Center of Excellence for Aerospace Particulate Emissions Reduction Research

Demonstration of an Aerospace Recommended Practice for Measuring Non-volatile PM Emissions from Gas Turbine Engines using a Prototype System

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Cambridge Particle Meeting
Cambridge, UK
18 May 2012

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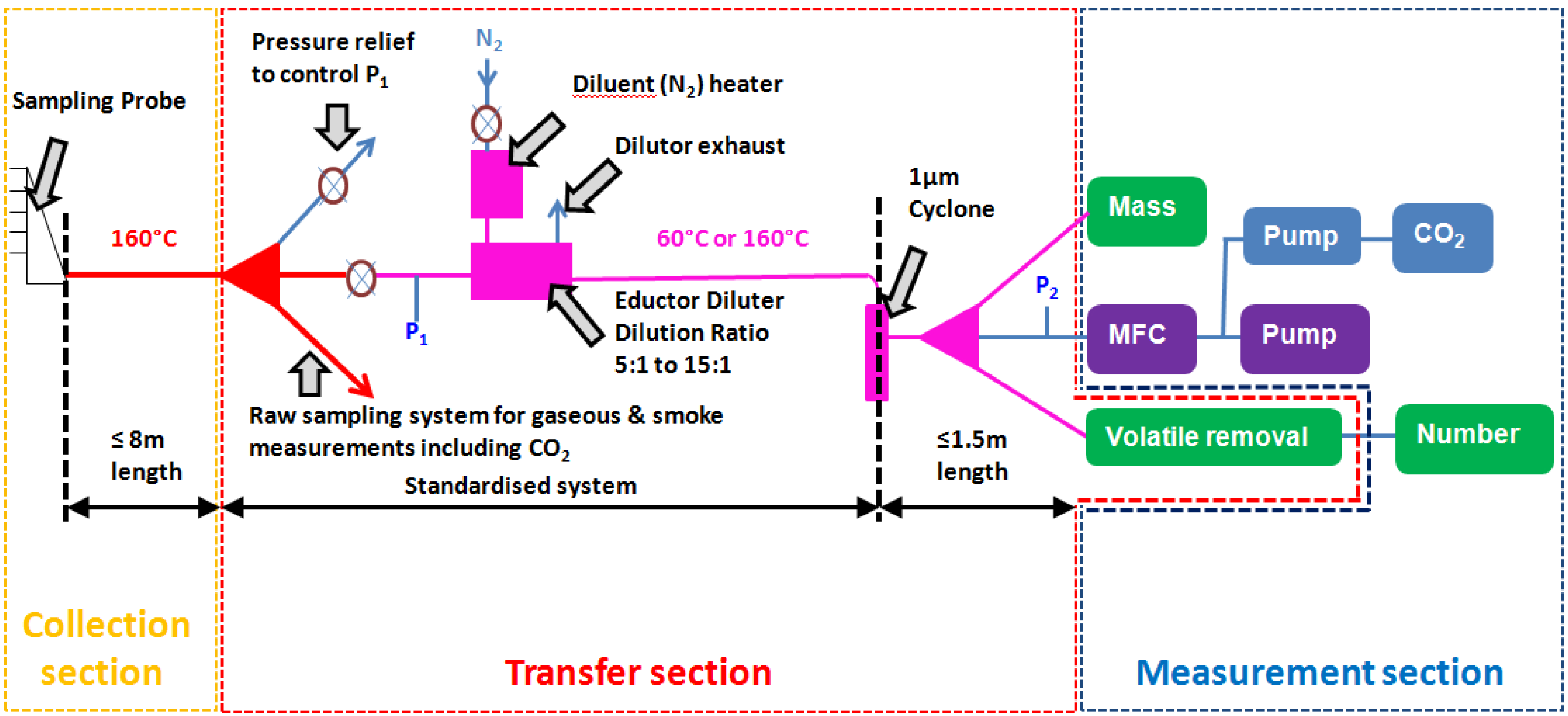
Background

- 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
- System development (to date)
  - SAMPLE II
  - MST Lab studies
  - AAFEX II
  - SAMPLE III
  - SR Technics Dec 2011
  - SAMPLE III.2

Concept ARP Sampling System



SR Technics Dec 2011 Campaign – Participants

FEDERAL AVIATION ADMINISTRATION

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TSI
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CONTREC
Quality in Science and Technology

DELTATECH

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)

