Observed Correlation Between Mean Size and Number- and Mass- Concentrations for Jet Engine Soot

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There is a growing concern for the environmental impact of jet engine exhaust emissions on the atmosphere, especially in the neighborhood around airports. An accurate assessment of the impact of these emissions on air quality requires that the number density, size, mass and composition of the aerosols within engine exhaust and aging plumes be understood and well characterized. Soot particles formed during fuel combustion constitute the primary solid (nonvolatile) particle fraction present in exhaust plumes. The SAE E31 committee is developing an Aerospace Recommended Practice (ARP) for aircraft non-volatile PM – procedures, sampling conditions, and instrumentation specifications. The PM parameters to be measured are number and mass concentrations. The concept ARP sampling system is shown in Fig. 1.

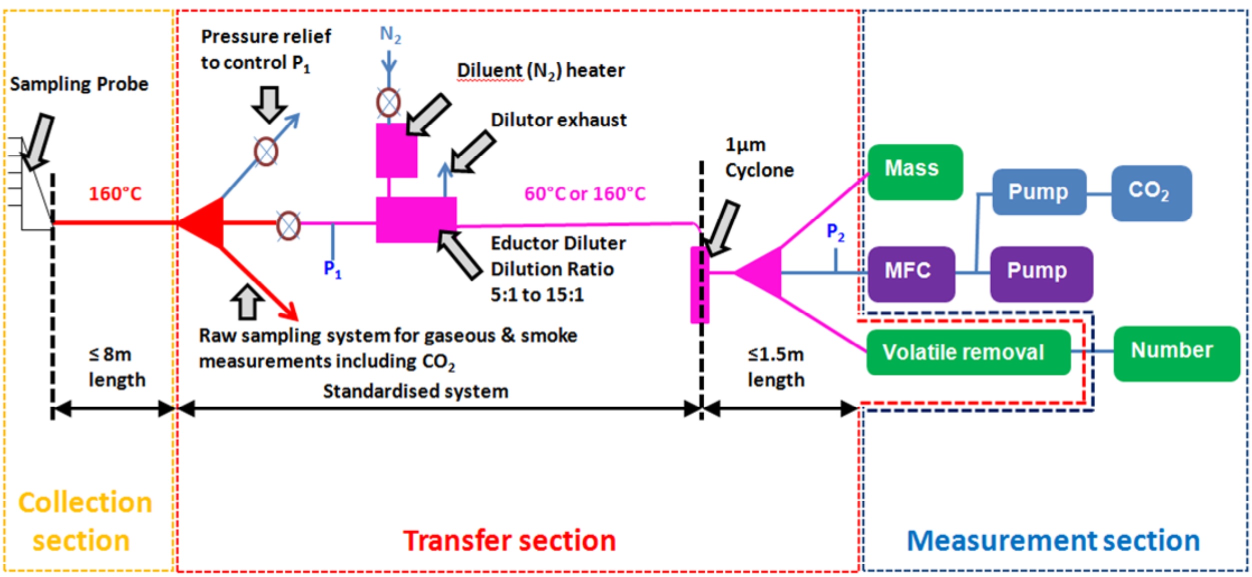

Fig. 1 Concept ARP Sampling System

The front end probe and rack system will be the ones currently in place at the engine manufacturers for use in engine certification for gas species and smoke. The length of the sample train will be fixed (~25 m), even if the manufacturer's facility could accommodate a shorter line. This length of line will entail significant particle losses, especially at small size. Introducing line loss correction factors, for number and mass, will require a reasonable estimate of the mean size of the aerosol at the downstream end, in spite of the fact that no direct size distribution measurement is to be made. The method for accomplishing this estimate is the objective of this presentation.

Engine exit plane emissions measurements have been made in several venues in recent years: NASA Dryden in April 2004 under project Apex1, Oakland airport in Aug. 2005 under project Jets-Apex2, Cleveland airport in Nov. 2005 under project Apex3, Peebles OH in Nov. 2007 under project GE Alt Fuels, and in Palmdale CA in Jan. 2009 under project AAFEX. Each of these campaigns used a sample train of length 25-30 m. Size distributions were made at the end of the sample train using a DMS500 fast particle spectrometer. These size distributions were used to generate total number (N) and mass (M) concentrations and a GMD (Geometric Mean Diameter). Data was taken for a variety of engine types, fuels, and power settings. PM number, mass, and size distribution were found to depend strongly on engine type, engine power condition, and fuel type. However a correlation was observed between number and mass and the corresponding geometric mean diameter of the exhaust aerosol. The following method was used to generate an estimated GMD (GMDc) from the computed number and mass concentrations:

$X = (6M/\pi\rho N)^{1/3}$ GMDc = aX.

"a" represents a constant associated with each sample train. For each test point in the campaign, values for N, M, and GMD were determined, and a value for GMDc was calculated using the model. The estimated GMDc was compared to the GMD computed from the size distribution. Table 1 gives the engines studied, the fuels used, the "a"

Campaign	Engines	Fuels	a	GMD Δ%
Apex 1	CFM56-2C1	JP8, JP8+S	0.664	20.8
		High aromatic JetA		
Jets Apex2	CFM56-3B1	Jet A	0.580	17.5
	CFM56-7B22			
Apex 3	CFM56-3B1	Jet A	0.603	17.6
	PW 4158			
	RB211-535E4B			
	CJ6108A			
	AE 3007A			
GE Alt Fuels	CFM56	JetA1, 20% Biojet	0.633	6.9
		40% Biojet, 50% FT		
		100% FT		
AAFEX	CFM56-2C1	JP8, FT-SASOL	0.597	19.7
		FT-Shell, JP8+FT Shell		
		JP8+FT SASOL		

Table 1. Previous engine exhaust sampling campaigns

values, and the RMS percent differences (GMD Δ%) between the estimated and actual geometric mean diameters. A concern with the above analysis is that the N and M were computed from the size distribution rather than direct measurement.

