on the GL.

The sample gas measured downstream of Diluter1 can be considered ‘dry’ as it will consist of at least 88% dry air or dry nitrogen. The diluted sample water content is negligible and consequently the CO_2 concentration is measured dry and no “wet” correction is required.

6. PARTICLE MASS MEASUREMENT REQUIREMENTS

The concentration of turbine engine nvPM mass is determined using compliant instrumentation installed and operated as specified below. The nvPM mass instrument (nvPMmi) used shall be capable of measuring black carbon concentration within a measurement range of 0 to 1000 μg/m^3, have a resolution of 1 μg/m^3 or better, and be insensitive to volatile PM (note that volatile insensitivity is established when the instrument meets the applicability specification in Table 3). The following subsections outline the recommended configuration and operation of the instrumentation, performance specifications, instrument calibration, and data requirements. Additional supporting information is included in A.5 of the Appendix. Figure 3 illustrates the interface between the nvPMmi and Section 4 of the nvPM sampling system.

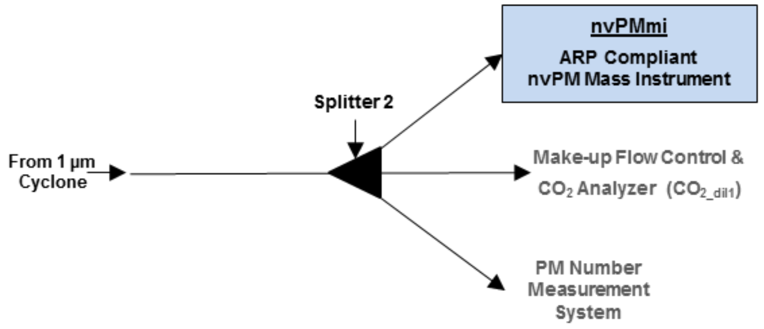


Figure 3 - Flow schematic of the particle mass concentration measurement system

6.1 Instrument Operating Procedures

A number of available instrument and equipment standard operating procedures (SOPs) are provided in the appended documents for user reference. The user is advised to use the latest version of the instrument operating manual.

6.2 Instrument Performance Specifications

The required specifications for the nvPMmi are listed in Table 3. The verification of these specifications is based on the procedures as defined by the International Standards Organization (ISO) Standard 9169-2006 [see 2.1.3.5] with modifications as outlined in the Appendix (A.4). A certificate should be supplied by the manufacturer (or other competent testing and calibration laboratory) indicating that the particular make and model analyzer used during certification meets the specifications listed in Table 3. The nvPMmi must comply with specifications in Table 3 after any hardware or software design changes which affects data acquisition and processing of the instrument make/model.

It is important to recognize that the performance specifications reflect the limits of the quantities that can be verified using thermal-optical analysis as outlined in ASTM Method D6877-13 [see 2.1.3.7] as the reference method. Note that there is no universally agreed and scientifically precise definition of soot or nvPM. Similarly, there is no known method that can deliver a precise sample of nvPM for use as a reference material. Thus, the values specified represent the expectations for the precision of calibration and verification using elemental carbon (EC) determined by ASTM D6877-13 and not the capabilities of the instruments themselves, which are known to have superior repeatability as compared to the reference method. Because of the expected uncertainties in the repeatability of the thermal-optical transmission (TOT) EC assays, a repeat of the above process at the same or a different laboratory may produce a different slope without any change in the response of the instrument. The accuracy specification in Table 3 is intended to account for such variability.

Table 3 - Performance specifications for nvPM mass instruments[a]

Performance Specification	Reference for Definition	Value
Repeatability	ISO* 6.4.5.3	10 µg/m^3
Zero drift	ISO 6.6 (for C_0 only)	1 µg/m^3/hr
Linearity	ISO* 6.4.5.4	15 µg /m^3
Limit of detection (LOD) or noise	ISO* 6.4.5.5 or ARP 6320 Appendix A5.1	1 µg/m^3
Rise time	ISO 6.3	2 seconds
Sample rate	ISO 2.1.7	1 Hz
Accuracy -- Agreement with EC determined by ASTM D6877-13	Slope of the linear regression between mass instrument and EC determined by ASTM D6877-13 after calibration (see Table 4)	±10%
Applicability – Agreement with EC	Validation on aircraft engine exhaust	±16%

[a]Note that the references to ISO 9169 in the table that are denoted by an asterisk refer to Sections for which modifications apply as described below.

6.3 Instrument Calibration

Each particular make and model of instrument shall be type-certified to the requirements shown in Table 3. All nvPMmi must be calibrated annually by a competent testing and calibration laboratory according to the requirements outlined in Table 4. Quartz filter sampling and EC analysis by ASTM D6877-13 (with temperature profile shown in Table 5) must be used for the purpose of calibration as described in the Appendix (A.5). Prior to each annual calibration, it is recommended that the performance of the nvPMmi be assessed in the "as found" condition at a target EC concentration of 100 µg/m^3 shown in Table 4. This assessment will allow traceability to prior calibrations and allow comparison of existing and new calibration constants.

Table 4 - Calibration sample desired EC loading parameters

Minimum EC Fraction to Total [EC/(EC+OC)]	Target Soot Concentration[a] (µg/m^3)	No. of Tests – Accuracy Certificate[b]	No. of Tests – Annual Calibration [b,c]
0 (blank run)	0 (blank run)	6	3
0.8	50	6	0
0.8	100	6	3
0.8	250	0	3
0.8	500	6	3

[a] EC Concentration Range as determined by ASTM D6877 elemental carbon (EC) analysis. Flow rate and collection time length are to be determined by the operator for each run to obtain an EC filter loading of 12 µg/cm^2 ± 5 µg/cm^2. One pre-fired, quartz filter in a stainless-steel filter holder shall be used. Actual concentration shall be within 20% of target concentration with the nvPMmi averaging time being equal to filter collection time.

[b] For manually collected samples, at least one punch shall be analyzed from each quartz filter sample collected during each test run. The diameter of the filter deposit shall be large enough to allow at least one punch to be collected from each filter. Only the accuracy performance specification value in Table 3 is applied in the annual calibration.

[c] ICAO recommendation is to also run three tests at 50 µg/m^3 [see 2.1.3.14].

Table 5 - Recommended temperature profile for the ASTM D6877-13 method

Carrier Gas	Temp. (°C)	Time at Temp. (s)	Carbon Removal
100%He	310	80	OC1
	475	80	OC2
	615	80	OC3
	870	110	OC4
	550	45	
90%He+10%O_2	550	45	EC1
	625	45	EC2
	700	45	EC3
	775	45	EC4
	850	45	EC5
	870	60	EC6
	930	120	EC7
Calibration Gas + He/Ox	0	120	

6.4 Measurement Uncertainty

The performance specifications presented in Table 3 represent limits that can be verified with reasonable effort from a reference method. Furthermore, caution should be exercised if these are used to estimate measurement uncertainty, since each specification includes uncertainties in the reference method that may not need to be included multiple times in an uncertainty analysis.

7. PARTICLE NUMBER MEASUREMENT REQUIREMENTS

The particle number concentration shall be measured using a system consisting of a Volatile Particle Remover (VPR) and a Condensation Particle Counter (CPC). The goal of the system is to accurately quantify only non-volatile particles from the engine exhaust. The VPR shall include a diluter to reduce particle concentrations to within the single count range of the CPC, and a device for the removal of volatile species (e.g., Catalytic Stripper (CS) or equivalent) [see 2.1.3.13]. The system shall be connected to the sample line from Splitter2 as shown in Figure 4. As for the entire sampling system, all components in the particle number system shall be designed to minimize deposition/loss of particles. The particle sample shall not pass through a pump before entering the CPC.

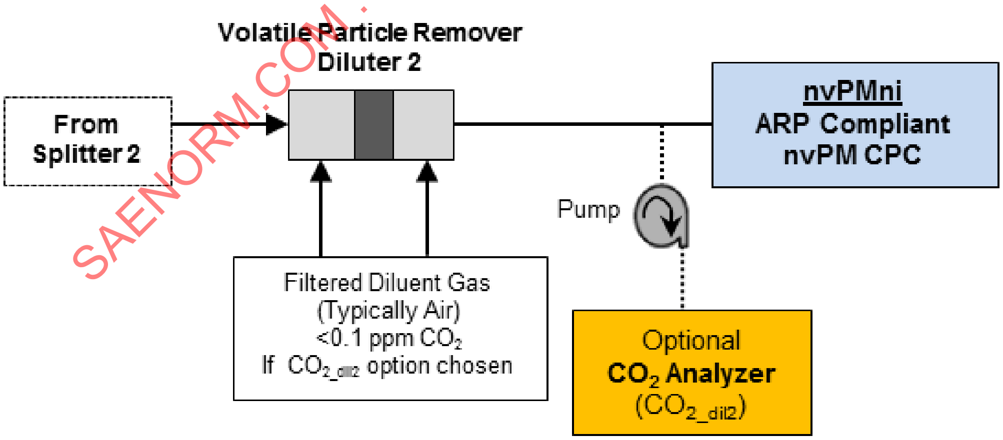


Figure 4 - Flow schematic of the particle number concentration measurement system

7.1 VPR Requirements

The VPR shall comply with the requirements listed in Table 6.

Table 6 - VPR requirements

Specification	System Requirement
Dilution	• Maintain particle number concentration within CPC single count mode and reduce sample temperature to between 283 to 308 K at CPC inlet. • Diluent shall be HEPA filtered. • Annual Calibration Certificate (as per A 6.1.2)
Non-volatile Particle Penetration	• Minimum allowed particle penetrations for each DF_2 setting: 30% - 15 nm, 55% - 30 nm, 65% - 50 nm, 70% - 100 nm • Annual Calibration Certificate (as per A 6.1.3)
Sample Pressure Control	Deliver diluted sample to CPC within ±15 kPa of ambient pressure (at CPC exhaust) not to exceed manufacturer maximum sample pressure specification.
Volatile Removal Efficiency	• >99.5% removal of 30 nm tetracontane (CH3(CH2)38CH3)>95% purity; particles with an inlet concentration ≥10000 particles/cm3 • Annual Calibration Certificate (as per A 6.1.4)
Heated Section	623 K
Volatile Removal Device	• With catalytic stripper: ○ Specify replacement interval. ○ Diluent must be air (10% minimum O_2 content) • No catalytic stripper: ○ Heated dilution temperature between 423 to 638 K ○ Total Dilution Factor >8
Heated Stages Control	Output signal to verify temperatures. Control to ±15 K of specified temperatures.

7.2 CPC Requirements

The CPC shall comply with the requirements listed in Table 7.

Table 7 - CPC requirements

Specification	System Requirement
Working Fluid	Reagent grade n-Butanol. Working fluid replaced at frequency per instrument manufacturer.
Sample Flow	The sample flow shall be full flow. No internal flow splitting is allowed.
Counting Accuracy	• ±10% from 2000 particles/cm^3 (or expected lower threshold) to the upper threshold of the single particle count mode against a traceable standard. • Annual Calibration Certificate (as per A 6.2)
Counting Efficiency	• ≥50% at 10 nm and ≥90% at 15 nm electrical mobility diameter using an Emery oil aerosol or equivalent. • Annual Calibration Certificate (as per A 6.2)
Coincidence Correction	Maximum of 10% correction shall be allowed. The coincidence correction function shall not use any algorithm to correct for or define the counting efficiency.
Resolution	>0.1 particles/cm^3 at concentrations <100 particles/cm^3
Response	• Linear response in single particle count mode range • Annual Calibration Certificate (as per A 6.2)
Counting Mode	Single count. Photometric mode not allowed.
Data Rate	≥1.0 Hz
$T_{10\text{-}90}$ Rise Time	<4.0 seconds
Particle Number Concentration	Reported at STP condition

7.3 VPR to CPC Interface

The tube connecting the VPR outlet to the inlet of the CPC shall meet the following requirements:

a. The material shall be electrically conductive.

b. The tube shall have an internal diameter greater than or equal to 4 mm.

c. The sample in the tube shall have a residence time less than or equal to 0.8 seconds.

If the reported concentration value is not at STP conditions, the CPC absolute inlet pressure shall be measured with an accuracy better than 2% so that the number concentration can be corrected to STP conditions following manufacturer's guidelines.

8. CALCULATION OF nvPM EMISSION INDICES

This procedure is used to calculate nvPM mass and number emission indices (EIs) for aircraft gas turbine engines burning hydrocarbon fuel in air. The example calculations below do not consider the size-dependent system loss corrections (up to a factor of ~2 and ~10 for particle mass and number respectively) that are required for the calculation of engine exit plane nvPM number and mass EIs. These correction factors are discussed in AIR6504.

Additional correction factors to account for fuel composition and ambient conditions may be required for accurate nvPM determination. The nvPM EI equations are derived based on the amount of nvPM in a control volume of exhaust sample normalized to the amount of fuel used to generate that sample. The amount of fuel used is derived from the CO_2, CO, and HC (as CH_4) emissions in the sample. Derivation of the equations is provided in the Appendix (A.7). This Section provides the complete and simplified mass and number nvPM EI equations and a calculation example. An nvPM EI calculator using these equations is also provided along with this ARP. Definitions for the parameters used are provided in Table 8.