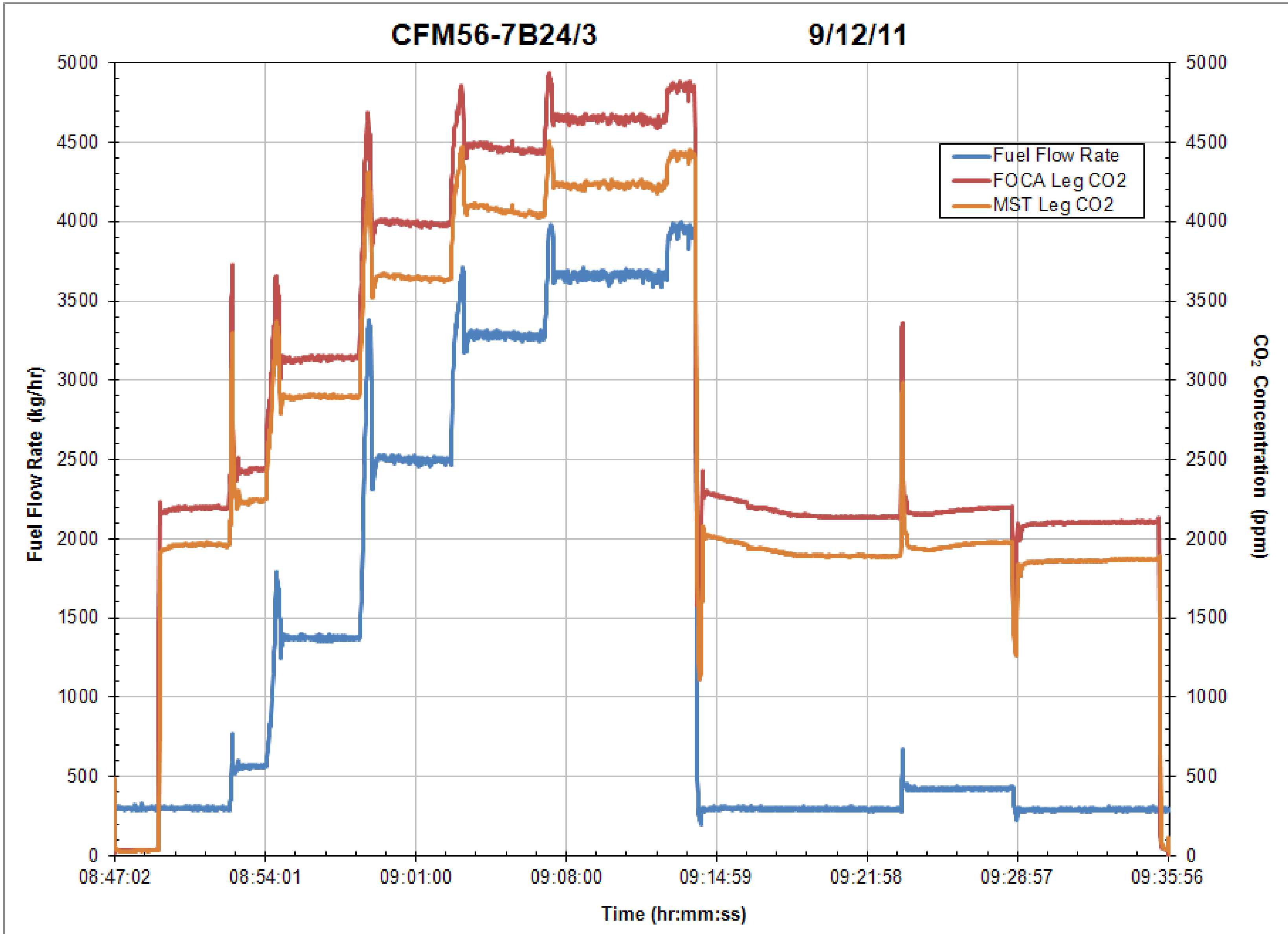
    Additionally,
    - Inter-compare performance of like instrument pairs (instrument package variability)
    - Evaluate the impact of 10nm vs. 23nm CPC size cutoff