A major gas turbine exhaust campaign was conducted during Dec. 2011 in an engine test cell at the SR Technics facilities in Zurich Switzerland. The primary objectives of the studies were (1) to compare the performance of two similar sampling systems built roughly to the specifications defined in a draft Aerospace Recommended Practice document in terms of PM number, mass, size and composition with the purpose of identifying and analyzing any sampling system variability, (2) to inter-compare performance of like instrument pairs (instrument package variability), and (3) to evaluate the impact of employing CN counters with 10nm vs. 23nmsize cutoffs. Sample line lengths were comparable to those used in previous campaigns. Emissions from several different engine types with current technology conventional combustion systems (CFM56-5C, -7B and PW4060), just after a maintenance cycle, were used as sources and all data were acquired during routine revenue generating engine tests. Measurement data are not considered representative for the different engine types. The campaign included CN counter and Laser Induced Incandescence (LII) instruments whose data could be used to examine the mean size (GMD) vs. number (N) and mass (M) concentration correlation with direct number and mass measurements. The exhaust was diluted with dry nitrogen to minimize volatile particle formation. Total PM size distributions were measured with a DMS500 size spectrometer. Engine runs were conducted on seven days; 70 runs were found to have sufficient number, mass, and size signals to exercise the model. Size distribution widths were found to be rather uniform with mean sizes ranging from 15 to 40 nm and a variation in geometric standard deviation of about 3%. The "a" value for the ARP-type sample train used here was found to be $a = 0.762$. For this campaign the differences between estimated and measured mean sizes are 21%, 18%, 14%, and 9% for four combinations of sample trains and instrument packages.

In conclusion, we find that the exhaust aerosol's geometric mean diameter can be estimated from measured number and mass concentrations with an uncertainty ~ 16%. This estimated GMD could be combined with the sample line penetration function to estimate line loss correction factors for number and mass.

Center of Excellence for Aerospace Particulate Emissions Reduction Research

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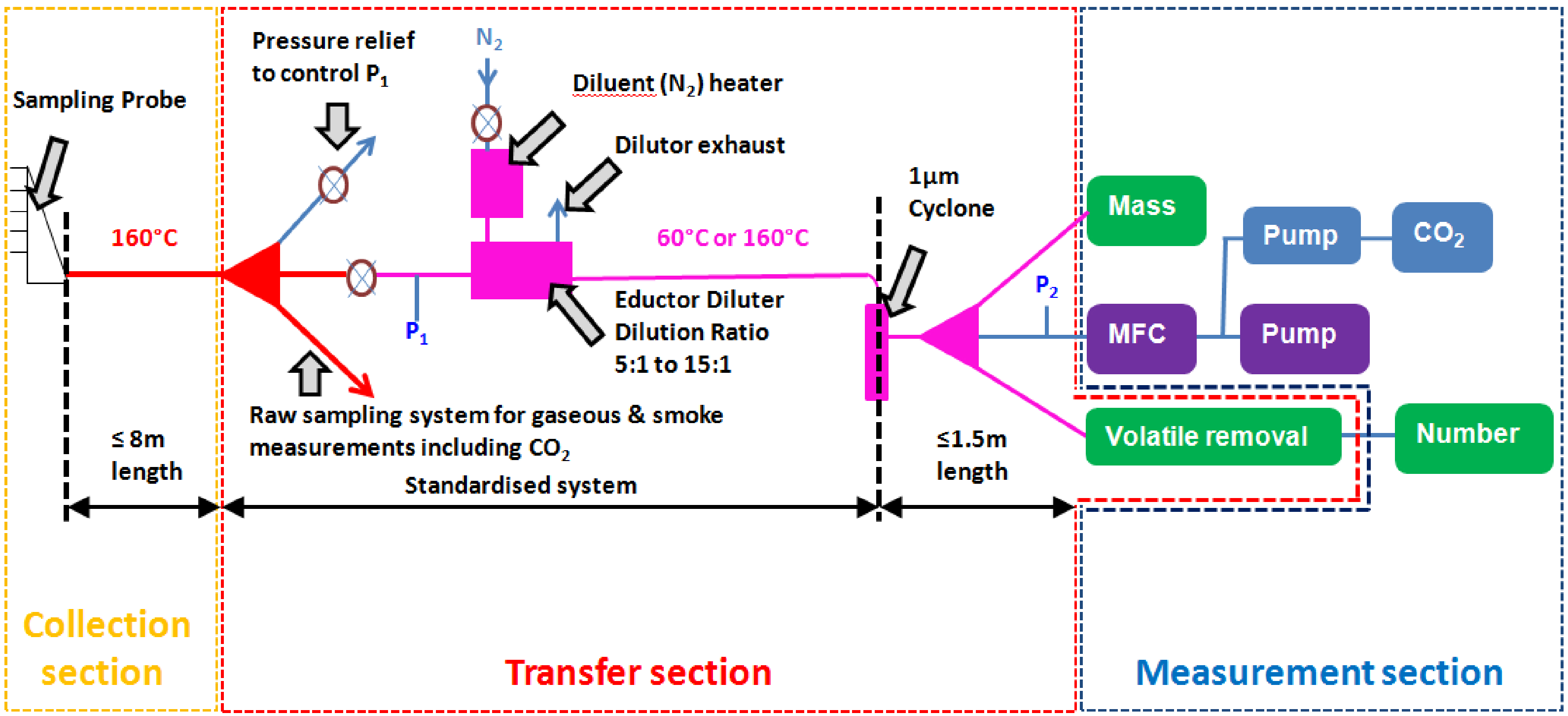
Background