Table 8 - Parameters used for nvPM EI calculations

Symbol	Unit	Definition
EI_{mass}	g/kg fuel	nvPM mass emission indices
EI_{num}	particles/kg fuel	nvPM number emission indices
α	None	Atomic hydrogen to carbon ratio (see typical values in Table 1 of ARP1533)
$[CO_2]$	Mole fraction	Mean concentration of CO_2 vol/vol in undiluted exhaust sample (wet basis)
$[CO_2]_s$	Mole fraction	Mean concentration of CO_2 vol/vol in undiluted exhaust sample (measured dry or semi-dry)
$[CO_2]_{dil1}$	Mole fraction	Mean concentration of CO_2 vol/vol after first dilution stage (wet basis)
$[CO_2]_{dil2}$	Mole fraction	Mean concentration of CO_2 vol/vol after second dilution stage (wet basis)
[CO]	Mole fraction	Mean undiluted vol/vol concentration of CO (wet basis)
[HC]	Mole fraction	Mean undiluted vol/vol concentration of hydrocarbon (wet basis) as CH_4.
[H2O]	Mole fraction	Mean water vol/vol concentration in undiluted exhaust sample
$nvPM_{mass\_STP}$	µg/m³	nvPM mass volumetric concentration measured after the first dilution stage at STP
$nvPM_{num\_STP}$	particles/cm³	nvPM number concentration measured after the second dilution stage at STP
k_{thermo}	None	Thermophoretic loss factor for measured nvPM mass and number concentrations
k_{SL_mass}[1]	None	System loss factor for measured nvPM mass concentration
k_{SL_num}[2]	None	System loss factor for measured nvPM number concentration
DF_1	None	Dilution factor of the first dilution stage
DF_{1_S}	None	Dilution factor of the first dilution stage calculated with $[CO_2]_s$ real time
DF_2	None	Dilution factor of the second dilution stage
BR	None	Engine bypass ratio = B/C, where B and C are mass flow rates for bypass and core
F_{mix}	None	Fraction of bypass air mixed with core flow air at the sampling probe plane
$F_{mass\_residual}$	None	Fraction of ambient nvPM mass surviving the core
$F_{num\_residual}$	None	Fraction of ambient nvPM number surviving the core
$[CO_2]_b$	Mole fraction	CO_2 concentration in ambient air at the engine inlet
$[HC]_b$	Mole fraction	Hydrocarbon concentration in ambient air at the engine inlet
$nvPM_{num\_b}$	particles/cm³	nvPM number concentration of ambient air at the engine inlet
$nvPM_{mass\_b}$	µg/m³	nvPM mass concentration of ambient air at the engine inlet
T_{EGT}	K	Engine performance-derived average exhaust exit gas temperature
T_1	K	Sample tube temperature at Diluter1 inlet, K

[1, 2] Note that these two values are set to 1 in the example calculations because size dependent system losses are not considered.

8.1 Complete nvPM EI Equations

The equations below calculate nvPM EI in mixed (core plus bypass) and non-mixed flow (core only) sampling. The complete nvPM EI equations include:

a. Full gaseous species (CO_2, CO, and HC) on a wet basis to calculate fuel burned. If species are not measured wet, they should be corrected using guidance in ARP1533.

b. Correction for thermophoretic particle loss (due to temperature reduction from probe tip to sampling line) derived using procedure in 4.4.1.

c. Corrections for ambient background residual (nvPM, CO_2 and HC).

d. nvPM system loss correction (estimated from AIR6504).

8.1.1 For Mixed Flow Sampling

$$EI_{mass} = \frac{22.4\times[\mathrm{nvPM}_{\mathrm{mass\_STP}}\times \mathrm{DF}_1 \times \mathrm{k}_{\mathrm{thermo}} \times \mathrm{k}_{\mathrm{SL\_mass}} - \mathrm{nvPM}_{\mathrm{mass\_b}} \times (\mathrm{BR}\times \mathrm{F}_{\mathrm{mix}} + \mathrm{F}_{\mathrm{mass\_residual}})/(\mathrm{BR}\times\mathrm{F}_{\mathrm{mix}}+1)]\times 10^{-6}}{\left([CO_2]_{dil1}\times DF_1 - [\mathrm{CO}_2]_{\mathrm{b}} + [CO] + [HC] - [HC]_b\right)\left(M_c + \alpha M_H\right)} \qquad \text{(Eq. 3)}$$

$$EI_{num} = \frac{22.4\times[\mathrm{nvPM}_{num\_\mathrm{STP}}\times \mathrm{DF}_1 \times \mathrm{DF}_2 \times \mathrm{k}_{\mathrm{thermo}} \times \mathrm{k}_{SL\_num} - \mathrm{nvPM}_{\mathrm{num\_b}} \times (\mathrm{BR\ x\ F}_{\mathrm{mix}} + \mathrm{F}_{\mathrm{num\_residual}})/(\mathrm{BR\ x\ F}_{\mathrm{mix}}+1)]\times 10^{6}}{\left([CO_2]_{dil1}\times DF_1 - [\mathrm{CO}_2]_{\mathrm{b}} + [CO] + [HC] - [HC]_b\right)\left(M_c + \alpha M_H\right)} \qquad \text{(Eq. 4)}$$

Where $DF_1 = [CO_2] / [CO_2]_{dil1}$ and $DF_2 = [CO_2]_{dil1} / [CO_2]_{dil2}$ or calibrated output per Diluter 2 setting.

8.1.2 For Non-Mixed Flow Sampling

The bypass ratio (BR) in Equations 3 and 4 is zero, which yields:

$$EI_{mass} = \frac{22.4\times(\mathrm{nvPM}_{\mathrm{mass\_STP}}\times \mathrm{DF}_1 \times \mathrm{k}_{\mathrm{thermo}} \times \mathrm{k}_{\mathrm{SL\_mass}} - \mathrm{nvPM}_{\mathrm{mass\_b}} \times \mathrm{F}_{\mathrm{mass\_residual}})\times 10^{-6}}{\left([CO_2]_{dil1}\times DF_1 - [\mathrm{CO}_2]_{\mathrm{b}} + [CO] + [HC] - [HC]_b\right)\left(M_c + \alpha M_H\right)} \qquad \text{(Eq. 5)}$$

$$EI_{num} = \frac{22.4\times(\mathrm{nvPM}_{num\_\mathrm{STP}}\times \mathrm{DF}_1 \times \mathrm{DF}_2 \times \mathrm{k}_{\mathrm{thermo}} \times \mathrm{k}_{\mathrm{SL}\_num} - \mathrm{nvPM}_{\mathrm{num\_b}} \times \mathrm{F}_{\mathrm{num\_residual}})\times 10^{6}}{\left([CO_2]_{dil1}\times DF_1 - [\mathrm{CO}_2]_{\mathrm{b}} + [CO] + [HC] - [HC]_b\right)\left(M_c + \alpha M_H\right)} \qquad \text{(Eq. 6)}$$

Where $DF_1 = [CO_2] / [CO_2]_{dil1}$ and $DF_2 = [CO_2]_{dil1} / [CO_2]_{dil2}$ or calibrated output per Diluter 2 setting.

8.2 Simplifications of nvPM EI Equations

The complete equations (Equations 3 to 6) can be simplified depending on the need and availability of data. The parameter settings for a limited number of cases are provided in Table 9. Two sets of example calculations with simplifications are given in 8.2.1 and 8.2.2.

Table 9 - Values of parameters in nvPM equations based on several simplified cases

Simplified Case	nvPM Equation Parameter Setting
System loss corrections not required	$k_{SL\_mass} = 1$, $k_{SL\_num} = 1$
Ambient HC is negligible	$[HC]_b = 0$
Ambient nvPM is negligible, not evaluated or not required	$PM_{mass\_b} = 0$, $PM_{num\_b} = 0$
Ambient nvPM is significant for bypass air and all survived through core	$F_{num\_residual} = F_{mass\_residual} = 1$
Ambient nvPM is significant for bypass air, but consumed in core flow	$F_{num\_residual} = F_{mass\_residual} = 0$
[CO] and [HC] are negligible or not measured	[CO] =0, [HC]=0
[CO], [HC] and [NO_x] not measured, not enough data to correct the measured undiluted $[CO_2]_s$ sample to wet basis	$DF_1 = DF_{1\_S}$

Notes:

- Simplifications can lead to different calculated EIs and should be reported. Special care should be taken not to compare EIs with and without system loss corrections.
- If any ambient nvPM survives the core combustion, setting $F_{num\_residual} = F_{mass\_residual} = 0$ will lead to a higher calculated nvPM EI. Users must estimate the $F_{num\_residual}$ and $F_{mass\_residual}$ on a case by case basis, depending on the chemical composition of ambient nvPM and the engine's core temperature.
- Setting [CO] and [HC] = 0 leads to slightly higher calculated nvPM EIs, especially for less efficient engine conditions (e.g., idle) or engines.

8.2.1 Full Gaseous nvPM EI Equations with No System Loss Correction

On a practical basis for turbine engine combustion, the contribution of ambient hydrocarbons and nvPM on emissions are often negligible ($[HC]b = 0$, $PM_{mass\_b} = 0$, $PM_{num\_b} = 0$). As noted previously, the example calculations in this ARP set $k_{SL\_mass} = k_{SL\_num} = 1$ to reflect that size dependent system losses (which depend on a number of parameters associated with the nvPM source and the sampling and measurement system) are not being considered. To calculate the engine exit plane EI values, these system losses must be considered using k_{SL_mass} and k_{SL_num} estimations from the methodology discussed in AIR6504.

Equations 7 and 8 should be used for nvPM EI mass and number calculations for both mixed-flow and non-mixed-flow sampling.

$$EI_{mass} = \frac{22.4 \times nvPM_{mass\_STP} \times 10^{-6}}{\left([CO_2]_{dil1} + \frac{1}{DF_1}\left([CO]-[CO_2]_b + [HC]\right)\right)\left(M_C + \alpha M_H\right)} \times k_{thermo} \qquad \text{(Eq. 7)}$$

$$EI_{num} = \frac{22.4 \times DF_2 \times nvPM_{num\_STP} \times 10^{6}}{\left([CO_2]_{dil1} + \frac{1}{DF_1}\left([CO]-[CO_2]_b + [HC]\right)\right)\left(M_C + \alpha M_H\right)} \times k_{thermo} \qquad \text{(Eq. 8)}$$

8.2.2 Simplified Gaseous nvPM EI Equations with No System Loss Correction

Since the combustion efficiencies of modern turbine engines are greater than 95%, it is reasonable to assume that all of the fuel carbon is converted to CO_2. nvPM and CO_2-only measurements could be used for determination of EI_{mass} and EI_{num} using the following simplified equations (based on same assumptions for Equations 7 and 8):

$$EI_{mass} \approx \frac{22.4 \times \mathrm{nv}PM_{mass\_STP} \times 10^{-6}}{([CO_2]_{dil1} - [\mathrm{CO}_2]_{\mathrm{b}} / DF_1) \times (M_c + \alpha M_H)} \times \mathrm{k}_{\mathrm{thermo}} \qquad \text{(Eq. 9)}$$

$$EI_{num} \approx \frac{22.4 \times \mathrm{nv}PM_{num\_STP} \times DF_2 \times 10^{6}}{([CO_2]_{dil1} - [\mathrm{CO}_2]_{\mathrm{b}} / DF_1)(M_c + \alpha M_H)} \times \mathrm{k}_{\mathrm{thermo}} \qquad \text{(Eq. 10)}$$

For modern engines, using Equations 9 and 10 result in a higher calculated EI_{mass} and EI_{num} of less than 0.1% for high power settings due to the high combustion efficiency, and less than 5% for idle conditions.

8.3 Examples of nvPM EI Calculation

The conditions: ambient nvPM and hydrocarbon concentrations are negligible ($[HC]_b = 0$; $nvPM_{mass\_b} = 0$; $nvPM_{num\_b} = 0$) and nvPM size dependent system loss corrections are not considered ($k_{SL\_mass} = 1$, $k_{SL\_num} = 1$).