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

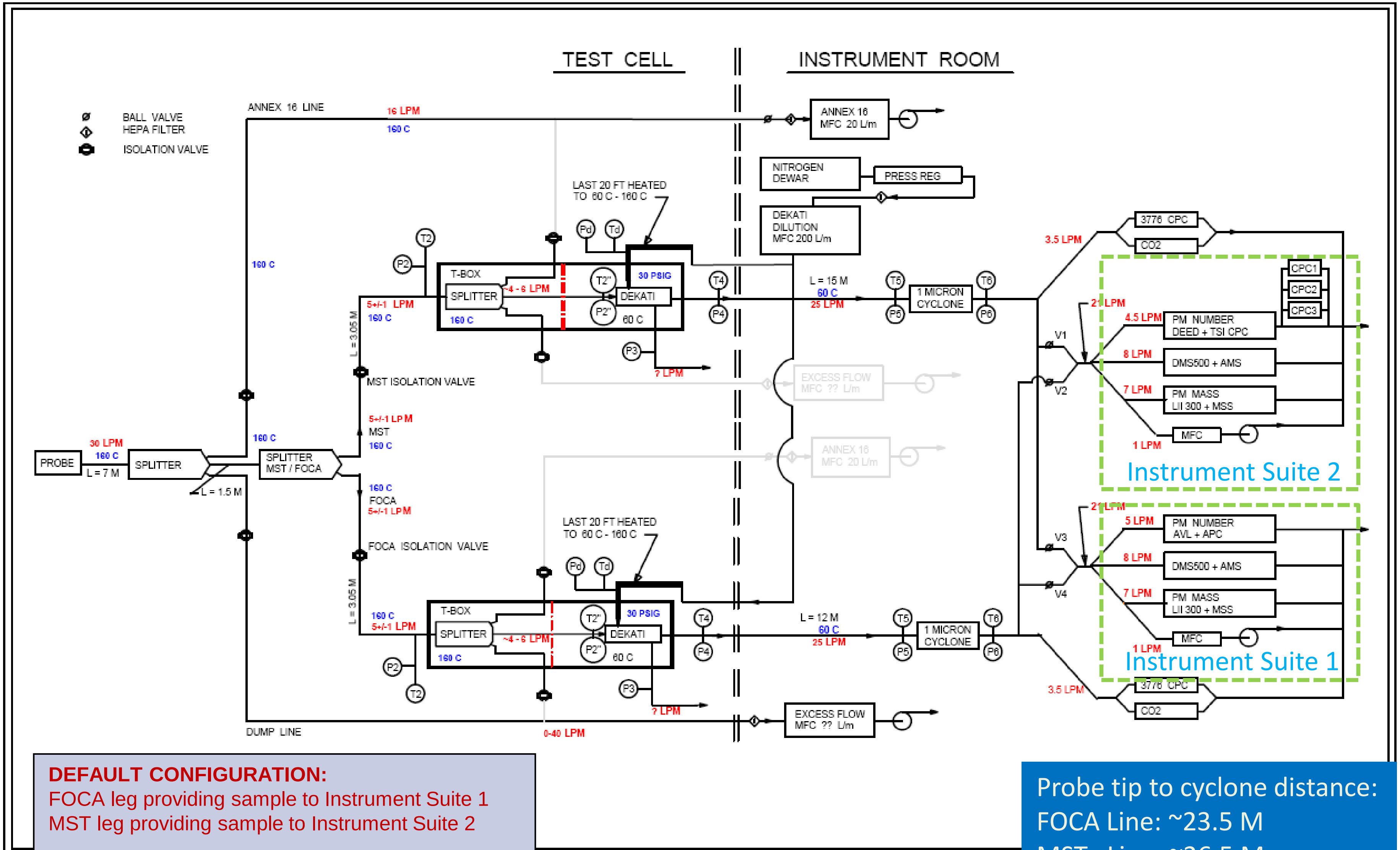
Engine Test Details

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

Test Matrix for the CFM56-7B24/3 Engine



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

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

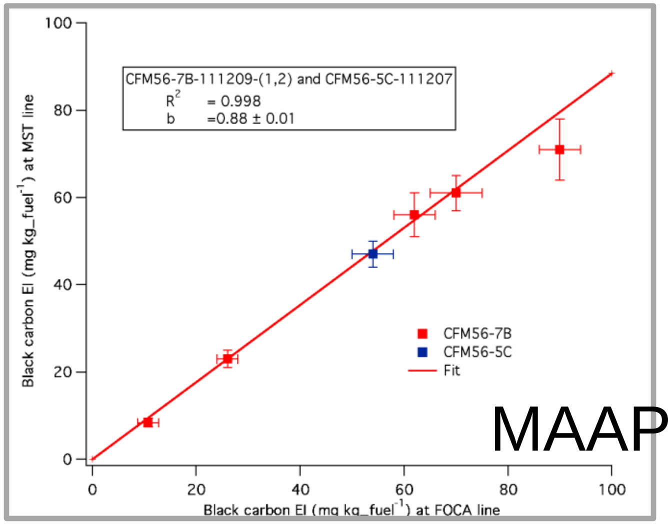
- Gas Phase measurements
  - NOx, CO, UHC, CO2

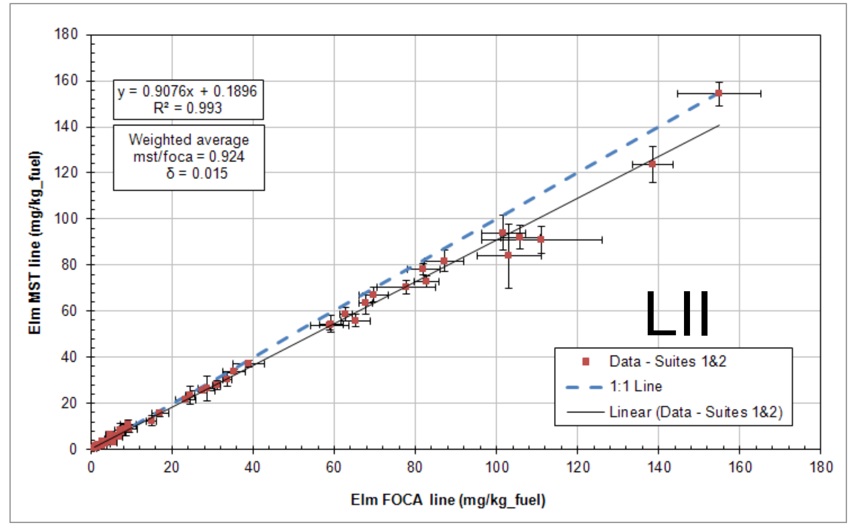
- PM sample leg monitors
  - MST leg (TSI 3776 CPC, LiCor 840A CO2 detector)
  - FOCA leg (TSI 3776 CPC, LiCor 840A CO2 detector)

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

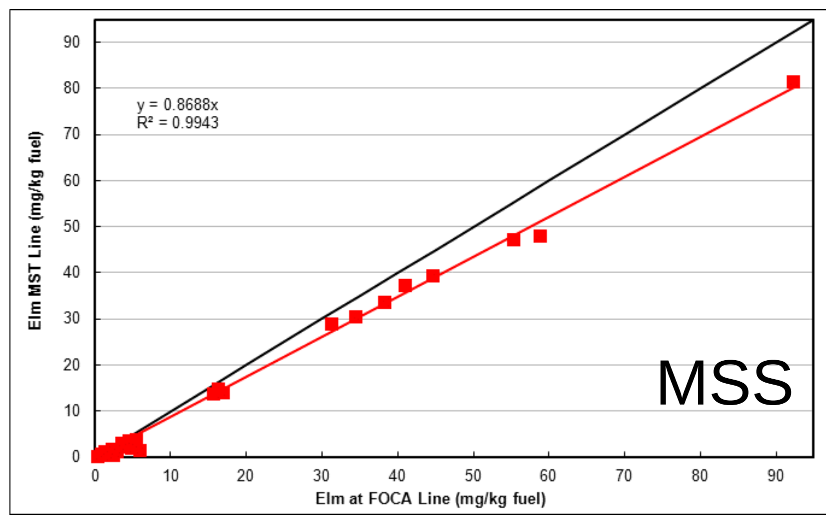
Comparison of the MST and FOCA Sampling Systems – PM Mass



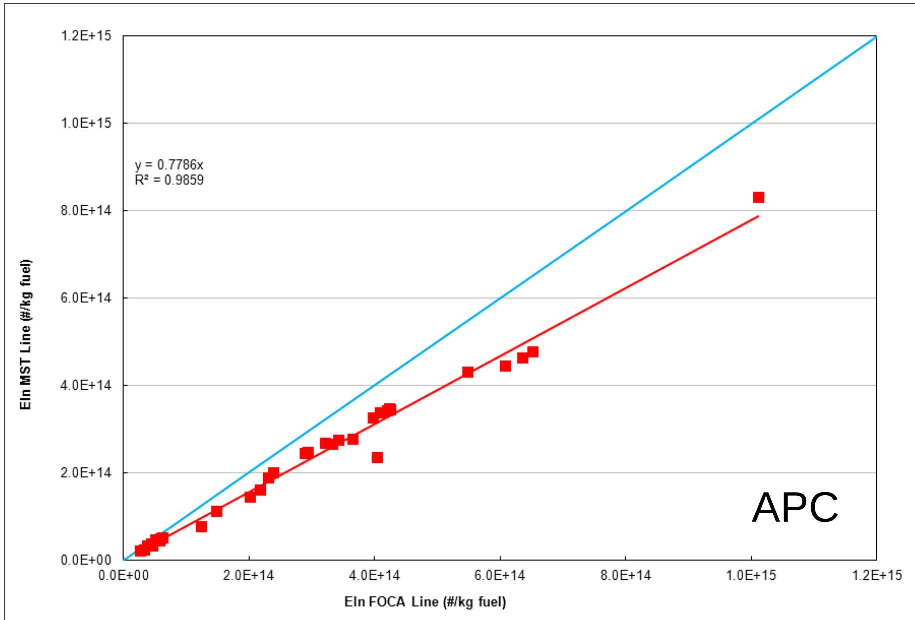


Good agreement in terms of PM mass between the MST and FOCA sampling systems as measured by MAAP, LII, and MSS

