Center of Excellence for Aerospace Particulate Emissions Reduction Research

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Partnership for Air Transportation
Noise and Emissions Reduction

Measurement of Aircraft Non-volatile PM Emissions using Aerospace Recommended Practice Compliant Systems during the A-PRIDE 4 Campaign

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Cambridge Particle Meeting
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Background

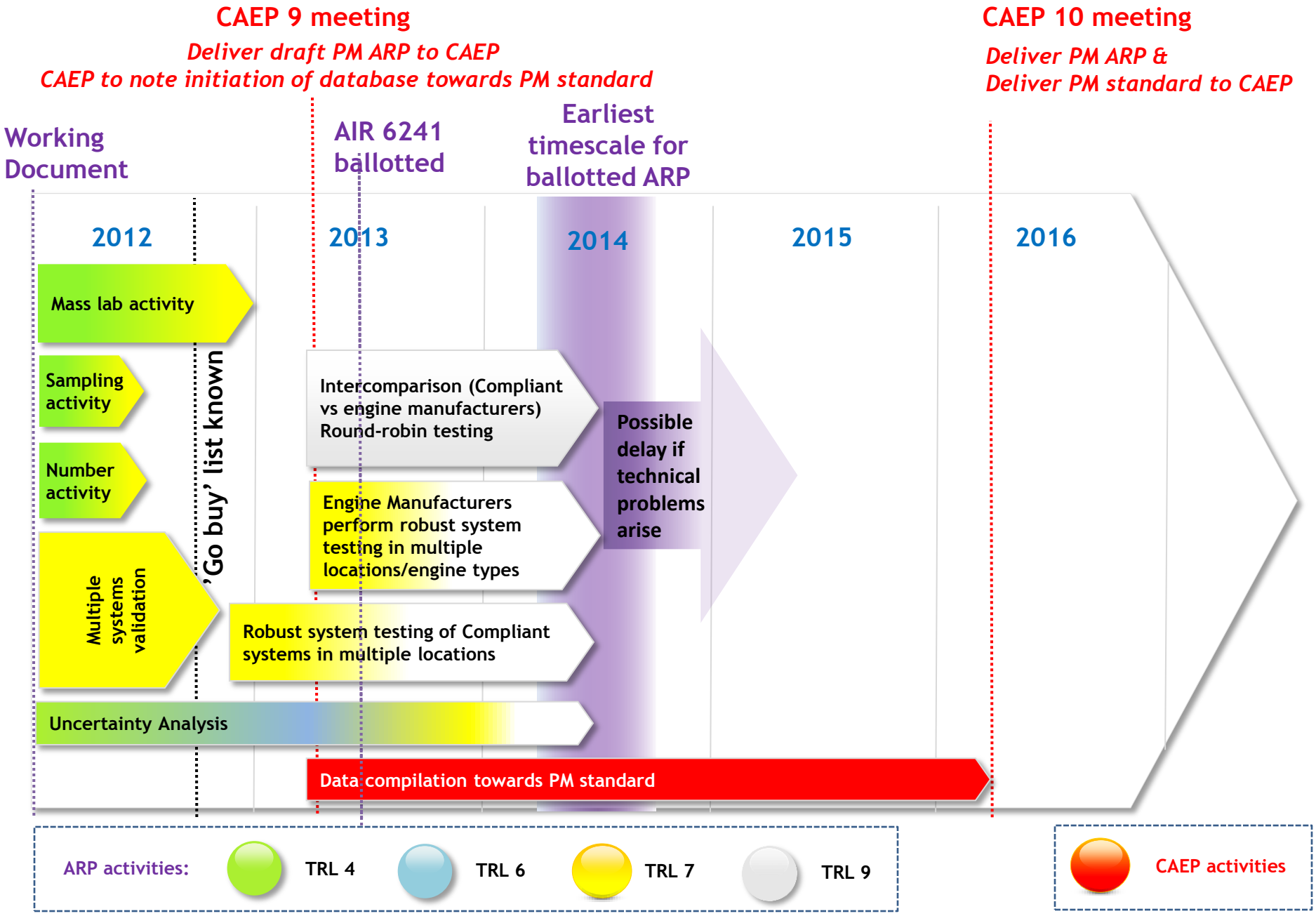
- ICAO has established limits for emissions from gas turbine engines (whose rated output is greater than 26.7 kN) in terms of NOx, CO, UHC, and smoke.

- Smoke number does not permit analysis of environmental impacts of gas turbine emissions and health impact assessments which rely on PM characteristics such as number, mass, size, and composition.