The given parameters are:

$[CO_2]_{dry}$ = 26051ppm

$[CO]_{dry}$ = 1012 ppm

$[H_2O]$ = 0.0244

Total HC (wet) = [HC]= 117 ppm by C

$[CO_2]_b$ = 370ppm

DF_2 = 100

T_1 = 436 K

T_{EGT} = 678 K

$nvPM_{num\_STP} = 2.18 \times 10^3$ particles/cm^3

$nvPM_{mass\_STP}$ = 19 µg/m^3

$[CO_2]_{dil1}$= 2591 ppm = 0.002591 (wet basis)

α = 1.897 for a typical Jet A fuel

Converting $[CO_2]_{dry}$ to wet basis, $[CO_2] = [CO_2]_{dry} \times (1 - 0.0244)$, $[CO_2]$ = 25415 ppm

Converting $[CO]_{dry}$ to wet basis, $[CO] = [CO]_{dry} \times (1 - 0.0244)$, $[CO]$ = 987.3 ppm

$DF_1 = [CO_2] / [CO_2]_{dil1} = 25415/2591 = 9.809$

$DF_{1\_S} = [CO_2]_{dry} / [CO_2]_{dil1} = 26051/2591 = 10.05$

Substituting T_1, T_{EGT} in Equation 2 yields,

$$k_{thermo} = 1/\left(\frac{436}{678}\right)^{0.38} = 1.18$$

8.3.1 Full Gaseous nvPM EI with No System Loss Correction

The example provided below uses Equations 7 and 8.

For the nvPM mass EI calculation, substituting the given values into Equation 7 with all gaseous concentrations x 10^{-6}, to convert ppm to vol/vol values:

$$EI_{mass} = \frac{22.4 \times \mathrm{nvPM}_{\mathrm{mass\_STP}} \times 10^{-6}}{\left([\mathrm{CO}_2]_{\mathrm{dil1}} + \frac{1}{\mathrm{DF}_1}\left([\mathrm{CO}] - [\mathrm{CO}_2]_{\mathrm{b}} + [\mathrm{HC}]\right) \right) (\mathrm{M}_{\mathrm{C}} + \alpha \mathrm{M}_{\mathrm{H}})} \times \mathrm{k}_{\mathrm{thermo}}$$

$$= \frac{22.4 \times 19 \times 10^{-6}}{\left(2591 + \frac{1}{9.815} \times (987.9 - 370 + 117 \right) \times 10^{-6} \times (12.011 + 1.897 \times 1.008)} \times 1.18$$

$$= 0.0135\ g / kg\ fuel = 13.5\ mg / kg\ \ fuel$$

For nvPM number EI calculation, substituting the given values into Equation 8, with all gaseous concentrations x 10^{-6} to convert ppm to vol/vol values:

$$EI_{num} = \frac{22.4 \times \mathrm{DF}_2 \times \mathrm{nvPM}_{\mathrm{num\_STP}} \times 10^{6}}{\left([\mathrm{CO}_2]_{\mathrm{dil1}} + \frac{1}{\mathrm{DF}_1}\left([\mathrm{CO}] - [\mathrm{CO}_2]_{\mathrm{b}} + [\mathrm{HC}]\right) \right) (\mathrm{M}_{\mathrm{C}} + \alpha \mathrm{M}_{\mathrm{H}})} \times \mathrm{k}_{\mathrm{thermo}}$$

$$= \frac{22.4 \times 100 \times 2.18 \text{ x } 10^{3} \times 10^{6}}{\left(2591 + \frac{1}{9.815} \times (987.9 - 370 + 117 \right) \times 10^{-6} \times (12.011 + 1.897 \times 1.008)} \times 1.18$$

$$= 1.56 \times 10^{14}\ particles / kg\ fuel$$

8.3.2 Simplified Gaseous nvPM EI with No System Loss Correction

The example provided below uses Equations 9 and 10.

For nvPM mass EI calculation, substituting the given values into Equation 9, with all gaseous concentrations x 10^{-6}, to convert ppm to vol/vol values:

$$EI_{\mathrm{mass}} \approx \frac{22.4 \times \mathrm{nv}PM_{mass\_STP} \times 10^{-6}}{([CO_2]_{dil1} - [\mathrm{CO}_2]_{\mathrm{b}} / DF_1) \times (M_c + \alpha M_H)} \times \mathrm{k}_{\mathrm{thermo}}$$

$$= \frac{22.4 \times 19 \times 10^{-6}}{(2591 - 370 / 9.815) \times 10^{-6} \times (12.011 + 1.897 \times 1.008)} \times 1.18$$

$$= 0.0141\ g / kg\ fuel = 14.1\ mg / kg\ \ fuel$$

For nvPM number EI calculation, substituting the given values into Equation 10, with all gaseous concentrations x 10^{-6} to convert ppm to vol/vol values:

$$EI_{\mathrm{num}} \approx \frac{22.4 \times \mathrm{nv}PM_{num\_STP} \times DF_2 \times 10^{6}}{([CO_2]_{dil1} - [\mathrm{CO}_2]_{\mathrm{b}} / DF_1)(M_c + \alpha M_H)} \times \mathrm{k}_{\mathrm{thermo}}$$

$$= \frac{22.4 \times 2.18 \times 10^{3} \times 100 \times 10^{6}}{(2591 - 370 / 9.815) \times 10^{-6} \times (12.011 + 1.897 \times 1.008)} \times 1.18$$

$$= 1.62 \times 10^{14}\ particles / kg\ \ fuel$$

8.4 Reporting of nvPM EI

The calculated nvPM EI_{num} shall be reported in particles/kg fuel with three significant figures in scientific notation, and the EI_{mass} in mg/kg fuel with three significant figures and a maximum of one decimal point. The EI units for PM mass emissions are reported in mg/kg fuel, compared to g/kg fuel for gaseous emissions, to accommodate the relatively low PM emission values for modern engines. The examples above and the PM EI calculator show the EI units for PM mass emissions converted from g/kg fuel to mg/kg fuel.

When the measured nvPM mass and number concentrations are below the Leakage Check requirements as defined in A.4.3.2, the calculated EI shall be reported as "< System LOD".

The nvPM EI calculations in the examples in 8.3 did not account for size dependent system losses. It should be noted that these system losses will be significant and must be considered when calculating engine exit plane EI_{num} and EI_{mass} values. A methodology for estimating nvPM system losses and associated uncertainties is discussed in AIR6504 (see 2.1.1.7).

9. OPERATION OF nvPM SAMPLING AND MEASUREMENT SYSTEM

The operational procedures for the nvPM sampling and measurement system are outlined below.

A system operation checklist, attached to this ARP, includes detailed checklists to aid the system operator to comply with the ARP requirements. Note that these checklists provide guidance to meet ARP specifications; however, system and/or instrument operation guidance provided by the manufacturer takes precedence and shall always be followed.

9.1 Calibration and Maintenance

All instruments shall be maintained conforming to the manufacturer's guidelines.

9.1.1 The nvPM Sampling System and Make-up Flow

The following nvPM sampling system and make-up flow components shall be calibrated and maintained as follows:

a. The cyclone separator collection reservoir shall be emptied and cleaned on an annual basis.

b. Make-up flow controller and inlet flow rates for nvPMmi, nvPMni, VPR shall be calibrated by a NMI-traceable flow meter on an annual basis. All calibrated flow rates should be within 5% FS.

c. Pressure transducers shall be calibrated by a NMI-traceable pressure transducer on an annual basis. All calibrated pressure measurements should be within 2% FS.

d. Over long time usage (typically >1 year but could be less depending on nvPM loading), DF_1 will increase compared to an initial value. When DF_1 approaches the upper range limit (14), clean Diluter1 as per manufacturer guidelines. As a minimum, Diluter1 sample inlet orifice nozzle shall be cleaned.

e. To indicate if Diluter1 sample inlet orifice nozzle is becoming blocked and/or to help ensure Diluter1 dilution factor operability at low power engine conditions, when probe inlet pressure is low, or when a different probe is utilized; an operational check may be performed prior to the engine test series using the procedure described in A.4.7 of the Appendix.

f. An additional system flow check prior to an engine test series can be performed to ensure the nvPM sampling and measurement system operates correctly during an engine test. Disconnect Section 3 from Section 2 and place a flow meter at Section 3 inlet to verify that the flow is within 25 slpm ± 2 slpm, while ensuring flow rates in each Splitter2 flow path are equal to those to be used during engine test. A measurement of sample pressure drop through Sections 3 and 4 during this check can be used to help flow validation during an engine test.

9.1.2 nvPMmi

The nvPMmi shall be annually calibrated by a competent laboratory to meet the calibration requirements prescribed in 6.3.

The nvPMmi shall demonstrate compliance to performance specifications listed in Table 3 by the instrument manufacturer or competent laboratory after any hardware or software changes to the nvPMmi which affects data acquisition and processing.

9.1.3 VPR

The VPR shall be annually calibrated by a competent laboratory to meet the requirements prescribed in 7.1. If the VPR contains a catalytic stripper, its replacement interval shall meet the manufacturer guidelines.

The VPR shall demonstrate compliance to performance specifications listed in 7.1 by the instrument manufacturer or competent laboratory after any hardware or software changes to the nvPMmi which affects data acquisition and processing.

9.1.4 nvPMni (CPC)

The CPC shall be annually calibrated by a competent laboratory to meet the calibration requirements prescribed in 7.2. The CPC working fluid shall be n-butanol and shall be replaced following the manufacturer guidelines (typically on a monthly basis). The wick shall be replaced following manufacturer guidelines.

The CPC shall demonstrate compliance to performance specifications listed in 7.2 by the instrument manufacturer or competent laboratory after any hardware or software changes to the nvPMmi which affects data acquisition and processing.

9.1.5 Gas Analyzers

Calibration of the gas analyzers shall follow ARP1256 procedures.

The CO_2 impurity concentration of the zero calibration gas for the CO_2 analyzer downstream of Diluter1 shall be less than 10 ppm. Note this impurity specification for the CO_2 analyzer downstream of Diluter1 is different than ARP1256.

The diluent for Diluter1 could be the same as the zero calibration gas used for the CO_2 analyzer because the CO_2 impurity criteria are the same.

9.2 Engine Test Series Operation

9.2.1 Prior to an Engine Test Series

Pre-test checks for the Collection Part and Transfer Part cleanliness and leakage, and VPR dilution factor (DF_2) shall be performed using the procedures described in A.4.2, A.4.3, and A.4.6 of the Appendix. The Collection Part and GL cleanliness check are not required if performing the simplified nvPM EI method.

9.2.2 During an Engine Test Series

If any component or section of the nvPM sampling system is new, cleaned since last use or used previously for a purpose other than sampling engine exhaust, then the nvPM sampling system shall sample aircraft engine exhaust for a minimum of 30 minutes at any engine power condition prior to obtaining nvPM measurements. Note that removal of soot blockage in the Diluter1 orifice does not constitute a cleaning process.

For gaseous measurements on the GL and downstream of Diluter1:

a. Apply appropriate zero calibration gas and make any necessary instrument adjustments.

b. Apply appropriate calibration gas at a nominal 90% FS concentration to span the ranges to be used, adjust and record gain settings accordingly.

The nvPM concentration measurements shall only be taken after all instruments and sample transfer lines are warmed up and stable (typically 1 hour).

The nvPMmi manufacturer recommended operability checks shall be performed

For nvPM number measurements, the following requirements shall be met:

a. The VPR heated stage is at 623 K ± 15 K (350 °C ± 15 °C).

b. If a catalytic stripper is used in the VPR, the diluent shall contain at least 10% of O_2.

c. The nvPMni working fluid is at the level required by the manufacturer.

d. The nvPMni saturator and the condenser have reached correct operating temperatures.

e. The nvPMni manufacturer-recommended operability checks shall be performed.

Ambient nvPM measurements shall be performed at the beginning and end of an engine test using the procedures described in A.4.5 of the Appendix. The ambient measurement also serves as an operational nvPMni response check.

Section 1 back-purging, as described in A.4.4 of the Appendix, should occur during engine start-up and shut down.

Gaseous analyzer zero and calibration span points shall be rechecked at the end of the test and also at intervals not greater than 1 hour during tests. If either has changed by more than ±2% of FS range, that portion of the test should be rerun.

During engine nvPM measurements, the following requirements shall be met:

a. If P_1 is at sub-atmospheric pressure, the P_1 Pressure Control Valve shall be closed; and if installed, the optional shut-off valve shall be closed.

b. Both the GL CO_2 concentration and the CO_2 concentration downstream of Diluter1, $[CO_2]_{dil1}$, shall be continuously measured and used for validating and controlling DF_1 in real time (DF_{1_S}) to within the range 8 to14. DF_{1_S} is defined as:

$$DF_{1\_S}=\frac{[CO_2]_S}{[CO_2]_{dil1}}$$

The calculation of DF_{1_S} does not require the CO_2 concentration on a wet basis.

The sample flow rate of 25 slpm ± 2 slpm in Section 3 shall be monitored by summation of the make-up flow and the inlet flow rates of the nvPMmi and the VPR. Note that flow validation can also be achieved by maintaining the same sample line pressure drop for the 25 slpm flow condition.

When the engine operation and measured nvPM mass and number, CO_2 and diluted CO_2 concentrations are stable at the required thrust setting, a minimum of 30 seconds of data shall be averaged and recorded.

If the nvPMmi lacks a sample pressure measurement, the pressure shall be measured at a location between the Splitter2 outlet and the make-up flow inlet, and recorded.

If the nvPMni lacks a sample pressure measurement, the pressure shall be measured at a location between the VPR outlet and nvPMni inlet, and recorded.