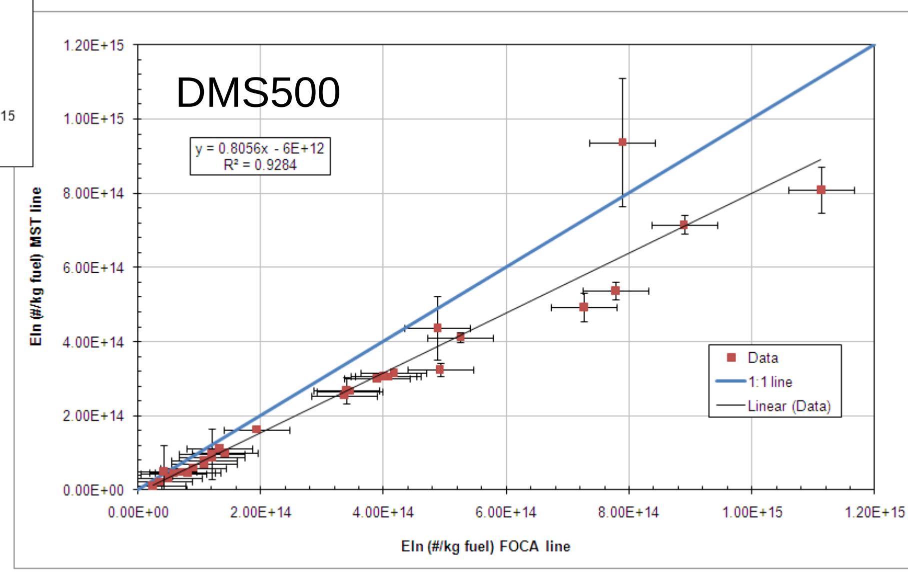
Difference between the two systems averaged ~12%



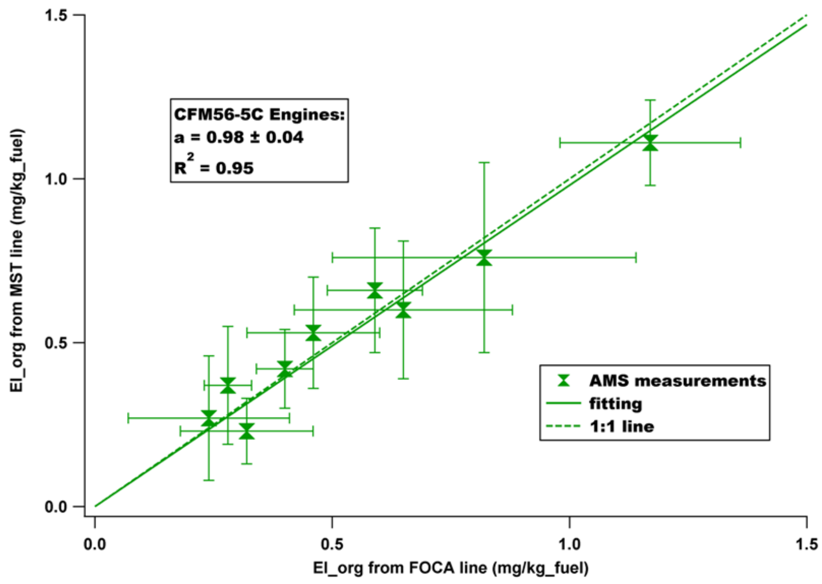
Comparison of the MST and FOCA Sampling Systems – PM Number