- SAE E31 committee is developing an Aerospace Recommended Practice (ARP) for aircraft non-volatile PM
  - procedures, required continuous sampling conditions, and instrumentation (number and mass)
- Sampling system consists of three sections: Collection, Transfer and Measurement
  - designed for simulations gaseous and PM emissions sampling and measurement
- PM Measurements
  - Number concentration
  - Mass concentration

Concept ARP Sampling System

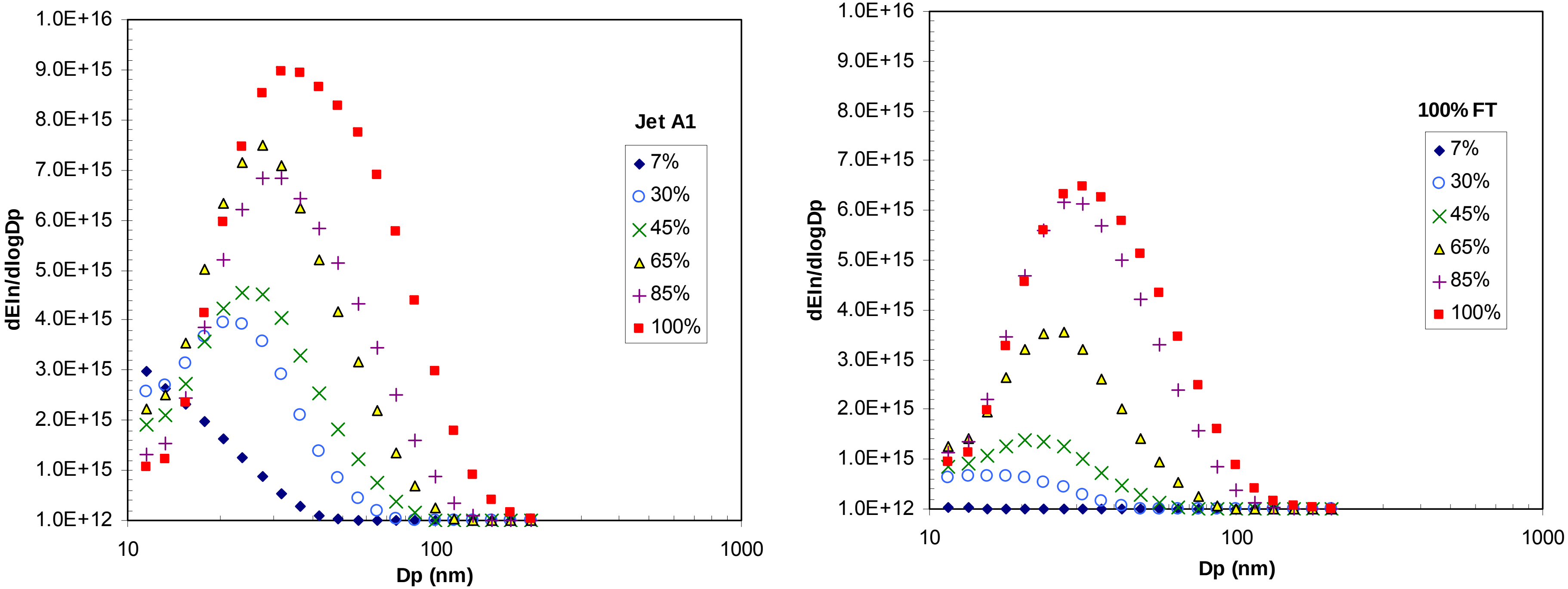


Campaign List

- Apex 1, NASA Dryden, Apr. 2004
- Jets Apex2, Oakland, Aug. 2005
- Apex 3, Cleveland, Nov. 2005
- GE Alt Fuels, Peebles OH, Nov. 2007
- AAFEX, Palmdale CA, Jan. 2009

Typical Size Distribution

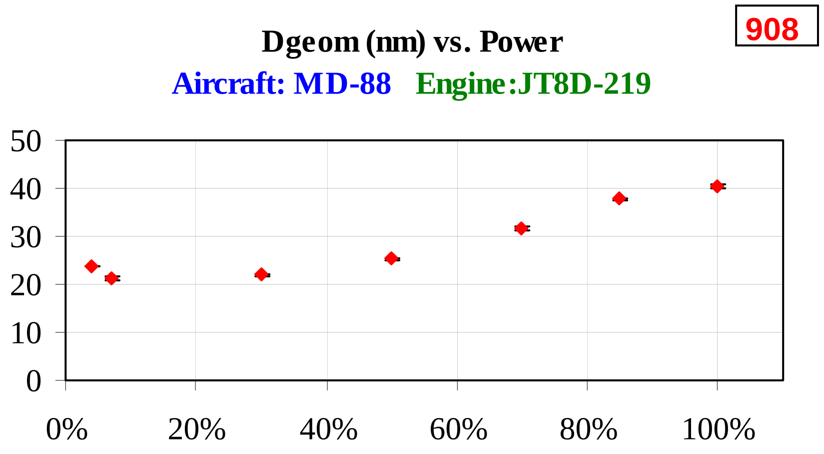
- Lognormal
- GMD range 15 – 50 nm
- GSD range   1.4 – 2.0
- Sample size distributions:

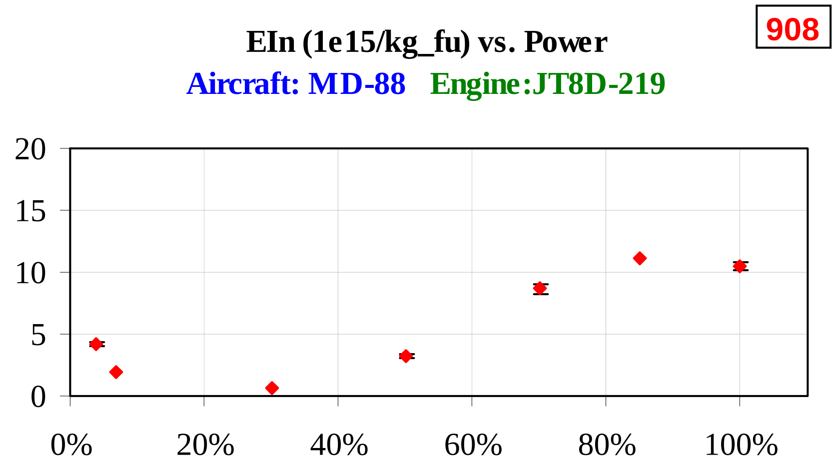


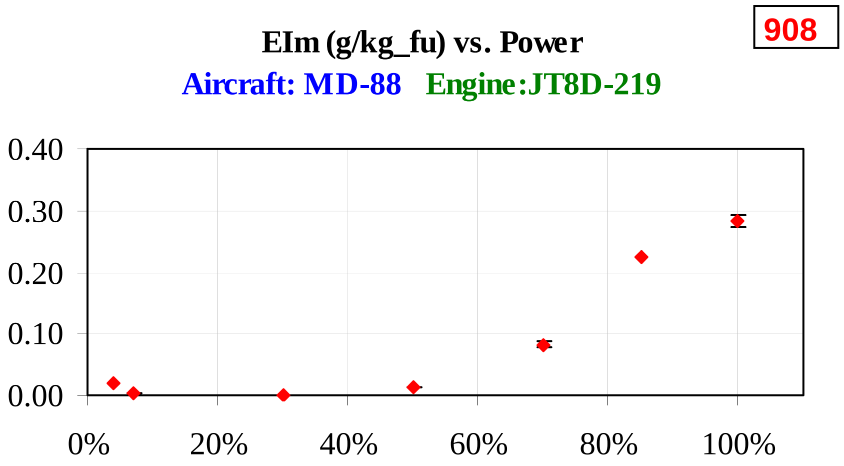
PM size distributions as a function of engine operating condition for the Jet A1 and 100% FT fuels

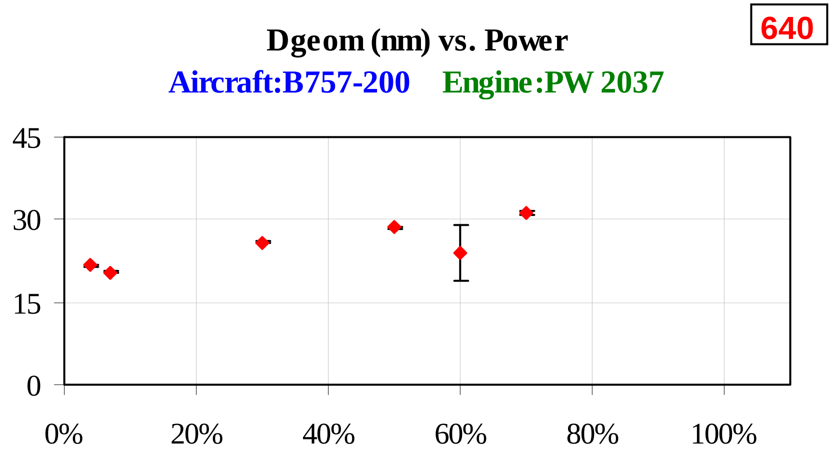
Size Distribution Parameters

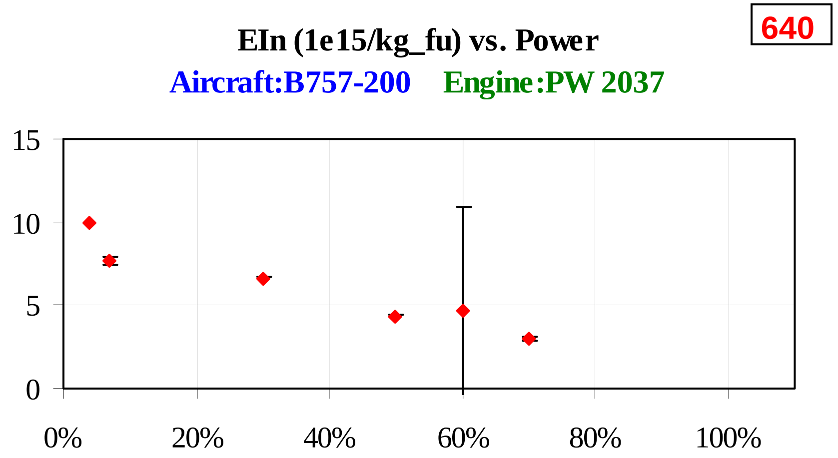
- $\{x_i, sn_i\}$ $sn_i = (dN/d\log x)_I$
- $\Delta_i = \Delta \log x_i = (\log x_{i+1} - \log x_{i-1})/2$
- $N = \Sigma_i \, sn_i \, \Delta_i$
- $M = (\pi\rho/6)\Sigma_i \, x_i^3 \, sn_i \, \Delta_i$
- $Am = (\Sigma_i \log x_i \, sn_i \, \Delta_i) / (\Sigma_i \, sn_i \, \Delta_i)$
- $GMD = 10^{Am}$