It is recommended that the parameters listed in Table 10 be reported during the test. In addition, all parameters used for calculating particle size-dependent transport losses (Table A2 in the Appendix) need to be reported.

If a more precise fuel analysis is performed, re-calculate EI_{mass} and EI_{num} with known fuel parameters.

It is recommended that the cleanliness test and average pre- and post-test readings of the ambient air are reported with its corresponding two standard deviation (2σ) variation.

Table 10 - nvPM measured parameters reported during engine tests

Parameter	Unit
Section 2 Inlet pressure	mbar
Diluent pressure	Bar
Diluter1 inlet Temperature	K
2σ Diluter1 inlet Temperature	K
Diluter1 exit temperature	K
Section 3 temperature	K
Section 4 cyclone separator temperature	K
Section 4 mass line temperature	K
Section 4 number line temperature	K
GL temperature	K
Mass analyzer flow rate	slpm
VPR analyzer flow rate	slpm
Makeup flow rate	slpm
Section 3 total flow rate	slpm
GL flow rate	slpm
Raw CO_2 concentration	%
2σ raw CO_2 concentration	%
Diluted CO_2 concentration	ppm
2σ diluted CO_2 concentration	ppm
DF_{1_s}	-
DF_1	-
DF_2	-
nvPM mass concentration ($nvPM_{mass\_STP}$)	$\mu g/m^3$
2σ nvPM mass concentration	$\mu g/m^3$
nvPM number concentration ($nvPM_{num\_STP}$)	particles/cm^3
2σ nvPM number concentration	particles/cm^3
Mass analyzer sample temperature	K
Mass analyzer sample pressure	Bar
Number analyzer sample temperature	K
Number analyzer sample pressure	Bar
EI mass	g/kg fuel
2σ EI Mass	g/kg fuel
EI Number	particles/kg fuel
2σ EI Number	particles/kg fuel
Average pre- and post-test ambient air particle mass concentration	$\mu g/m^3$
2σ ambient particle mass concentration	$\mu g/m^3$
Average pre- and post-test ambient air particle number concentration	particles/cm^3
2σ ambient particle number concentration	particles/cm^3
Cleanliness test – particle mass concentration	$\mu g/m^3$
2σ cleanliness particle mass concentration	$\mu g/m^3$
Cleanliness test – particle number concentration	particles/cm^3
2σ cleanliness particle number concentration	particles/cm^3

10. NOTES

10.1 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE SUBCOMMITTEE E-31P, PARTICULATE MATTER OF
COMMITTEE E-31, AIRCRAFT ENGINE GAS AND PARTICULATE

APPENDIX A

The Appendix provides information on the nvPM measurement system that was only briefly discussed in the main body of the ARP. Information covered herein includes: specifications of system components, system/instrumentation standard operating procedures (SOP), PM mass and number instrumentation calibration guidelines, brief discussions on calculations of sampling system line losses, derivation of EI equations and uncertainty analysis, and other supplementary information to help the user build, operate and maintain the nvPM sampling and measurement system. The Appendix is divided into the following Sections:

- A.1 nvPM Sampling and Measurement System Flowchart
- A.2 nvPM Sampling System Best Practices
- A.3 nvPM Sampling System Particle Transport Losses
- A.4 Procedures for System Operation
- A.5 Particle Mass Concentration Measurement
- A.6 Particle Number Concentration Measurement
- A.7 nvPM EI and Uncertainty Calculations

A.1 NON-VOLATILE PM SAMPLING AND MEASUREMENT SYSTEM FLOWCHART

The flowchart in Figure A1 displays the main sections and components of the non-volatile PM sampling and measurement system.

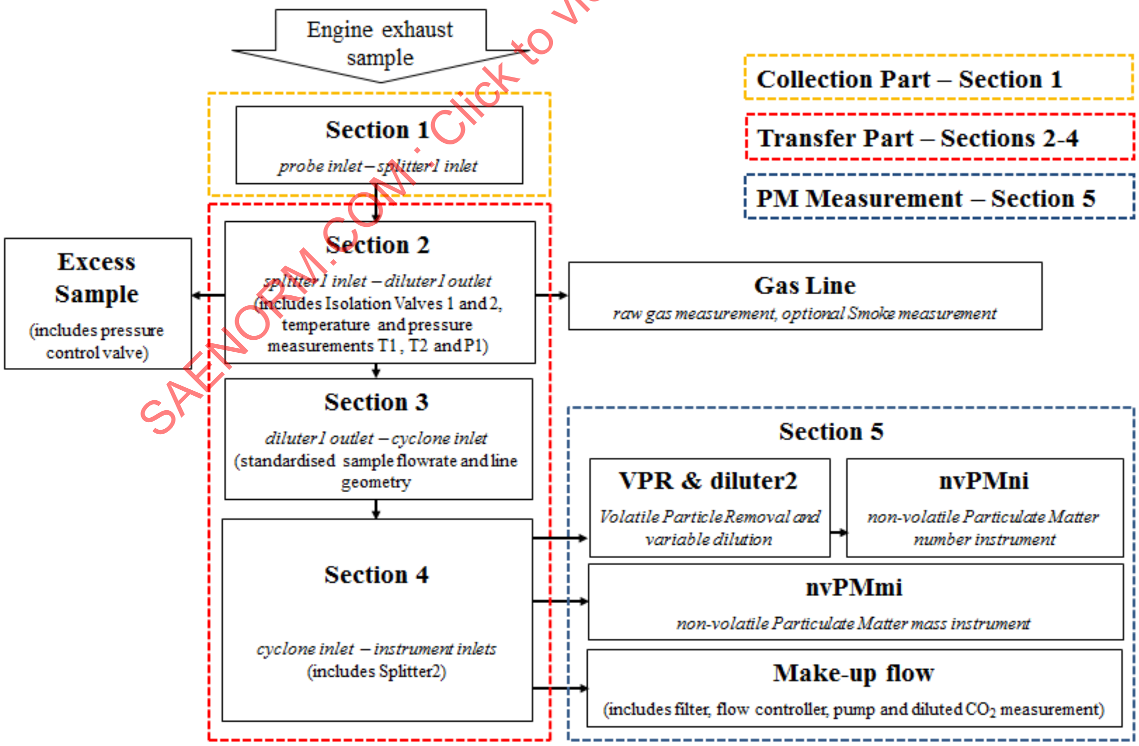


Figure A1 - Flowchart of the non-volatile PM measurement system

A.2 nvPM SAMPLING SYSTEM BEST PRACTICES

A.2.1 Splitter Design

Figures A2 and A3 show examples of splitter geometries and assemblies that meet the requirements and are acceptable for use. Note that there are many other possible geometries and assemblies that could meet the requirements and could be acceptable for use. Splitter design is not based upon hydraulic flow considerations but on the desire for standardization between sampling systems.

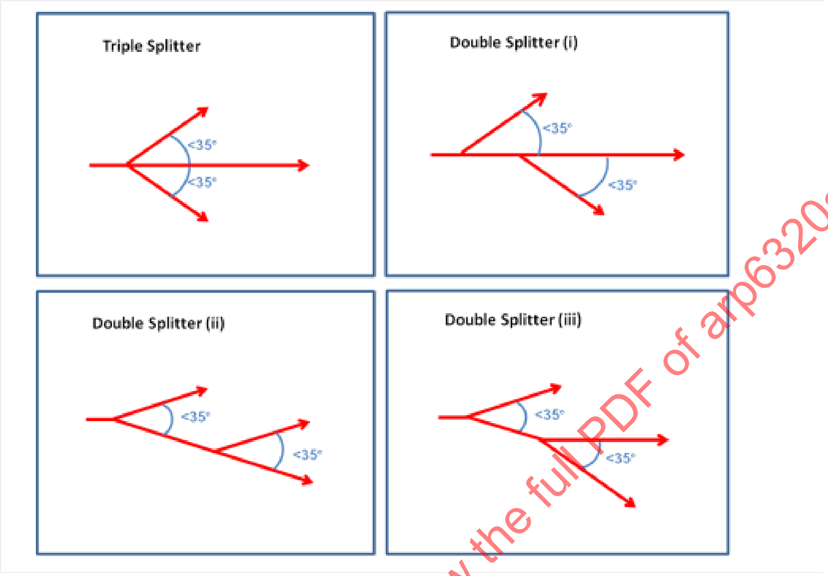
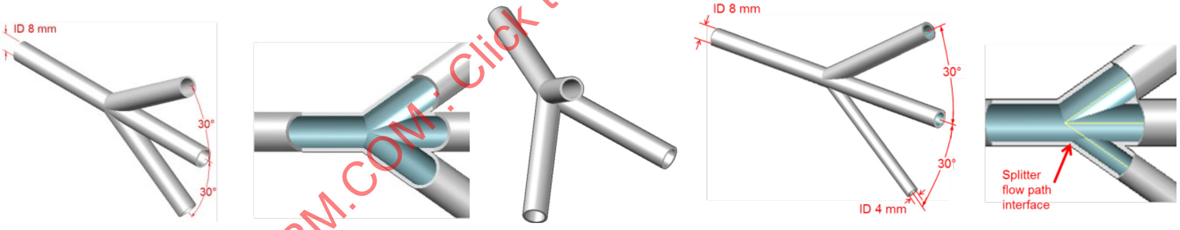


Figure A2 - Schematic examples of splitter geometries



(a) (b) (c)

Figure A3 - Example of triple splitter geometry as (a) single plane, (b) multi-plane; and (c) line diameter change

A.2.2 Sections 1 through 4 Sample Line Thermal Connection Requirements

Best practice shall be to heat throughout the union connection interface. If this is not practical, as a minimum, the sample line shall be isolated from the interface surface and heated up to within 5 cm of the interface surface and thermally insulated throughout. An example is shown in Figure A4. If required, bulkhead fittings shall only occur at the interfaces between Sections and where required within Section 4.

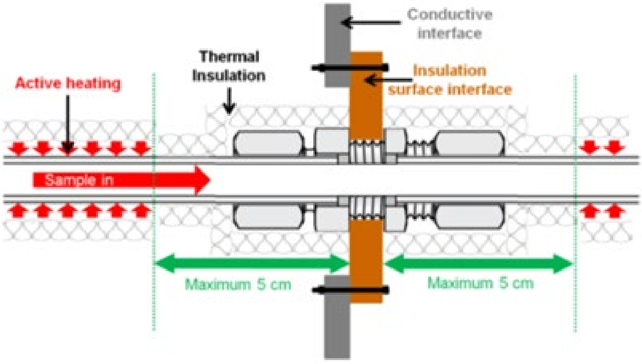


Figure A4 - Example of bulkhead union interface heating

Other connection fittings within Sections 1 through 4 shall be heated across the connection where possible. If this is not practical, the sample line shall be heated up to within 5 cm of the next heated section, and thermally insulated in between as shown in Figure A5.

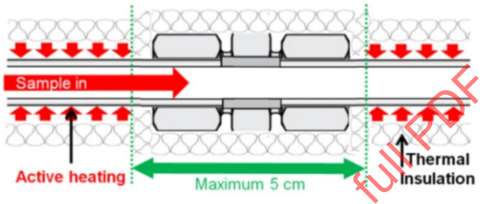


Figure A5 - Example of sample line connection heating

A.2.3 Section 3 Flow Rate Control

Figure A6 shows an example of two flow controllers installed in the Make-up flow line to provide Section 3 system flow control. In the figure, Section 3 flowrate of 25 slpm is the sum of the nvPMmi (4 slpm), VPR (4 slpm), Primary Pump Flow Controller (14 slpm) and CO_2 Pump Flow Controller (3 slpm).

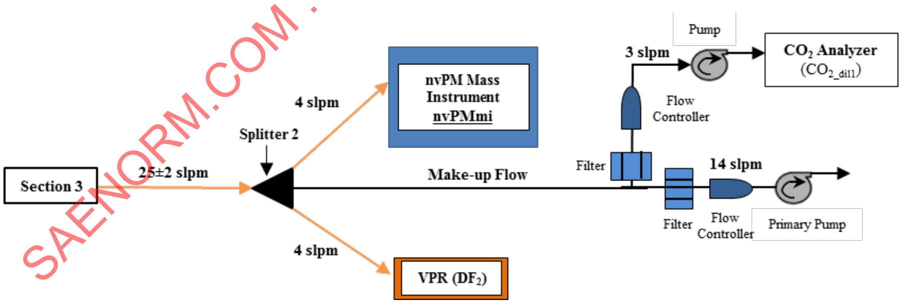


Figure A6 - Example of system flow rates that ensure Section 3 flow rate satisfies 25 slpm ± 2 slpm

A.2.4 Make-Up Flow Sampling Configuration

It is recommended that HEPA filters be placed upstream of flow controllers to prevent damage to components.

A.2.4.1 CO_2 Analyzer Sampling Configuration

For the [CO_{2_dil1}] sampling, there are multiple approaches using several flow controllers and pumps. Figure A7 shows possible examples of sampling layout options for performing nvPM sampling system flow control and [CO_{2_dil1}] measurement for determination of the first stage dilution factor DF_1.