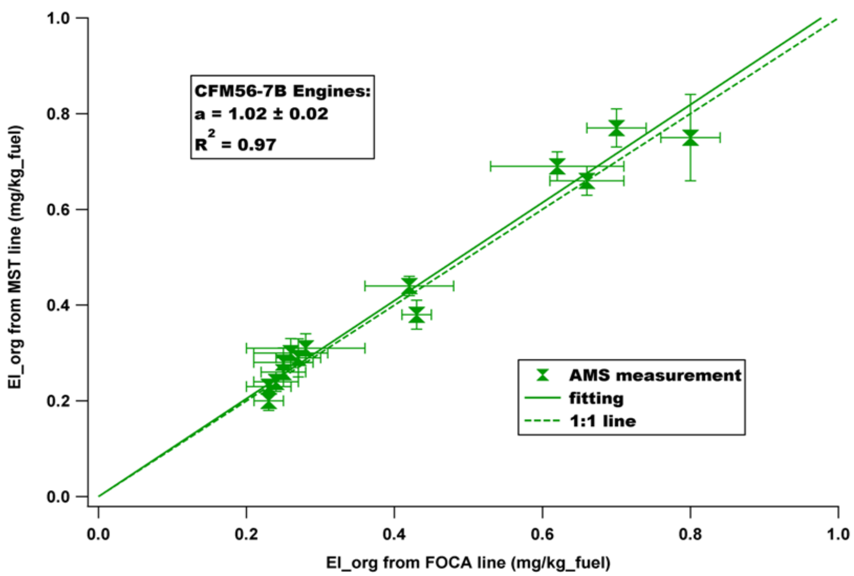


Difference between the two systems as measured by APC and DMS500 averaged ~ 21%



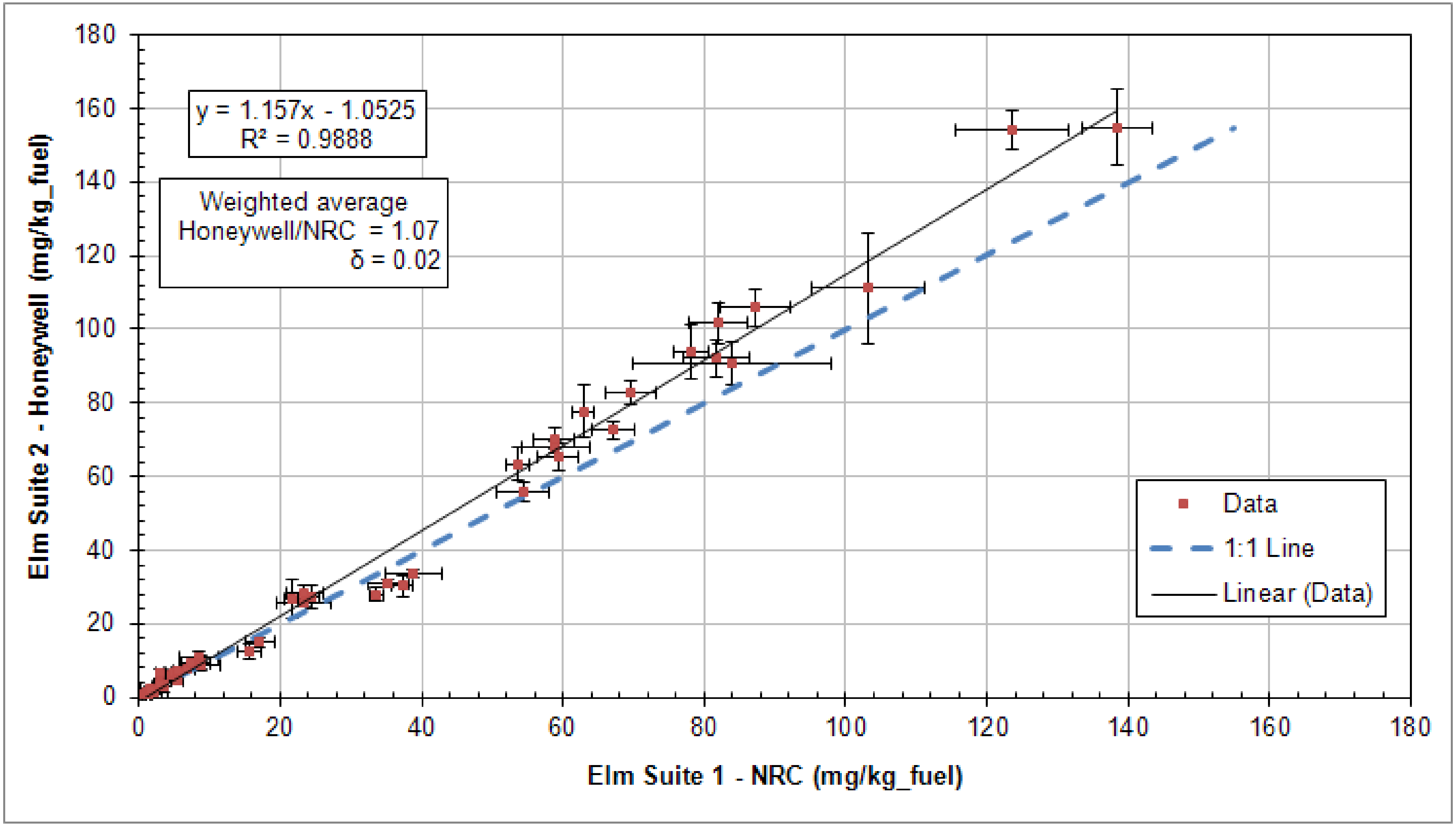
Comparison of the MST and FOCA Sampling Systems – PM Organics



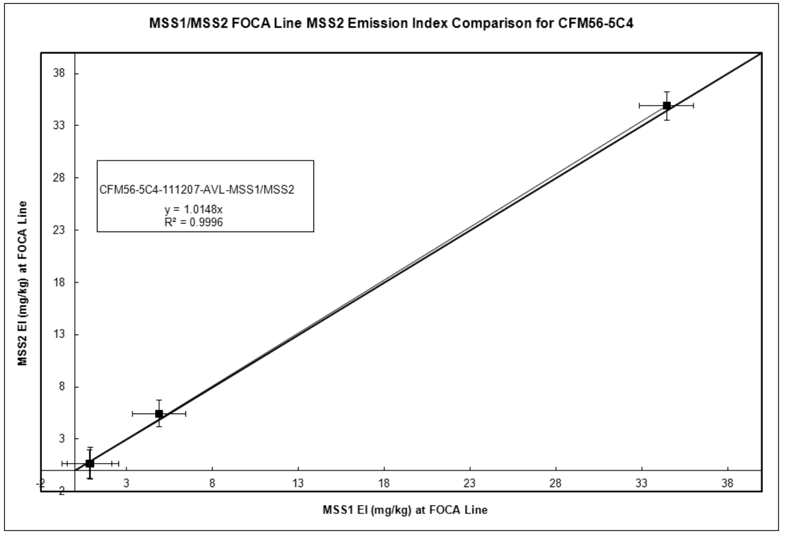


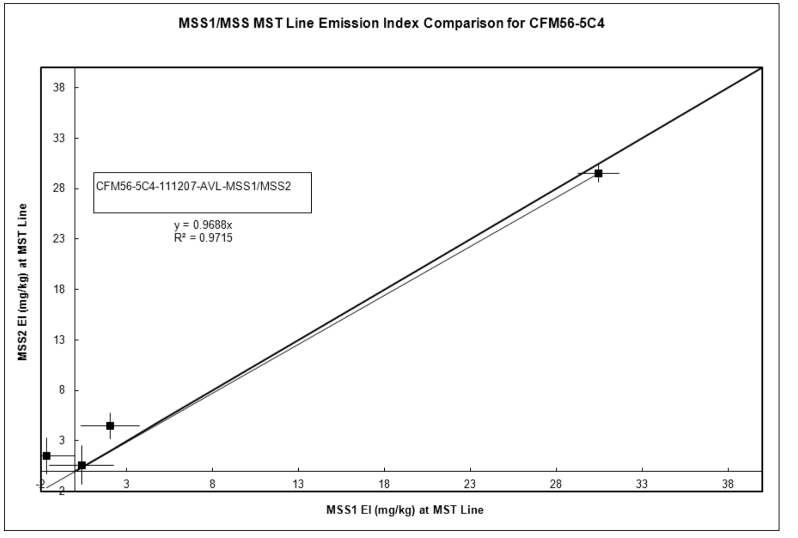
Difference between the two systems in terms of PM organic content was ~ 2%