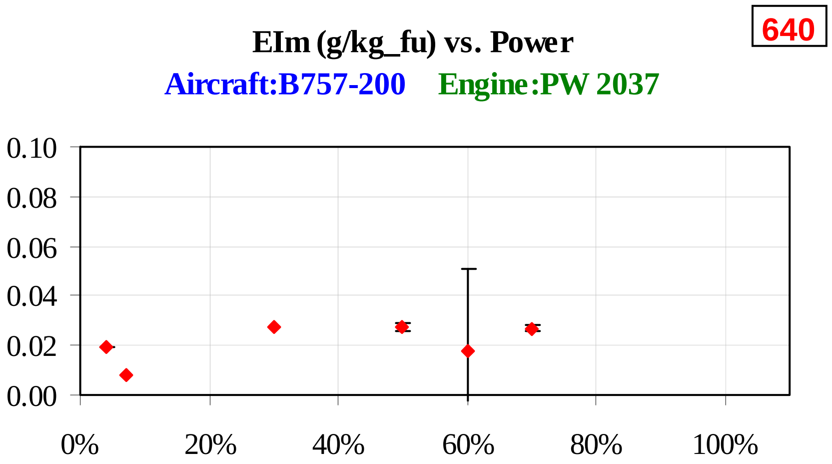

908
Dgeom (nm) vs. Power
Aircraft: MD-88 Engine:JT8D-219
50
40
30
20
10
0
0%
20%
40%
60%
80%
100%

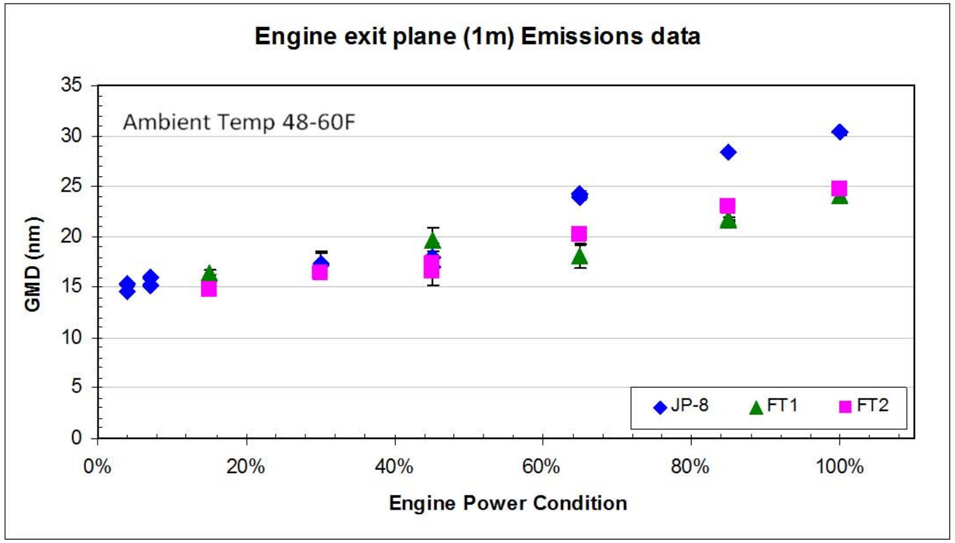

908
EIn (1e15/kg_fu) vs. Power
Aircraft: MD-88 Engine:JT8D-219
20
15
10
5
0
0%
20%
40%
60%
80%
100%

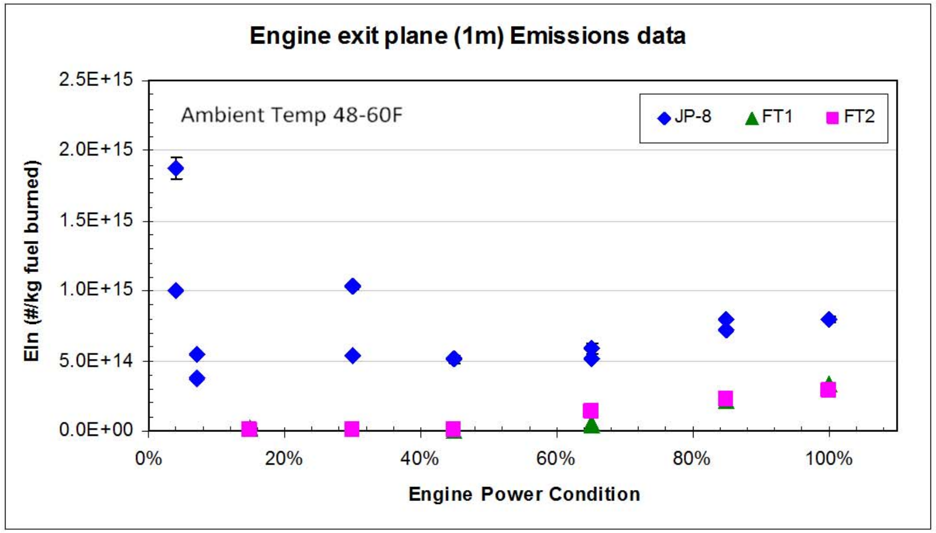

908
EIm (g/kg_fu) vs. Power
Aircraft: MD-88 Engine:JT8D-219
0.40
0.30
0.20
0.10
0.00
0%
20%
40%
60%
80%
100%

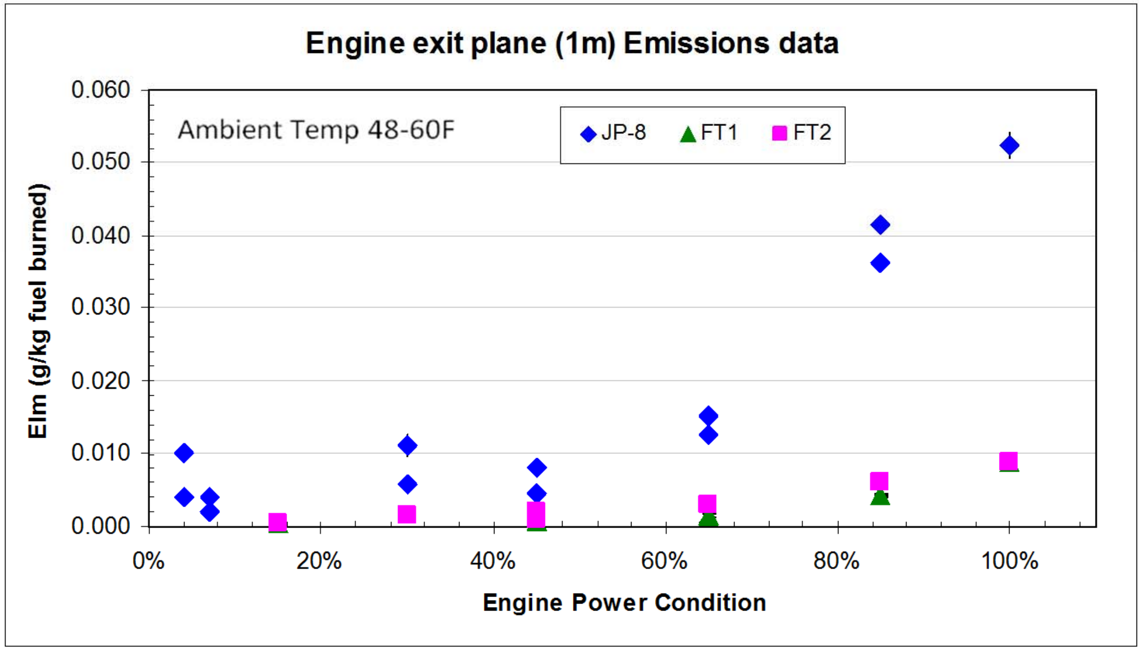

640
Dgeom (nm) vs. Power
Aircraft:B757-200 Engine:PW 2037
45
30
15
0
0%
20%
40%
60%
80%
100%


640
EIn (1e15/kg_fu) vs. Power
Aircraft:B757-200 Engine:PW 2037
15
10
5
0
0%
20%
40%
60%
80%
100%


640
EIm (g/kg_fu) vs. Power
Aircraft:B757-200 Engine:PW 2037
0.10
0.08
0.06
0.04
0.02
0.00
0%
20%
40%
60%
80%
100%


Engine exit plane (1m) Emissions data
Ambient Temp 48-60F
GMD (nm)
35
30
25
20
15
10
5
0
0%
20%
40%
60%
80%
100%
Engine Power Condition
JP-8
FT1
FT2


Engine exit plane (1m) Emissions data
Ambient Temp 48-60F
EIn (#/kg fuel burned)
2.5E+15
2.0E+15
1.5E+15
1.0E+15
5.0E+14
0.0E+00
0%
20%
40%
60%
80%
100%
Engine Power Condition
JP-8
FT1
FT2


Engine exit plane (1m) Emissions data
Ambient Temp 48-60F
EIm (g/kg fuel burned)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
0%
20%
40%
60%
80%
100%
Engine Power Condition
JP-8
FT1
FT2

Method

- Given number and mass concentrations, N and M, ➔ GMD.
- $X = (6M/\pi\rho N)^{1/3}$
- GMDc = aX

Previous Campaigns

Campaign	Engines	Fuels	GMD Δ%
Apex 1	CFM 56-2C1	JP8, JP8+S	20.8
		High aromatic JetA	
Jets Apex2	CFM 56-3B1	JetA	17.5