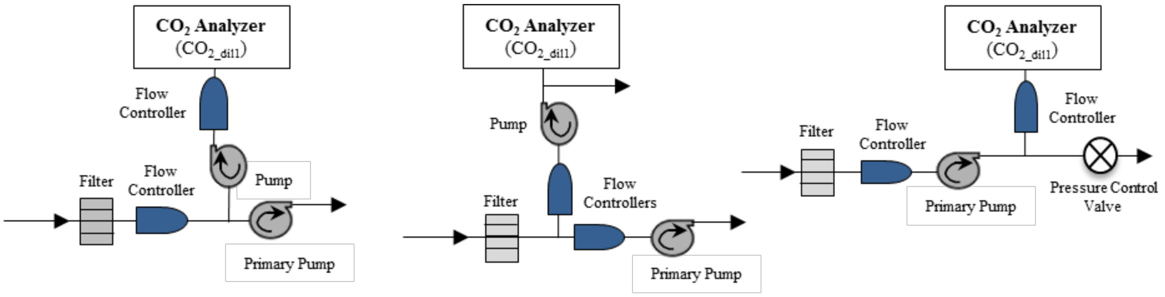


Figure A7 - Examples of sampling layout for nvPM sampling system flow control at first stage dilution measurement

A.3 nvPM SAMPLING SYSTEM PARTICLE TRANSPORT LOSSES

Reporting of parameters in Table A2 is needed for size-dependent particle loss calculation.

Table A2 - System parameters required to calculate particle size-dependent transport losses

Parameter	Unit
Probe inlet temperature (Equivalent to performance-predicted engine exit exhaust gas temperature T_{EGT})	K
Measured Diluter1 inlet temperature (T_1)	K
Individual flow rates (Measured Sections 3 and 4; Practical estimation Section 1, Section 2)	slpm
Individual pipe inner diameters for Sections 1 to 4	cm
Individual lengths for Sections 1 to 4	cm
Individual pipe wall temperatures for Sections 1 to 4	K
Total angle of sampling tube bend(s) for Sections 1 to 4 and flexible tubing in Section 5	degrees
Cyclone Separator D_{50} cutpoint (Manufacturer Specification)	nm
Cyclone Separator sharpness (Manufacturer Specification)	decimal fraction
Diluter1 four penetration fractions (Table 2)	decimal fraction
VPR calibration four penetration values (Table 6)	decimal fraction
CPC calibration two counting efficiencies	decimal fraction
First stage dilution factor, DF_1	
Second stage (VPR) dilution factor, DF_2	
Measured nvPM mass concentration ($nvPM_{massSTP}$)	$\mu g/m^3$
Measured nvPM number concentration ($nvPM_{numSTP}$)	particles/cm^3

A.4 PROCEDURES FOR SYSTEM OPERATION

A.4.1 Collection Part and Gas Line (GL) Leakage Check

A.4.1.1 Leakage Check Procedure

Prior to an engine test series, the Collection Part and the GL shall be checked for leakage using ARP1256 methodology. This can be performed by:

a. Isolate the GL from the nvPM Measurement Part using the Isolation Valve 1, the P_1 Pressure Control Valve and, if installed, the optional shut-off valve.

b. Isolate the probe and the analyzer.

c. Connect and operate a vacuum pump to verify the leakage flow rate.

d. The vacuum pump shall have a no-flow vacuum capability of –75 kPa with respect to atmospheric pressure; its full-flow rate shall not be less than 26 slpm.

Figure A8 shows the sample flow path for this check.

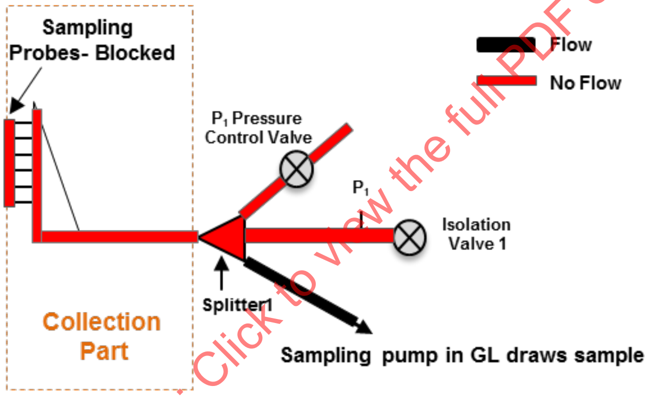


Figure A8 - Flow schematic for collection part and GL leak check

A.4.1.2 Leakage Check Requirement

The leakage flow rate shall be satisfactorily if less than 0.4 slpm (no more than 2 standard liters pass in a 5 minute period).

A.4.2 Collection Part and Gas Line Cleanliness Check

This check is only performed if using the full gaseous nvPM EI calculation method.

A.4.2.1 Cleanliness Check Procedure

The Collection Part and GL shall be checked for cleanliness using the following procedure:

a. Isolate the GL from the nvPM Measurement Part using Isolation Valve 1 and the P_1 Pressure Control Valve.

b. Isolate the GL from the probe and connect the end of the sampling line to a source of zero gas.

c. Warm the system up to the operational temperature needed to perform hydrocarbon measurements.

d. Operate the sample flow pump and set the flow rate to that used during engine emission testing.

e. Record the hydrocarbon analyzer reading.

A.4.2.2 Cleanliness Check Requirement

The hydrocarbon reading shall not exceed 1% of the engine idle emission level or 1 ppm (both expressed as carbon), whichever is the greater.

It is recommended to monitor the inlet air quality at the start and end of an engine test and at least once per hour during a test. If HC levels are considered significant, then they should be taken into account.

A.4.3 Transfer Part Cleanliness/Leakage Check

Cleanliness checks can fail due to contaminated Transfer Part components or leaks in the Transfer and/or Measurement Parts. A system leakage will result in ambient air particles drawn into the system.

A.4.3.1 Cleanliness/Leakage Check Procedure

Prior to an engine test series, the Transfer Part shall be checked for cleanliness and leaks using the following procedure:

a. Flow HEPA-filtered diluent through Diluter1 with the Isolation Valve 1 closed.

b. The flow rates in each Splitter2 path shall be equal to those used during engine testing.

c. Set the DF_2 to the lowest setting of the VPR.

When the measured nvPM mass and number concentrations are stable, record data for a minimum of 30 seconds. The flow schematic for the Transfer Part cleanliness check is shown in Figure A9.

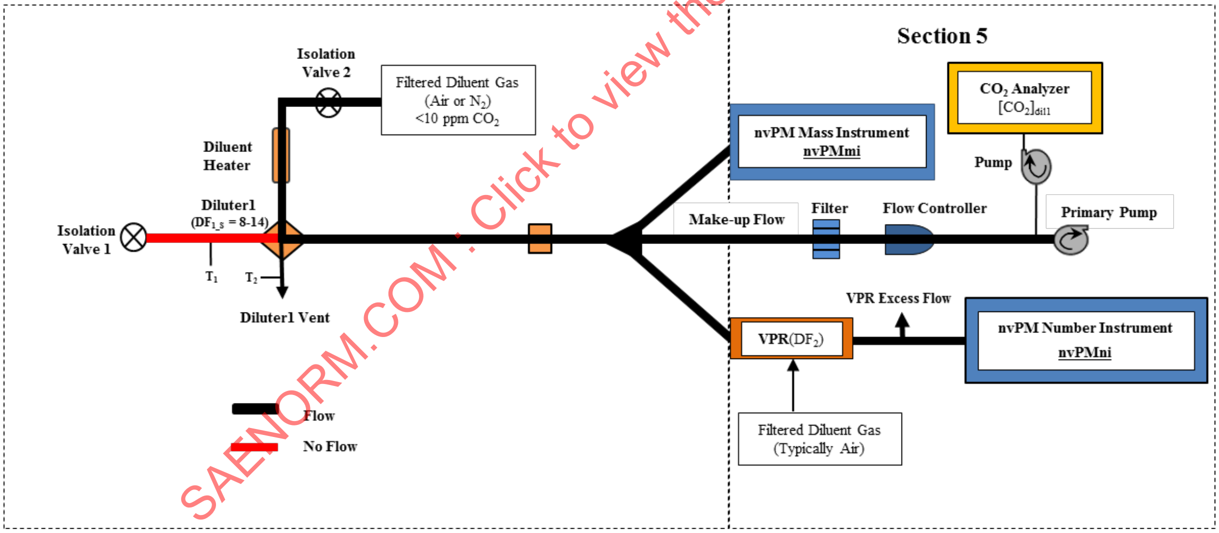


Figure A9 - Flow schematic for the transfer part cleanliness check

A.4.3.2 Cleanliness/Leakage Check Requirement

The 30 seconds averaged nvPM mass concentration ($nvPM_{mass\_STP}$) shall be less than 1 µg/m^3 and the 30 seconds averaged CPC nvPM number concentration ($nvPM_{num\_STP}$) shall be less than 2.0 particles/cm^3.

If the cleanliness check fails, the system should be first inspected for leakage. If no leaks are detected, the cyclone separator collection reservoir should be inspected and cleaned. If the cleanliness check still fails, segments of the sampling system may need cleaning or replacement.

A.4.4 Collection Part Back-Purging

In order to maintain the Section 1 sampling probes and lines clear of unburned fuel, Section 1 shall be back-purged during engine start-up and shutdown as depicted in Figure A10.

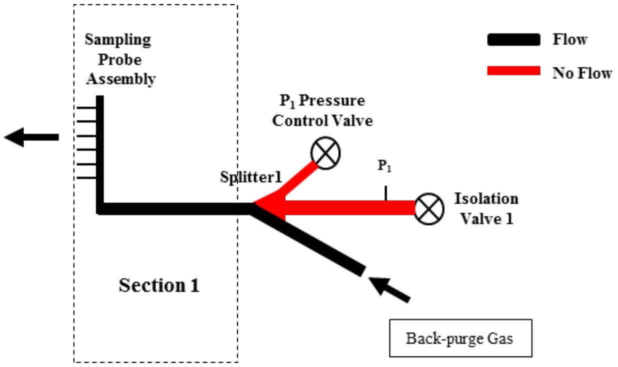


Figure A10 - Flow schematic for Section 1 back-purge

A.4.5 Ambient nvPM Measurement

Ambient nvPM mass and number concentrations representative of engine air inlet shall be obtained before and after an engine test and reported as the average of these two measurements.

For an enclosed test cell, to achieve representativeness it is recommended that the ambient particle measurements are obtained while the engine is running. The first ambient measurement should be obtained a minimum of 5 minutes after engine start-up.

A.4.5.1 Ambient nvPM Sampling Procedure

The ambient nvPM mass and number concentrations representative of engine air inlet shall be sampled by either Method 1 or 2 as described below.

1. Method 1 - Sampling through Diluter1 vent

The nvPM Sampling and Measurement system shall be used to sample through Diluter1 vent.

When sampling through the Diluter1 vent the following procedure shall be used:

a. Turn off the diluent flow supply to Diluter1 by closing Isolation Valve 2 and ensure that the Isolation Valve 1 is closed.

b. The diluent heater should be protected from overheating when the diluent flow is turned off.

c. Ensure flow rates in each Splitter2 flow path are equal to those to be used during engine testing.

d. When the measured nvPM mass and number concentrations are stable, record data for a minimum of 3 minutes.

The flow schematic for the Method 1 ambient nvPM measurement in shown in Figure A11. This setup shall only be used if the vent exhaust location is representative of engine inlet air.