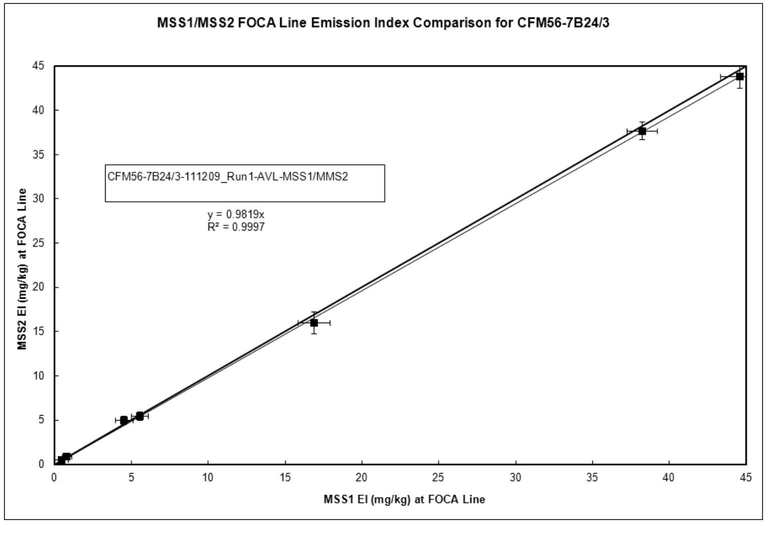
Suites 1 and 2 – LII (data from all tests)

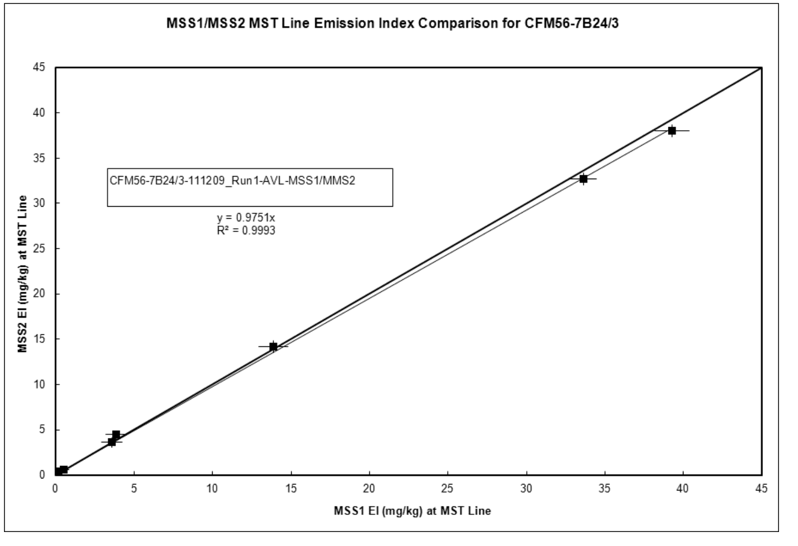


Suites 1 and 2 – MSS









Impact of CPC cut size

- 3 CPCs were installed downstream of the Dekati DEED to measure PM number concentrations

CPC	D_{50}	Working Fluid	Single Particle Counting (p/cc)	Flow rate (L/min)
TSI 3788 CPC	2.5nm	Water	0 - 400,000	1.5
TSI 3772 CPC	10nm	1-Butanol	0 - 10,000	1
TSI 3790 CPC	23nm	1-Butanol	0 - 10,000	1

Impact of CPC cut size

CFM56-5C4

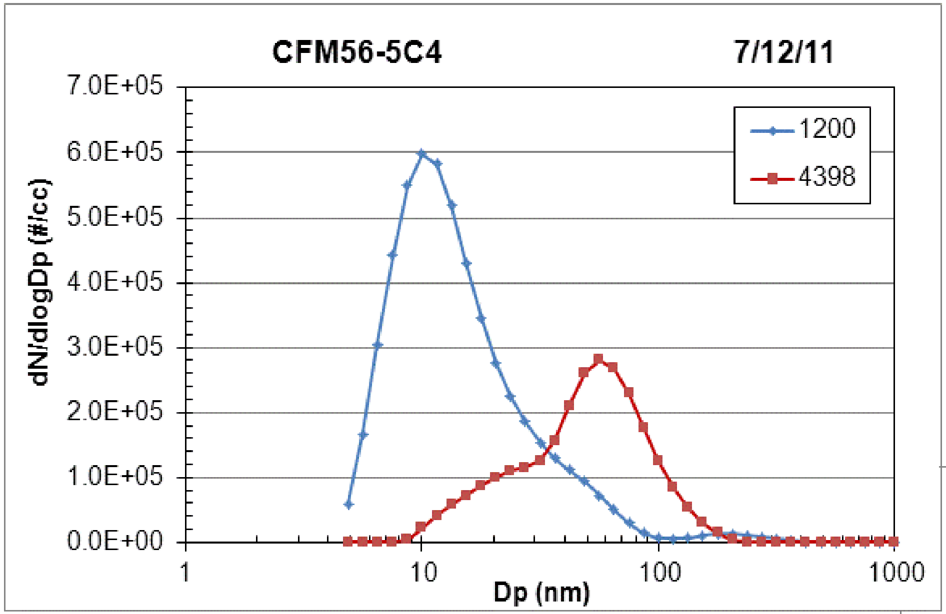
Test Point	Engine Condition (RPM)	Percent difference between 3772 and 3790
1D	1200	76 ± 19
1S	1200	73 ± 39
2S	3000	66 ± 3
3D	3800	41 ± 5
4D	4190	33 ± 2
5D	4398	31 ± 2
5S	4398	34 ± 2
6S1	1500	79 ± 1
6D1	1500	76 ± 4
6S2	1500	79 ± 3

CFM56-7B24/3 (Cycle 1)