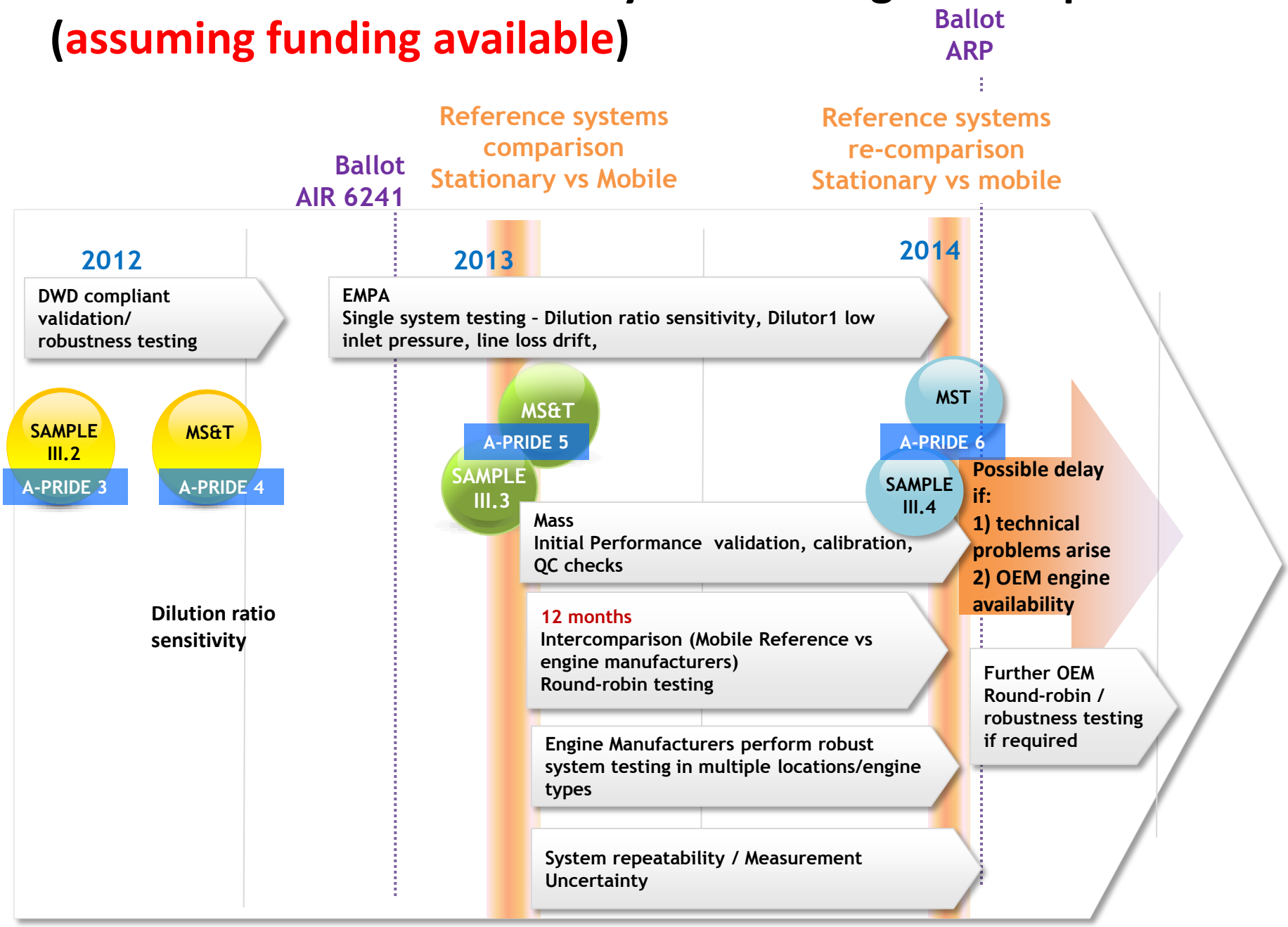
- ICAO emission databank records the engine certification data for gaseous emissions and smoke, however, no such database for PM emissions characteristics is currently available.
  - First-order approximation (FOA) 3.0 has been used to estimate mass-based emission indices using the reported smoke number data, however this approach is only an "*approximation*"

- SAE E-31 committee is in the process of developing an Aerospace Recommended Practice (ARP) for the measurement of non-volatile PM number- and mass-based emissions from gas turbine engines

TRL PM standard roadmap (assuming funding available)



Possible PM measurement system testing roadmap (assuming funding available)