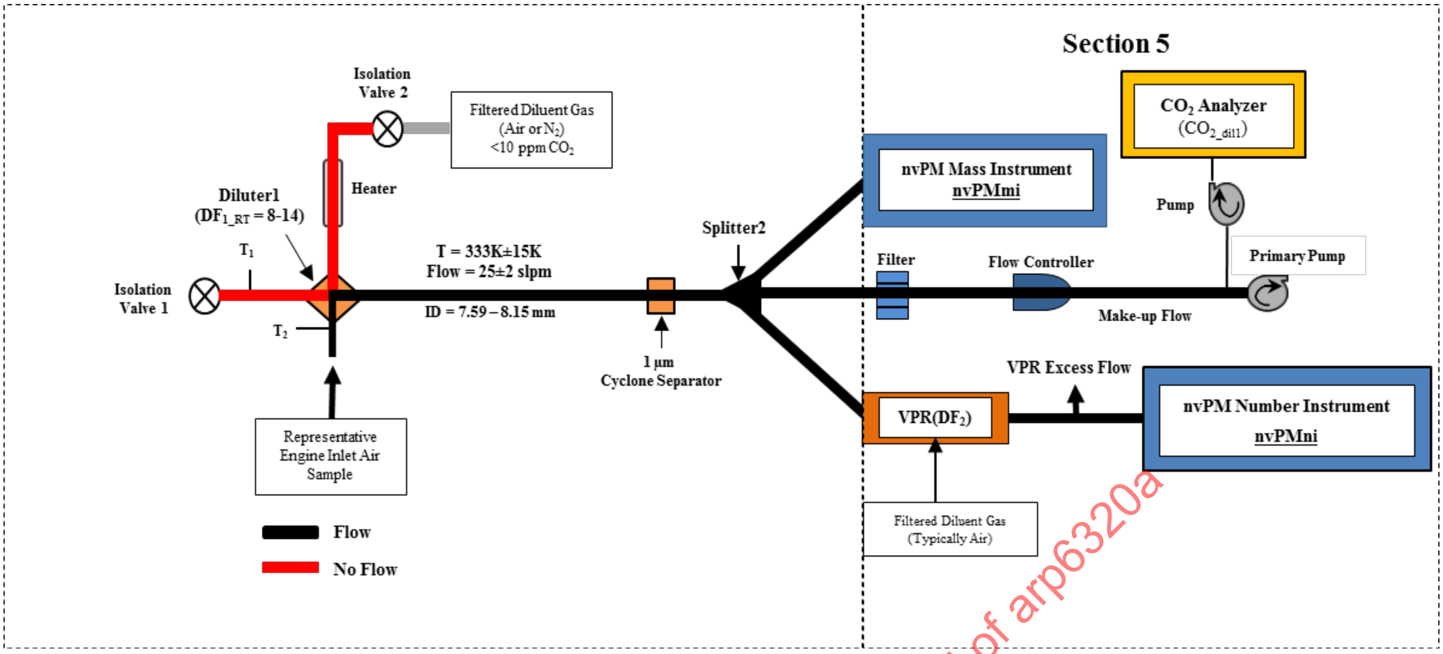


Figure A1 - 1 Flow schematic for ambient particle air measurement

2. Method 2 – An additional nvPM measurement system

An additional ambient nvPM sampling and measurement system shall meet the following requirements:

a. The ambient nvPM sampling system shall conform to Sections 4 and 5 sampling system requirements in this ARP.

b. The nvPMmi, VPR and nvPMni shall comply with Sections 7 and 8 of this ARP.

c. The ambient nvPM sampling system inlet shall be located within 50 m of the engine intake plane.

When sampling with an additional nvPM sampling and measurement system, the following procedure shall be used:

a. Ensure flow rates in each Splitter2 path are equal to those to be used during engine testing.

b. When the measured nvPM mass and number concentrations are stable, record data for a minimum of 3 minutes.

A.4.5.2 Ambient nvPM Measurement Requirement

The 3 minutes averaged nvPM mass concentration ($nvPM_{mass\_STP}$) and nvPM number concentration corrected for DF$_2$ ($DF_2 \times nvPM_{num\_STP}$) shall be reported. Note the ambient level of nvPM mass concentration may be below the LOD of the nvPMmi.

The average nvPMni concentration value corrected for DF$_2$ should be greater than 10 times the value measured for the cleanliness check. If this check fails, the system operation should be verified (valve positions, flow rates, pressures, and temperatures) and the measurement should be repeated.

If ambient nvPM levels are considered significant, then they should be taken into account for the calculation of PM EIs as discussed in A8.1.

A.4.6 VPR Dilution Factor (DF_2) Check

The VPR dilution factor (DF_2), anticipated during the engine test, shall be checked using either:

1. Method 1 – Off-line operational VPR dilution checks of the DF_2 values from a Competent Laboratory

   A CO_2 gas analyzer and a test gas of appropriate CO_2 concentration with ≤1% uncertainty are needed. The test gas shall be either a high concentration CO_2 gas (greater than 99.0%) or a blended CO_2 gas with either nitrogen or zero air as acceptable diluents. The CO_2 analyzer shall meet ARP1256 performance specifications with an appropriate total range. The analyzers used to measure $[CO_2]_s$ or $[CO_2]_{dil1}$ are considered to be suitable for this purpose. The test gas CO_2 concentration(s) should be selected such that the anticipated diluted CO_2 value for the VPR dilution setting(s) to be evaluated, falls within the working range of the analyzer to be used.

   a. Connect the CO_2 gas analyzer to the outlet of the VPR with a tee fitting to prevent over pressurization of CO_2 sample. The flow schematic for the VPR dilution factor check is shown in Figure A12

   b. Connect the high concentration CO_2 gas to the inlet of the VPR using a tee fitting and flow control valve to provide a VPR inlet pressure as on engine test.

   c. Allow the sample at the inlet of the VPR to have the same flow rate, and pressure as used during an engine test using a valve upstream of the VPR inlet.

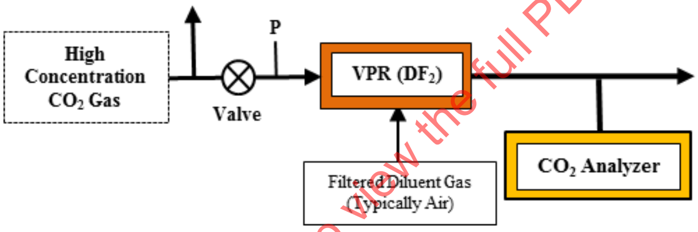


Figure A12 - VPR dilution factor check setup

The VPR dilution factor (DF_2) shall be checked using the following procedure:

a. Warm-up the VPR and ensure operating temperatures are reached.

b. Check that the VPR inlet is pulling a sample flow.

c. Warm-up the CO_2 analyzer accordingly and prepare for data logging.

d. Apply appropriate zero calibration gas to the CO_2 analyzer and make any necessary instrument adjustments.

e. Apply appropriate calibration gas at a nominal 90% FS concentration to the CO_2 analyzer to span the ranges to be used, adjust and record gain settings accordingly.

f. Ensure the sample flow to the CO_2 analyzer is adequate (typically 1 to 2 slpm, a pump may be required upstream of the CO_2 analyzer).

g. Flow the high concentration CO_2 gas to the inlet of the VPR, ensuring that there is excess flow at the vent upstream of the VPR inlet.

h. Set the VPR to a dilution factor setting.

i. Adjust the flow control valve at the VPR inlet, creating a pressure drop to simulate a typical sub-ambient sample pressure at the VPR inlet during an engine test nvPMni measurement operation.

j. Sample the VPR diluted exhaust flow with the CO_2 gas analyzer.

k. When the CO_2 gas analyzer reading is stable, record 1 Hz CO_2 concentration data points within a 3 minute period and calculate the mean.

l. Calculate the mean DF_2 value as a ratio of the mean of CO_2 measurements and the certified CO_2 gas concentration.

m. Repeat steps h) to l) for each VPR dilution setting to be used during engine testing.

n. Calculated DF_2 mean values shall be compared against the results of a Competent Laboratory calibration. If the difference is:

   (1) less than or equal to ±10%, DF_2 values from a Competent Laboratory calibration shall be used.

   (2) greater than ±10%, the real time $[CO_2]_{dil2}$ measured values shall be used for the DF_2 calculation.

2. Method 2 – Real time measurements

An alternative to performing the operational VPR dilution checks of the DF_2 values from a Competent Laboratory is using real time measurements of CO_2 at the CPC inlet downstream of the second stage dilution, $[CO_2]_{dil2}$, as shown in Figure A13. Using this method eliminates the need for dilution factor operational checks pre- and post-engine test series.

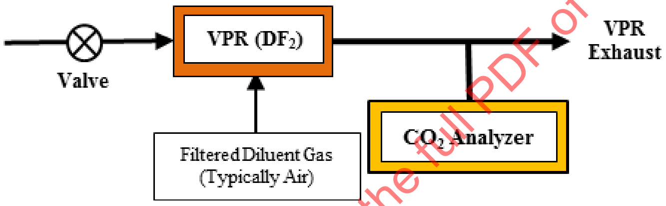


Figure A13 - Alternative setup (Method 2) to determine DF_2

CO_2 measurement capability for concentration levels as low as 5 ppm is needed for this procedure. The suitable range for the CO_2 analyzer is typically 30 to 70 ppm FS. Ideally, the measured sample gas concentrations should be in the 20 to 95% FS range. If this alternative method is performed, the VPR diluent gas shall contain less than 0.1 ppm of CO_2. The measured gas sample does not need to be dried.

During an engine test, DF_2 as calculated below should be used to check if the VPR meets the calibration DF_2 values provided by the Competent Laboratory within 10%. If greater than ±10, the real time $[CO_2]_{dil2}$ measured values shall be used for the DF_2 calculation.

$$DF_2 = \frac{[CO_2]_{dil1}}{[CO_2]_{dil2}}$$

A.4.7 Diluter1 Operability

To help ensure Diluter1 operability at low power engine conditions, when probe inlet pressure is low, an optional operational check may be performed prior to an engine test series using the following recommended procedure:

- CO_2 calibration gas containing between 3 to 5% CO_2 should be connected to the sampling probe such that it enters Section 1 at near ambient pressure.
- The nvPM sampling and measurement system should be operated at the flow rates and temperatures used during engine testing.
- P1 Pressure Control Valve on the excess sample flow path should be closed.
- DF1 should be calculated. If DF1 is found to be above 14, then the GL flow rate should be reduced.

Blockage of Diluter1 sample inlet orifice nozzle may cause DF_1 to increase above 14 indicating that the orifice needs to be cleaned. The flow schematic for the optional Diluter1 operability check is shown in Figure A14.

An alternative method for checking Diluter1 operability is to measure the ambient CO_2 instead of CO_2 from a calibration gas using the procedure described above. However, the gas analyzer shall measure accurately at very low CO_2 levels of ~30 to 40 ppm.

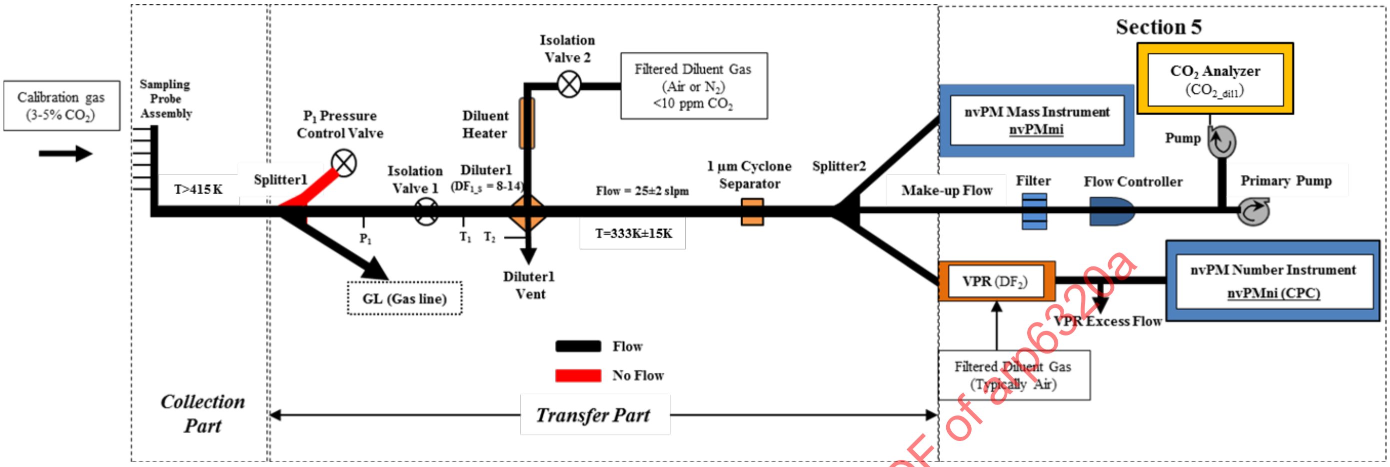


Figure A14 - Flow schematic for Diluter1 operability check

A.5 PARTICLE MASS CONCENTRATION MEASUREMENT

Non-volatile PM (nvPM) is defined as those particles present at the aircraft engine exit plane which do not volatilize at temperatures below 623 K. The nvPM consists mainly of nanometer size black carbon with trace amounts of ash and metallic particles emitted by aircraft engines under normal operating conditions. Total nvPM mass cannot be directly measured except by filter sampling and analysis which is expensive and time consuming. Therefore, the on-line measurement of black carbon mass concentration is considered the most appropriate method for representing the nvPM emissions from aircraft engines. For calibration purposes, however, the mass of elemental carbon (EC) determined by thermal-optical analysis is used as a surrogate for black carbon mass since it is the most applicable method at the present time.

Information is provided in this Section for determination of compliance with the performance specifications listed in Table 3 of the main text along with the required equipment and procedures for the calibration of mass analyzers used for the measurement of turbine engine nvPM mass emissions.

A.5.1 Modifications to ISO Standard 9169-2006 for Determination of Instrument Performance

The International Standards Organization (ISO) Standard 9169-2006 (Air Quality – *Definition and determination of performance characteristics of an automatic measuring system*) provides the basis for the determination of most performance characteristics of nvPM mass concentration instrumentation (nvPM mi) specified in Table 3 of the main text [see 2.1.3.5]. The following discussion describes the standard and provides modifications to make it applicable for a reference material that is not repeatable.