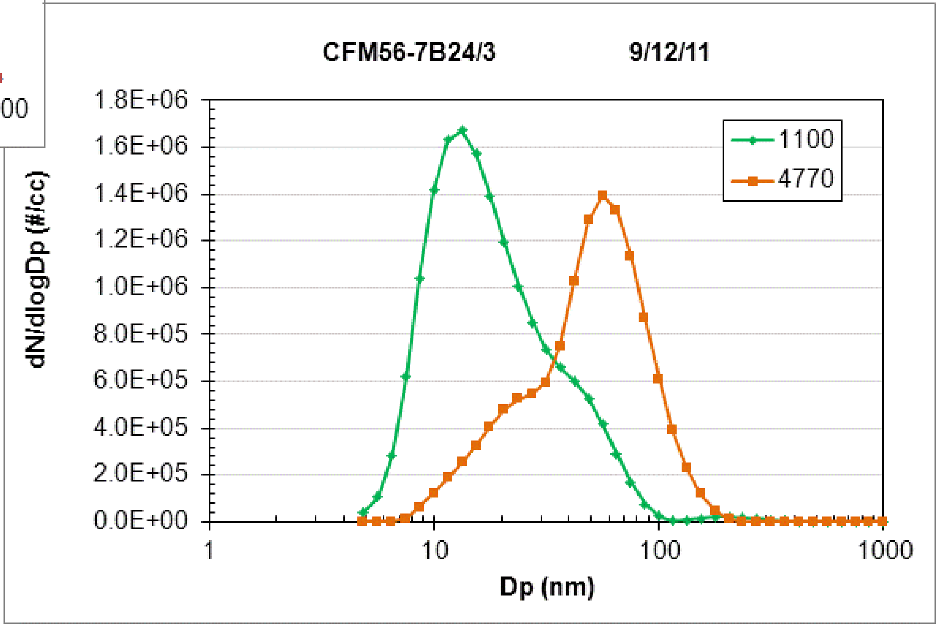
Test Point	Engine Condition (RPM)	Percent difference between 3772 and 3790
1D	1100	73 ± 4
2S	3300	69 ± 11
2D	3300	67 ± 2
3D	4200	40 ± 2
3S	4200	43 ± 2
4S	4600	35 ± 1
4D	4600	32 ± 2
5D	4770	30 ± 1
5S	4770	33 ± 1
6S1	1100	72 ± 1
6D1	1100	68 ± 2
6S2	1100	73 ± 2
6D2	1100	70 ± 4
7D	1300	78 ± 5
7S	1300	82 ± 1

D = DEFAULT configuration
S = SWITCH configuration

PM Size Distributions



Size Distributions were measured with the DMS500 which was part of Instrumentation Suite 2



Size distributions presented here were recorded with the system operating in the DEFAULT Configuration, and were made on a parallel line to CPCs but without any additional (VPR) dilution.

** no line loss corrections applied

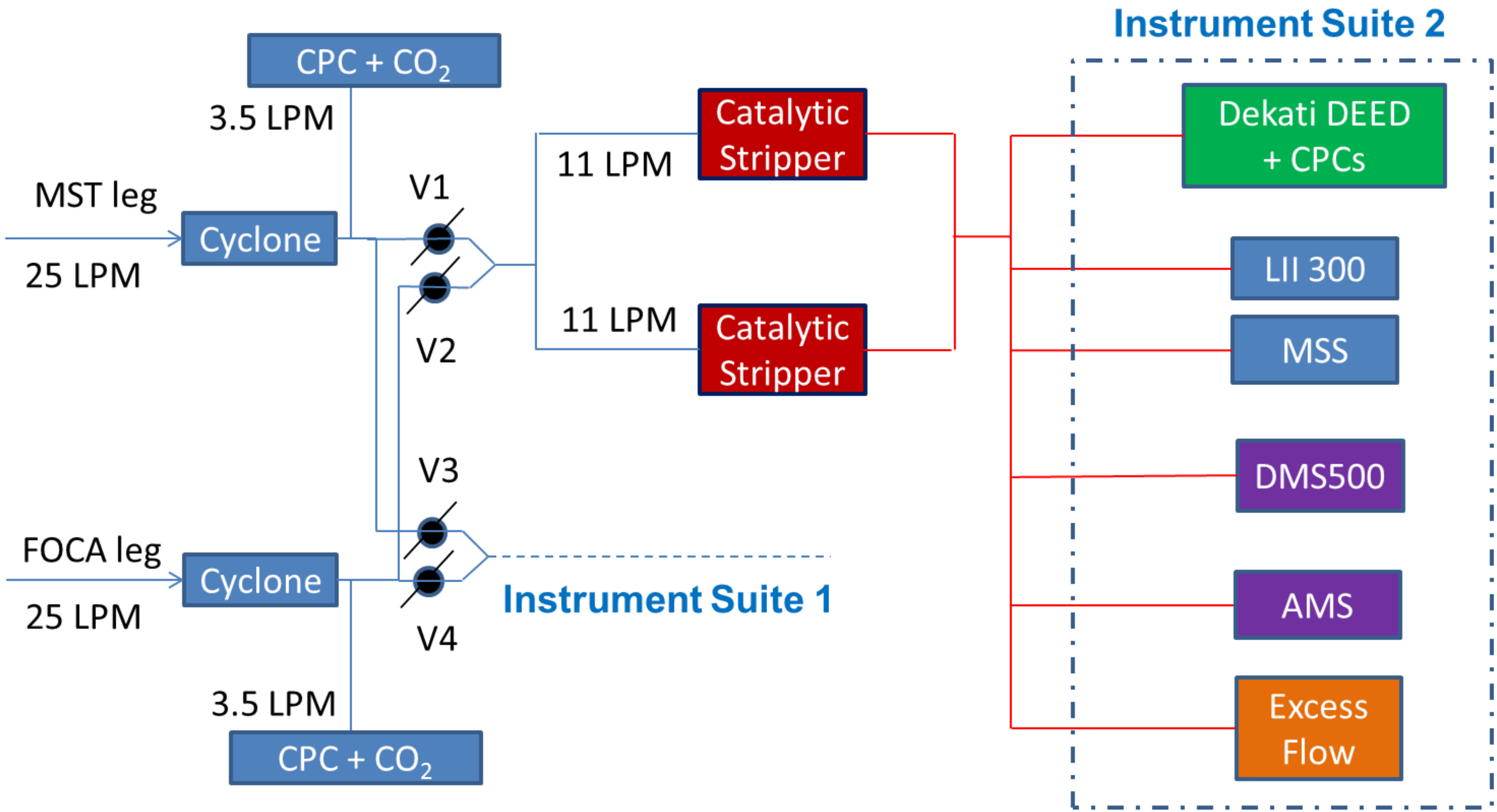
CPC cut size data interpretation with an LTO cycle perspective