	CFM 56-7B22		
Apex 3	CFM 56-3B1	JetA	17.6
	PW 4158 (big)		
	RB 211-535E4-B (big)		
	CJ 6108A (sml, Learjet)		
	AE 3007A (sml, ERJ)		
GE Alt Fuels	CFM 56	JetA1, 20% Biojet	6.9
		40% Biojet, 50% FT	
		100% FT	
AAFEX	CFM 56-2C1	JP8, FT-SASOL	19.7
		FT-Shell, JP8-FT Shell	
		JP8-FT SASOL	

Average a

- a = .597 AAFEX
  = .603 Apex 3
  = .664 Apex 1
  = .633 GE Alt Fuels
  = .580 Jets Apex 2

Overall $\langle a \rangle = 0.615$

Problem

- Given number and mass concentrations, N and M, ➔ GMD.
- Take N and M from size distribution.
- Need to confirm that it works for directly measured N and M.
- $X = (6M/\pi\rho N)^{1/3}$
- GMDc = aX

  a = 0.615

SR Technics Dec 2011 Campaign – Participants

Federal Aviation Administration

Missouri S&T

Aerodyne Research

Missouri University of Science and Technology

(Center of Excellence for Aerospace Particulate Emissions Reduction Research)

United States Environmental Protection Agency

National Research Council Canada

ETH

Eidgenössische Technische Hochschule Zürich

Swiss Federal Institute of Technology Zurich

SR Technics

Schweizerische Eidgenossenschaft

Confédération suisse

Confederazione Svizzera

Confederaziun svizra

Swiss Confederation

University of Cambridge

University of Alberta

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CONTREC

Quality in Science and Technology

Personnel and instruments from 15 institutions in 7 countries

Test Objectives

- Primary objective
  - Compare the performance of the MST and FOCA systems in terms of PM number, mass, size and composition (sampling system variability)