The ISO 9169 procedures require that the average values needed for the performance characteristics be calculated from primary measurements over an averaging time that should include at least 30 primary measurements. The time interval for the primary measurements and the averaging time are not specified in the Standard, but they are to be chosen appropriately for the given instruments and the particular measurement application. For nvPM mass measurements, this ARP anticipates that a 30 second average of instrument readings taken 1 second apart will reasonably assure that the nvPM mass concentration of an engine under test can be captured while the engine is maintained in a stable state. Thus, the requirement is that instruments provide data at a minimum 1 Hz data rate, i.e., that the maximum time interval for the primary measurement be no more than 1 second, and that the average of these measurements over 30 seconds shall comprise the instrument response for measurements in the field.

The reference material for mass concentration has been chosen to be combustion soot generated by a diffusion flame whose elemental carbon (EC) concentration is determined by the ASTM D6877-13 method [see 2.1.3.7]. This thermo-optical EC/OC analysis requires that a sample of PM is obtained by drawing a known volume of gas containing the sample through a quartz filter until sufficient mass is obtained for analysis. As the concentration of the generated PM may vary over the filter collection time, the averaging time referred to in ISO 9169 is taken to be the same as the filter collection time.

Unlike the concentration of a gas in a calibration bottle, the reference material may not be the same in consecutive measurements taken over the averaging time, i.e., each determination of the reference material's value may be different, albeit well known as determined by the ASTM method. The modifications to ISO 9169 needed to accommodate this are included here.

To supplement ISO 9169 section 3*, Symbols and abbreviated terms*, the following symbols are added to support modified equations shown below:

$C_{i,j}$	is the jth instance of the reference material concentration at level i
$E_{i,j}$	is the residual = the difference between $C_{i,j}$, and $Y_{i,j}$
E_i	alternative definition of the average over j of the $E_{i,j}$
RM_{ij}	is the ith reference material having an accepted C_i, of the measured with a known uncertainty
s_{Yi}	the standard deviation over j of the $Y_{i,j}$ for level i
S_{Ci}	the standard deviation over j of the $C_{i,j}$ for level i
$Y_{i,j}$	is the result of measurement by the instrument of the reference material $C_{i,j}$
Γ	is the intercept of the regression function applied in the lack of fit test
Δ	is the slope of the regression function applied in the lack of fit test

In ISO 9169, Section 6.4.2, *Requirements for the repeatability determination under stable laboratory conditions* of the ISO Standard, the following text is modified to permit collecting fewer than ten repeats at each level of the reference material.

Perform for each level, i, at least 6 consecutive measurements providing results of measurement Yi,j obtained over the averaging time …

In ISO 9169, Section 6.4.3, *Requirements for lack of fit determination under stable laboratory conditions* of ISO 9169, the formula for determining the lack of fit residual is modified to average the individual residuals rather than the instrument response (because the reference material may not be at exactly the same level during each repeat measurement). The residuals E_i (lack of fit) shall be determined according to:

$$E_{i,j} = Y_{i,j} - \left(\Gamma + \Delta \times C_{i,j}\right)$$

$$E_i = \frac{\sum_{j=1}^{n} E_{i,j}}{n}$$

In ISO 9169, Section 6.4.5.3, *Repeatability under stable laboratory conditions* of the Standard, the formula for determining the repeatability of the instrument response is modified to account for the effect of the imperfect repeatability of the reference material. For each accepted value, C_i, the standard deviation of repeatability, s_{ri}, and the repeatability limit at 95% confidence (given as a $\pm$ $r_{0.95}$ interval) shall be determined from the available n results of measurement according to:

$$s_{r_i}^2 = s_{Y_i}^2 - \Delta^2 \cdot s_{C_1}^2$$

$$s_{Y_i}^2 = \frac{\sum_{j=1}^{n}\left(Y_{i,j} - \bar{Y}_i\right)^2}{(n-1)}$$

It may happen that the sample variance of repeatability so determined is negative, indicating that the variance of the measurement could not be discriminated from the variability of the reference material. Should this occur for all target concentration levels, i, of the reference material, the test can be repeated with additional attention given to the stability of the reference material source (diffusion flame nvPM source flow and pressure settings) and the accuracy of the determination of the reference material level (ASTM D6877-13 loadings and procedures). Failing this, the reproducibility can be reported as “significantly better than $\Delta \cdot s^2_{Y_i}$”.

In ISO 9169, Section 6.4.5.5, *Limit of detection under stable laboratory conditions*, the determination of limit of detection is modified to accommodate an instrument that may not produce a measurement at each primary measurement interval, if there is no stimulus for it in the reference material. In this section add the text:

If under the condition of zero stimulus, C_0, the instrument does not automatically make a measurement during each primary measurement interval (2.1.7), such that the statistic above is not able to be calculated, then a higher level of the reference material, C_1, may be used. C_1 for this purpose should be a low level just above 0% of range such that the instrument produces regular readings.

$$Y_{D,0.95} = \bar{Y}_1 - C_1 + 2 \times t_{\nu,0.95} \times s_1$$

If it is infeasible to determine the C_1 value of the reference material at this low but non-zero level, then the LOD statistic as defined in ISO 9169, Section 6.4.5.5 is not able to be determined. In this case the noise level at this low level may be used as an alternative to the LOD performance specification. The noise level (N_0) can be calculated as:

$$N_0 = 2 \times t_{\nu,0.95} \times s_1$$

A.5.2 Instrument Calibration

A.5.2.1 Scope and Application

This Section provides written instructions on the calibration of mass analyzers used for measuring nvPM mass emissions from aircraft turbine engines. In order to standardize the nvPM mass instrument’s calibration, the performance of each instrument must be compared to that of an established reference method by a competent testing and calibration laboratory [see 2.1.3.8]. The protocol outlined here uses ASTM D6877-13 [see 2.1.3.7] as the reference method, a diffusion flame as a source of nvPM, and a Thermal/Optical – Transmittance (TOT) Carbon Analyzer [see 2.1.3.6] for the determination of elemental carbon content of the test aerosol either collected manually on a pre-fired quartz filter, or directly measured via an automated in-line instrument (i.e., Semi-Continuous TOT Carbon Analyzer). Additionally, the reference method addresses the formation of OC as an artifact due to the conditioning and transport of the sample. The TOT analyzer reports the OC and EC contents in micrograms per square centimeter ($\mu g / cm^2$) of filter area and has a detection limit on the order of 0.2 $\mu g/cm^2$ filter area for both OC and EC.

The analytical procedures used for instrument calibration are in accordance with the existing International Standard (ISO) 9169:2006, *Air quality - Definition and Determination of Performance Characteristics of an Automatic Measuring System* [see 2.1.3.5] and the National Institute for ASTM International Standard Test Method D6877-13 for Monitoring Diesel Particulate Exhaust in the Workplace Analysis [see 2.1.3.7]. The Semi-Continuous TOT Carbon Analyzer is a currently acceptable variation of ASTM D6877-13 which uses the same temperature ramp, optical analysis, etc., but a different sampling handling method (i.e., analysis of the entire filter area instead of just a filter punch) and gas analysis technique (i.e., direct measurement of evolved CO_2 by non-dispersive infrared [NDIR] analysis instead of a methanator and flame ionization detector) as described below.

A.5.2.2 Overview of Calibration Method

ASTM International has established an evolved gas analysis which can speciate elemental carbon (EC) from organic carbon (OC), and is performed by a thermal-optical transmission (TOT) analyzer with timed heating ramps and “cool-down” cycles (Figure A15). This method is originally based on National Institute of Occupational Safety and Health (NIOSH) Method 5040 [see 2.1.3.6] for Diesel Particulate Matter. While the stated analyte for ASTM 6877-13 is elemental carbon, the method measures all carbon species that evolve during the analysis and provides total carbon (TC) loading on the filter. All carbon evolving from the filter is oxidized to form carbon dioxide (CO_2), which is then reduced to methane (CH_4) and measured using a flame ionization detector (FID) in the laboratory TOT analyzer or measured directly by a NDIR analyzer in the semi-continuous instrument.

A red light (wavelength of 670 nm) laser and a photocell are used to monitor transmittance of a filter punch of known area, which typically darkens as refractory OC chars during a non-oxidizing heat ramp and then lightens as the char burns off during an oxidizing heat ramp. Figure A15 illustrates the heat cycles of the ASTM method. Calculation software, contained within the instrument, divides TC into OC and EC by evaluating the split time between when the transmittance of the filter returns (after darkening then lightening) to its original value from the beginning of the analysis. One should note that since the instrument uses light transmittance through the filter to speciate the carbon types, any artifacts that remain on the filter (due to lack of complete charring, etc.) can be determined as elemental carbon rather than organic carbon during analysis. According to the published method, the limit of detection for EC is about 0.2 μgC/cm^2 and the precision (pooled relative standard deviation at 95% confidence level) for EC was found to be between 4% and 10% for three major studies.

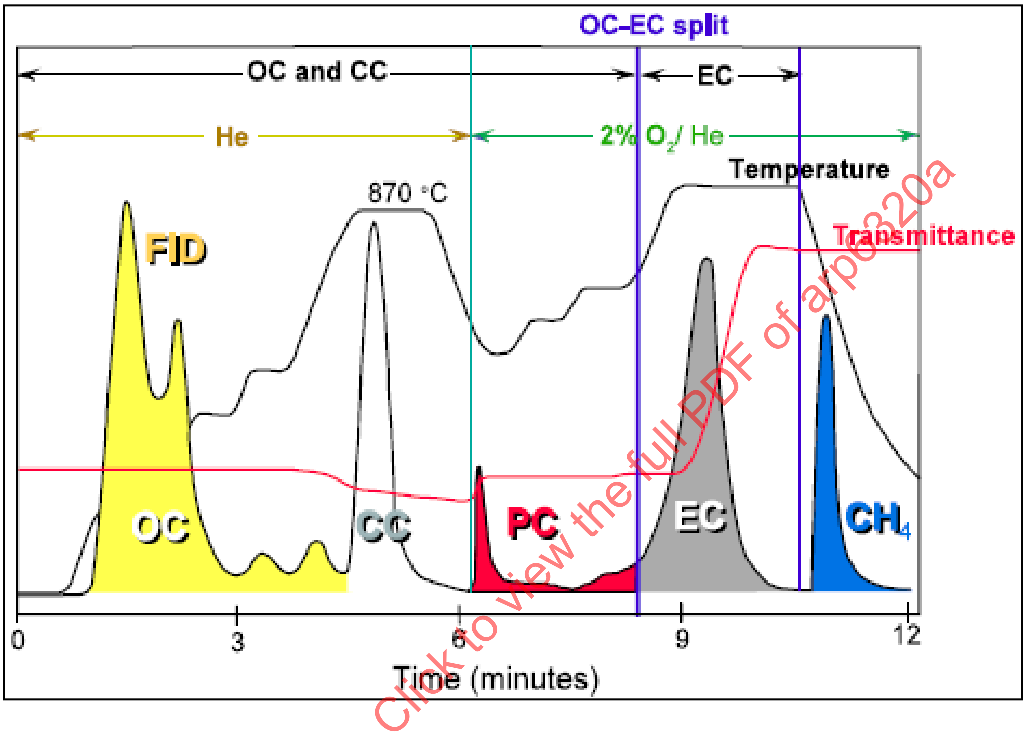


Figure A15

Example thermogram for filter sample containing organic carbon (OC), carbonate carbon (CC), and elemental carbon (EC). PC is pyrolytically generated carbon. The curves indicated with the OC, CC, PC, EC, and CH_4 labels are CH_4 concentrations being measured by a flame ionization detector (FID). The final peak is the methane calibration peak (see 1.1.1.17).

The ASTM D6877 laboratory method is based on the preferential oxidation of organic carbon (OC) and elemental carbon compounds (EC) at different temperatures (see Table 5 for temperature profiles). The carbon compounds are removed from the sample quartz filter by introducing varying temperature and oxidation environments. Organic compounds are volatilized from the sample in a helium (He) rich atmosphere at lower temperatures, while the EC is not oxidized or removed. Once heated, the OC is (and any pyrolysis compounds are) converted to carbon dioxide (CO_2) by passing the volatilized carbon through an oxidizing oven containing heated manganese dioxide (MnO_2). The CO_2 is then transported in a He stream, mixed with hydrogen (H_2) gas, and is converted to methane (CH_4) by passing through a "methanator" – a hydrogen-enriched nickel catalyst. A flame ionization detector (FID) is then used to quantify the methane. The remaining sample is then cooled and exposed to an oxidizing helium/oxygen gas transport mixture. This transport stream is heated and the EC component of the sample is oxidized, and the EC is analyzed in the same manner as the OC.