LTO Cycle Emissions data for a CFM56-7B Engine

Mode	TiM (mins)	Fuel usage per mode	PM number generated per mode	PM mass generated per mode
Idle/Taxi	26	39.36%	10.62%	0.92%
Take-off	0.7	11.89%	26.32%	48.02%
Climb out	2.2	29.35%	52.81%	48.99%
Approach	4	19.41%	10.25%	2.07%

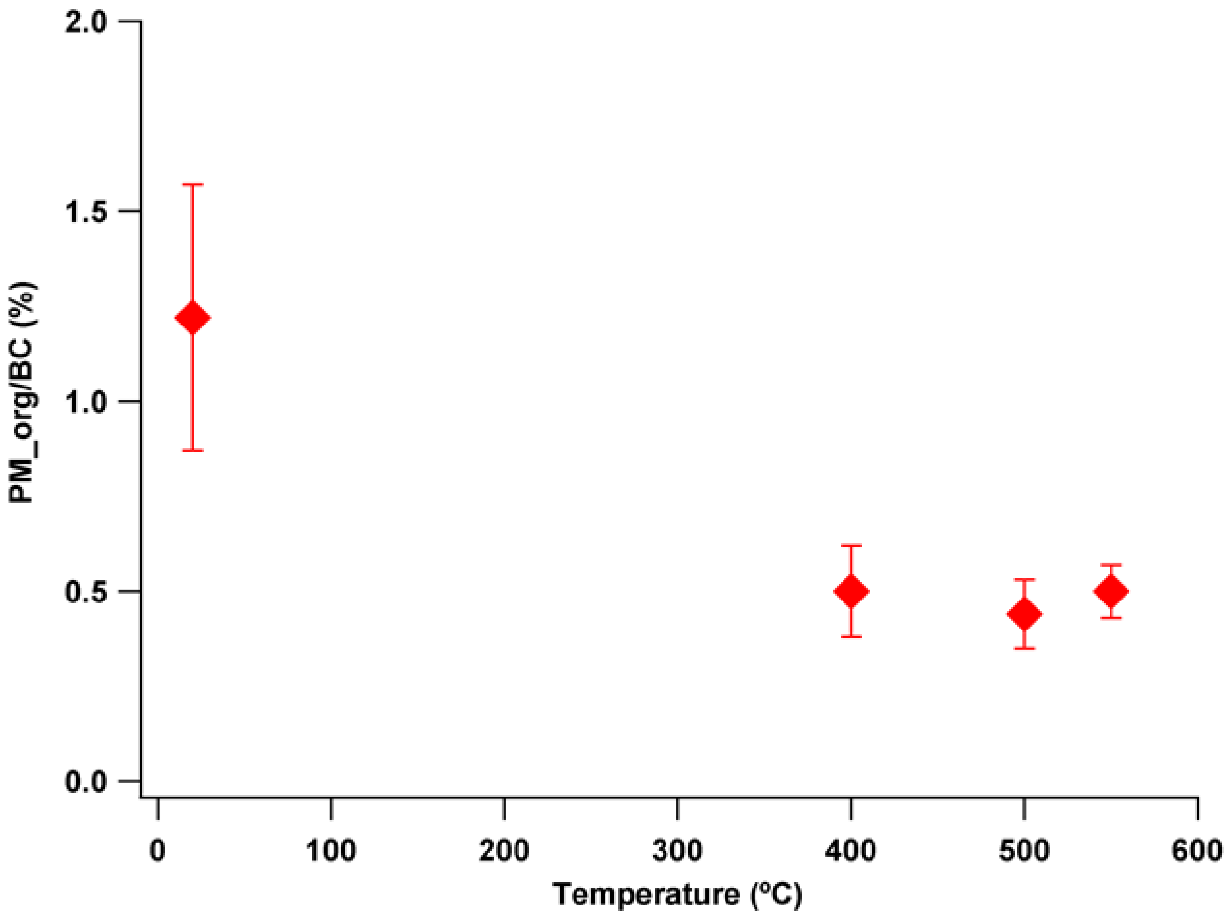
- During take off and climb out
  - >80% of PM number and mass for a CFM56-7B engine is emitted
  - Using a 23nm cut size would underestimate PM number by ~30%
  - Using a 10nm cut size would not result in an underestimation of PM number

System Configuration for tests with Catalytic Stripper



Impact of Volatile PM removal using a Catalytic Stripper

Ratio of Organic PM measured by the AMS and black carbon mass measured by the MAAP



Temperature of the Catalytic Stripper

Summary

- Assembled and evaluated two ARP concept systems
- Achieved simultaneous sampling on the MST and FOCA legs for all engine tests
  - Similar set of instruments on both legs
  - Switched instrument suites between the MST and FOCA legs
- Successfully achieved all major test objectives
  - Comparison of the two sampling systems
    - ~20% difference in PM number
    - ~12% difference in PM mass
    - ~2% difference in PM organic content
  - Impact of CPC cut size on PM number
    - 3788 (2.5nm) and 3772 (10nm) CPC concentrations agreed to within 6%
    - Significant difference observed between the 3772 (10nm) and 3790 (23nm) CPCs
      - ~80% difference at idle, ~30% difference at high power
    - As engine power increases, the mean size increases and the difference between the 3772 and 3790 CPCs decreases
  - Impact of Catalytic Stripper on the removal of volatile PM
    - Volatile PM content reduced from ~1% of BC mass to ~0.5%

Acknowledgements

This work was partly funded by the FAA through the
Partnership for AiR Transportation for Noise and Emissions Reduction (PARTNER) –
a FAA-NASA-Transport Canada-US DoD-US EPA-sponsored Center of Excellence,
under Cooperative Agreement No. 09-C-NE-MST Amendment No. 005

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