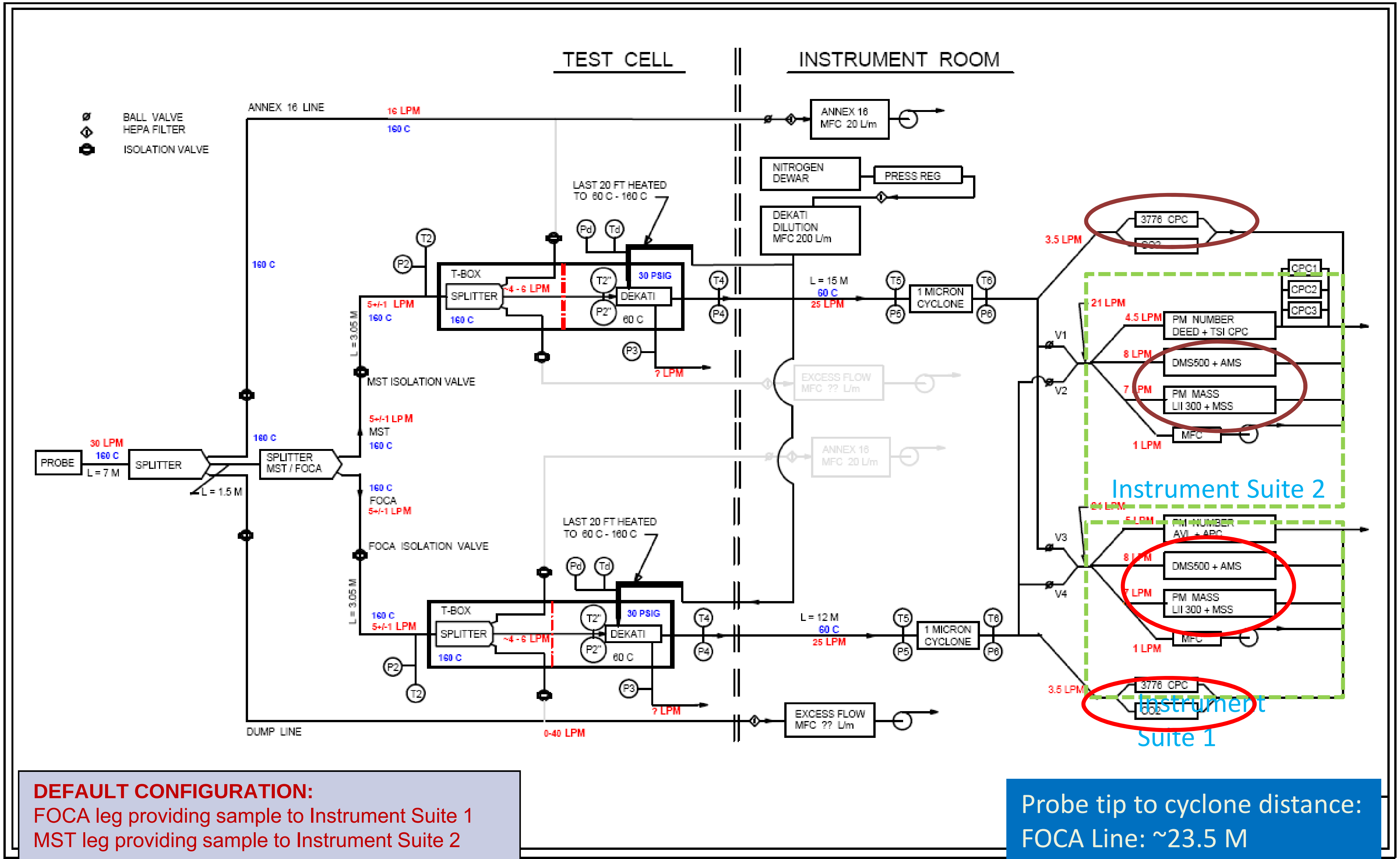
    Additionally,
    - Inter-compare performance of like instrument pairs (instrument package variability)
    - Evaluate the impact of 10nm vs. 23nm CPC size cutoff

- Secondary objective
  - Explore the impact of volatile PM removal using a catalytic stripper

Engine Test Details

Date	Test #	Start Time	Stop Time	Engine	Test Cycle	Notes
5/12/11	1	13:12	13:34	CFM56-7B27/3	Warm up	Shakedown Test
6/12/11	2	13:36	14:25	CFM56-5C4/P	Seal Test	Mixed flow engine
7/12/11	3	15:15	16:00	CFM56-5C4	Seal Test	Mixed flow engine
9/12/11	4	08:47 11:06	09:36 11:55	CFM56-7B24/3	Seal Test	Ran 2 cycles
12/12/11	5	10:05	10:57	PW4060-1C	Seal Test	
12/12/11	6	15:47	16:36	CFM56-5C4	Seal Test	Mixed flow engine
13/12/11	7	13:35	14:12	PW4060-1C	Vibration Test	All switching valves set to open
15/12/11	8	11:23	12:25	CFM56-7B27	Seal Test	Catalytic Stripper
15/12/11	9	13:19	13:35	CFM56-7B27	Vibration Test	Catalytic Stripper
15/12/11	10	14:07	16:25	CFM56-7B27	Trim Balance Test	Catalytic Stripper