The optical component of the analyzer is used to correct for pyrolysis of organic carbon compounds to elemental carbon in order to avoid underestimation of OC and overestimation of EC. In order to ensure a proper OC/EC split, calibration of the internal oven temperature should be conducted according to the manufacturer's specifications. The sample reflectance and transmittance are continuously monitored by a helium-neon laser and a photo detector throughout the thermal cycle. When pyrolysis takes place, there is an increase in light absorption resulting in a decrease in reflectance and transmittance. Thus, by monitoring the reflectance/transmittance, the portion of the elemental carbon peak corresponding to pyrolyzed organic carbon can be correctly assigned to the organic fraction. An example of the laser transmission amplitude (red curve denoted with the "Transmittance" label) is shown in Figure A15.

In the Semi-Continuous TOT Analyzer, a quartz filter is mounted directly in the instrument and samples are collected for the desired time period. Once the collection is complete, the oven is purged with helium and a stepped-temperature ramp increases the oven temperature to 1143 K (870 °C), thermally desorbing organic compounds and pyrolysis products into a manganese dioxide (MnO_2) oxidizing oven. As the carbon fragments flow through the MnO_2 oven, they are quantitatively converted to CO_2 gas. The CO_2 is swept out of the oxidizing oven with the helium stream and measured directly by a self-contained NDIR detector. A second temperature ramp (oven temperature up to 1203 K (930 °C)) is then initiated in a He/O_2 gas stream and any elemental carbon is oxidized off the filter and into the oxidizing oven and NDIR. The elemental carbon is then detected in the same manner as the organic carbon.

A.5.2.3 Calibration System Set-Up

The calibration system for nvPM measurements should be located in a well-ventilated area and contain a diffusion flame combustion source including proper inlet source gases, a dilution system using HEPA filtered diluent to control target EC mass concentrations, a 1 µm cut-point cyclone separator upstream of the TOT instrumentation and nvPMmi, a plenum manifold system or a splitter assembly meeting, A.2.1, and stainless steel, carbon-loaded, electrically grounded PTFE, or equivalent anti-static tubing meeting ISO Standard 8031 [see 2.1.3.3] to connect the manual quartz filter sampler, or a semi-continuous EC/OC analyzer, and the nvPMmi. All tubing should be of the same material, length, and temperature from the split point to the instrument inlets. Figure A16 and Table A3 outline an example calibration system set-up. Another example using an ejector, plenum, and manifold system is shown in Figure A17.

Care should be taken if using a splitter assembly. Best aerosol physics judgement should be used to avoid a potential for particle concentration bias between sampling legs. To reduce risk of a concentration bias between the filter sampler and instrument, plenum manifold systems are typically the preferred choice for instrument calibration systems, as long as the source aerosol is well mixed.

The exact instrumentation set-up should be based on the standard operating procedure (SOP) for each instrument being utilized. SOPs for the mass instruments are attached as indicated in 2.1.2 of the main text. Once the calibration system is operational, in order to verify consistently accurate nvPM measurements of all instrumentation included within the sampling system, a tiered level of target soot concentrations should be pursued, and at each concentration level, each sample should be taken for the same amount of time, if possible, in order to establish a relatively repeatable filter loading (µg/m^2) soot concentration. These target soot levels – outlined in Table 4 – will provide a relatively wide range of data points to determine if the mass measurement instrument will be able to accurately detect nvPM.

The EC/OC instrument tends to have a lower detection limit (on the order of 0.2 µg/cm^2 of filter area) for both OC and EC, which should be considered when comparing the mass measurement instrument results to those shown from the EC/OC calibration. Additionally, as the EC/OC instruments have internal programming to account for any OC charring during a measurement cycle, no additional outside corrections will be required for the purposes of this calibration.

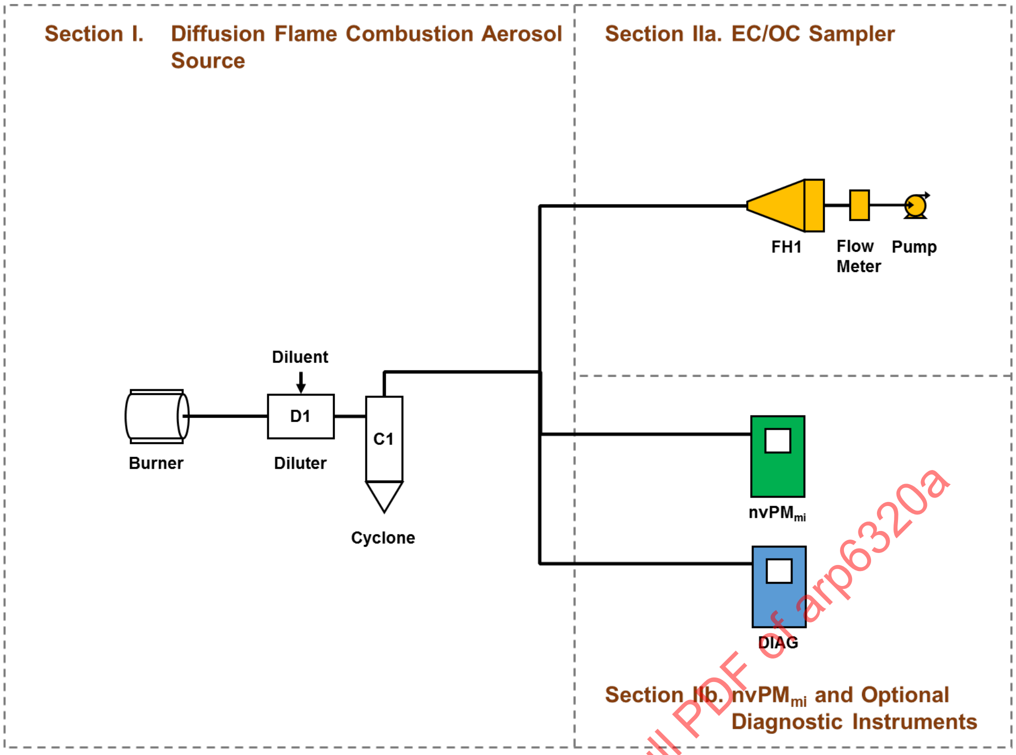
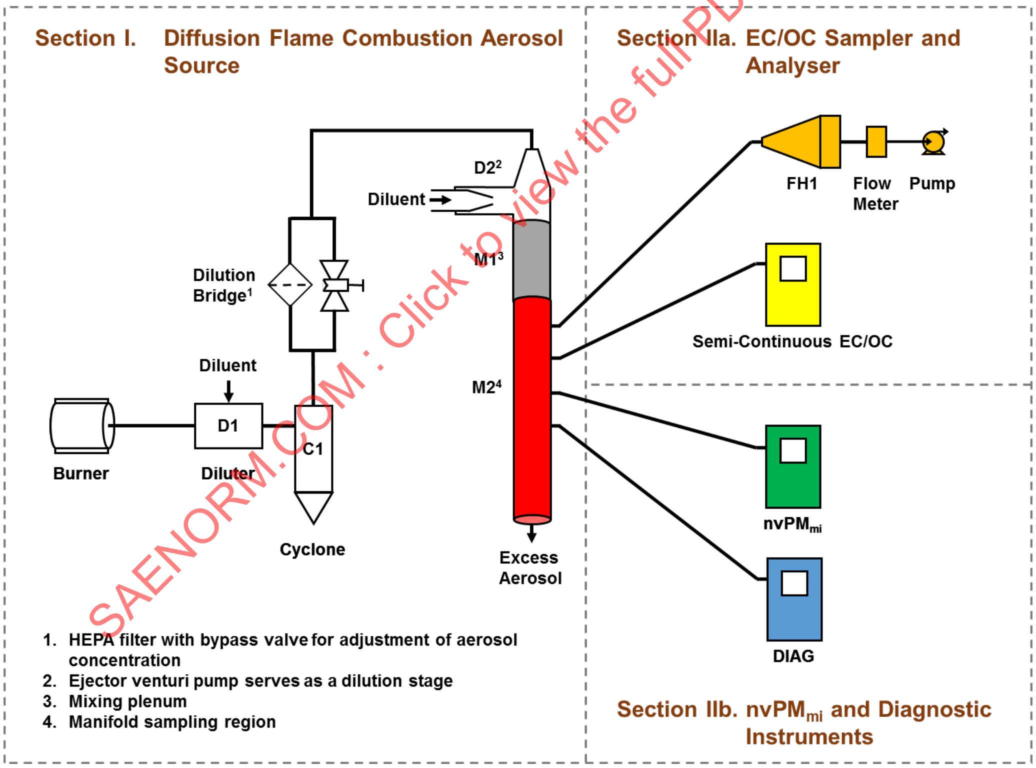


Figure A16 - Calibration diagram with instrumentation schematic. Note that sample line lengths from cyclone to instruments must be identical.

Table A3 - Breakdown of sections and major components of calibration system

Section	**I – PM combustion source**	**II – Sample collection**	
Sub-section	I. Diffusion Flame Combustion Source	IIa. EC/OC analysis	IIb. nvPMmi and diagnostic analyzer(s)
Major component(s)	Burner : diffusion flame burner C1 : 1 µm cut point cyclone D1 : diluter (N_2 or air) D2 : Ejector venturi pump M1 : Mixing plenum M2 : Manifold sampling region	Either: FH1: stainless steel quartz filter holder for EC/OC determination using manual filter preparation and laboratory EC/OC analyzer (shown) Or: Semi continuous EC/OC analyzer (not shown)	nvPMmi A-DIAG : optional diagnostic particle analyzer



1. HEPA filter with bypass valve for adjustment of aerosol concentration
2. Ejector venturi pump serves as a dilution stage
3. Mixing plenum
4. Manifold sampling region

Figure A17 - Second example calibration system

A.5.2.4 Calibration Equipment List

The following is a list of the major equipment needed to implement quartz filter sampling and the manual version of the ASTM D6877-13 analytical procedure [see 2.1.3.7]:

- Thermal/Optical – Transmittance (TOT) Carbon Analyzer
- Stainless steel filter holder having a tapered inlet section with a ≤12.5 degree half-angle operated at a filter face velocity not exceeding 0.5 m/s at actual operating conditions.

- Pre-fired quartz fiber filters (25- to 47-mm diameter) prepared in accordance with ASTM D6877-13 [see 2.1.3.7]. The filter area must be large enough to allow at least one punch (~ 1.5 cm^2) to be collected from each filter and analyzed appropriately.

- Electronic mass flow controller for manual collection of filter samples calibrated to a NMI-traceable calibration source within 1 year of use.

- Diffusion burner soot source, capable of producing an average EC content of the collected mass on the filter of 80% or higher.

- Stainless steel or anti-static tubing meeting the specifications shown in ISO 8031-2009 [see 2.1.3.3] to connect the manual filter holder and the nvPMmi.

If a semi-continuous TOT analyzer is used (~ 16 mm filter diameter), it shall be operated within the same range of filter face velocity as manually collected samples and the “clean oven” function of the analyzer shall be used to prepare the filters for measurement.

A.5.2.5 TOT Method Procedures

The samples collected are to be analyzed using the ASTM D6877-13 protocol, which specifies the necessary reagents and materials, instrument calibration and standardization, quality control, and analyzer operation and calculation of EC concentration. The following additional requirements must also be followed to provide the collection of high quality data:

- The temperature sensor controlling the oven temperature of the laboratory instrument shall be calibrated using a traceable transfer standard within 1 year prior to any TOT analyses. It is not currently possible to perform a similar calibration on the semi-continuous instrument.

- Both method blanks and field blanks shall be analyzed along with the samples collected. A method blank is a pre-fired quartz filter without addition of sucrose but handled in the same manner. A field blank for the manual method consists of a pre-fired quartz filter installed in the filter holder and immediately recovered without any sample gas passing through it. For the semi-continuous instrument, a field blank is the measurement of the internal filter set without any sample gas being passed through the filters. For the FID in the laboratory analyzer and NDIR in the semi-continuous instrument, a minimum of three method blanks and three sucrose solution samples should be analyzed to ensure the instrument response is within 95 to 105% of the theoretical recovery of OC prior to analysis of each sample set. At least one field blank should also be analyzed per sample set. An EC mass loading ≥0.3 μg/cm^2 for a field blank represents contamination.

- If the manual TOT analyses require more than 1 day, a single quality control check using stock sucrose solution shall be spiked to a properly prepared quartz filter and analyzed accordingly. The results should be between 95% and 105% of the theoretical mass of carbon.

- For calculation of the ≥80% EC required by the diffusion flame soot generator, final sample results must always be corrected for gas phase OC artifacts using the same operating conditions used for sample collection. For laboratory analyses, a Teflon filter followed by a pre-fired back-up quartz filter or two pre-fired quartz filters in series should be used with the back-up filter analyzed for OC content. Any OC found on the back-up filter must be subtracted from the OC found on the sample filters. In the case of the semi-continuous instrument, a Teflon filter is inserted into the sampling train immediately upstream of the analyzer. Any OC measured by the instrument is then subtracted from the OC found during sample measurement.

- If a 25 mm quartz filter is used for sample collection, 11.2 of ASTM D6877-13 for replicate sample analysis does not apply.