System Overview

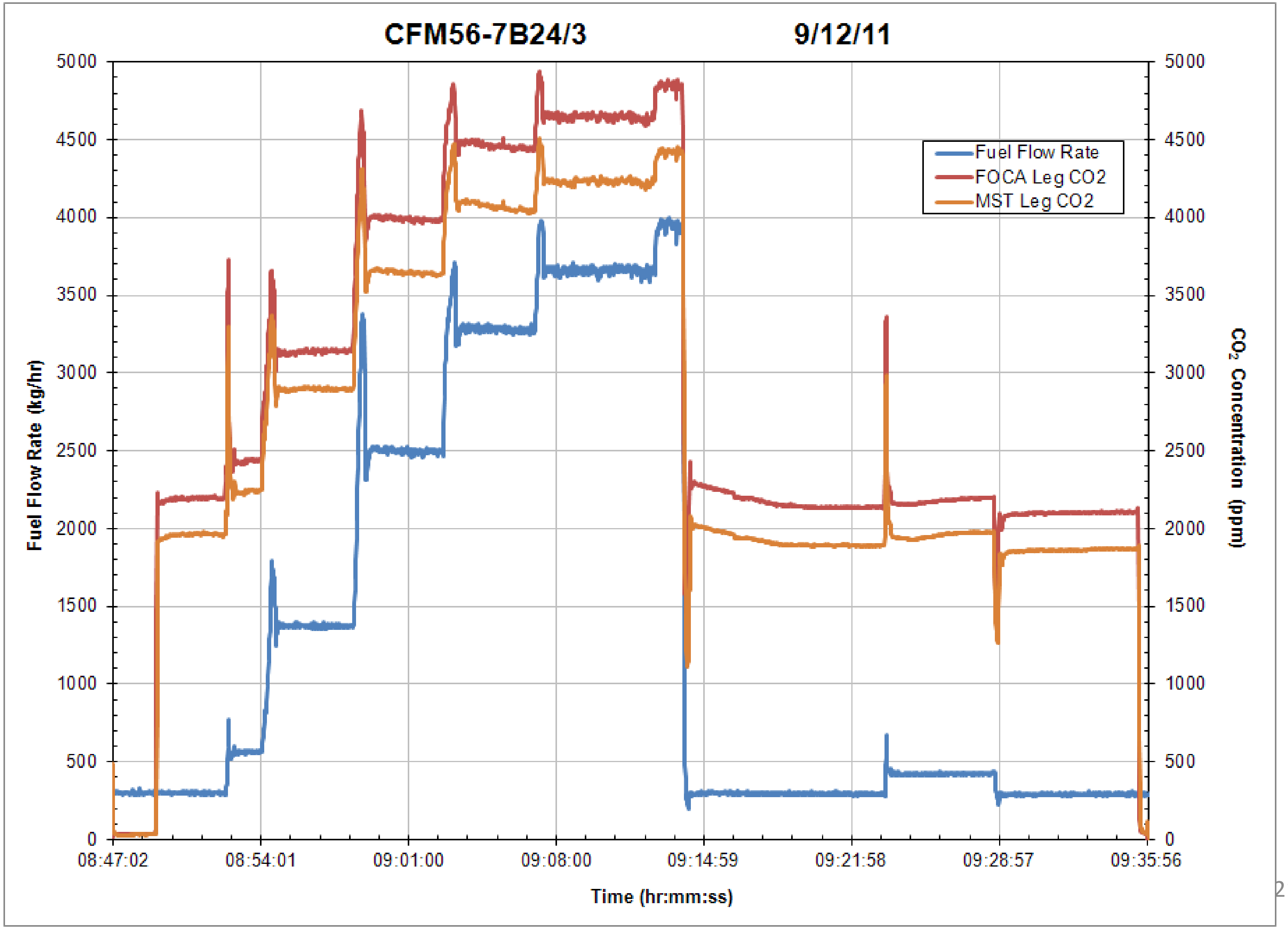


DEFAULT CONFIGURATION:
FOCA leg providing sample to Instrument Suite 1
MST leg providing sample to Instrument Suite 2

SWITCH CONFIGURATION:
FOCA leg providing sample to Instrument Suite 2
MST leg providing sample to Instrument Suite 1

Probe tip to cyclone distance:
FOCA Line: ~23.5 M
MST Line: ~26.5 M

Test Matrix for the CFM56-7B24/3 Engine



Instruments

- Instrument Suite 1
  - AVL APC
    - with catalytic stripper and 10nm cutoff CPC
  - LII
  - MSS
  - DMS500/MAAP
    - switched in between test points
  - SP-AMS

- Instrument Suite 2
  - Dekati DEED
    - with 23nm,10nm, and 2.5nm cutoff CPCs
  - LII
  - MSS
  - DMS500
  - AMS

- Gas Phase measurements
  - NOx, CO, UHC, CO2

- PM sample leg monitors
  - MST leg (TSI 3776 CPC, LiCor 840A CO2 detector)
  - FOCA leg (TSI 3776 CPC, LiCor 840A CO2 detector)

DEFAULT CONFIGURATION:
FOCA leg providing sample to Instrument Suite 1
MST leg providing sample to Instrument Suite 2

SWITCH CONFIGURATION:
FOCA leg providing sample to Instrument Suite 2
MST leg providing sample to Instrument Suite 1

GMDc

- $X = (6M/\pi\rho N)^{1/3}$
- GMDc = aX
  - a = 0.615 (initial guess)
- Adjust a to minimize $\Sigma(GMD - GMDc)^2$
  - Solution a = 0.762
- RMS%Δ (calc vs meas GMDs):

Suite	1mst	1foca	2mst	2foca
	21	18	14	9

- < RMS%Δ> = 15.5

Conclusions

- The exhaust aerosol's GMD can be estimated from measured number and mass concentrations.
- δ GMD ~ 16%
- This estimated GMD can be used to estimate sample line penetration correction factors for number and mass.
- Current work focus is on number and mass correction factors.

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