A-PRIDE** and SAMPLE Studies

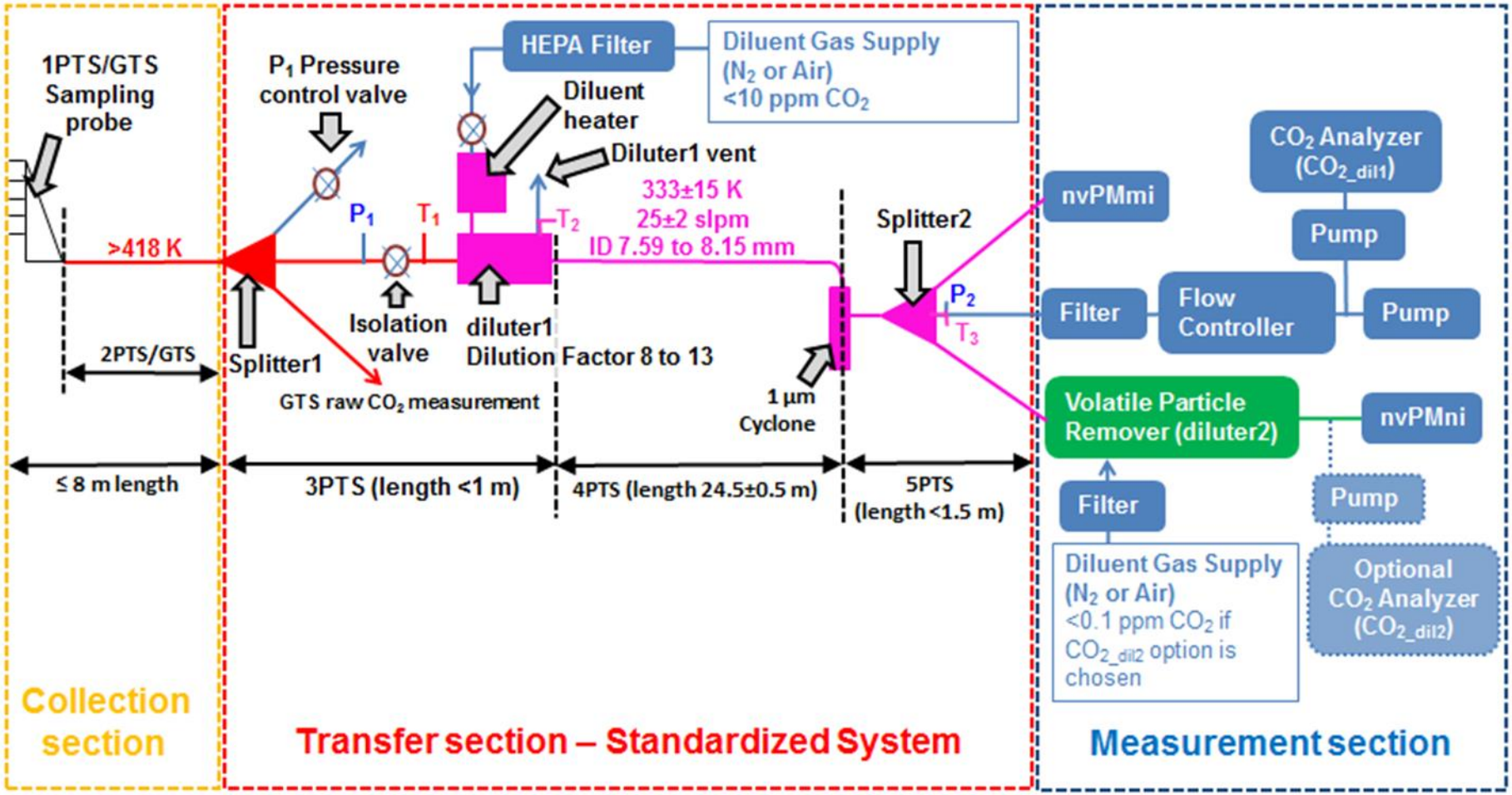
- SAMPLE II RR engine test (Nov 2010)
- AAFEXII engine test (Mar 2011)
- SAMPLE III.1 APU test (Jun 2011)
- A-PRIDE 1: AVL/TSI Campaign (Aug 2011)
- A-PRIDE 2: SR Technics Campaign MST/FOCA (Nov/Dec 2011)
- A-PRIDE 3: SAMPLE III.2 (Apr/May 2012)
- **A-PRIDE 4: MST/FOCA-EMPA (Nov 2012)**

Major Accomplishments:

- Assisted in the development of the methodology for the DWD/AIR/ARP
- Comparison and performance evaluation of compliant systems

** **A**viation **P**article **R**egulatory **I**nstrumentation **D**emonstration **E**xperiments

Components of an ARP System



A-PRIDE 4 Objectives

- **Primary objective**
  - Performance evaluation and comparison of two DWD/AIR compliant systems

- **Secondary objectives**
  - **E-31**
    - Mass instrument intercomparison (LII vs. MSS)
    - ARP Operational checklist implementation
  - **EMPA/ETH**
    - Particle density measurement using DMA-CPMA
    - Mass closure between CPMA + SMPS (using density + size distribution = mass distribution) and mass instruments
    - Particle chemical composition (restricted size range) using SP-AMS
    - Inter-comparison between AMS and SP-AMS for non-refractory material

Test Team

- **MST**: **Prem Lobo**, Steven Achterberg, Elizabeth Black, Max Trueblood, Don Hagen, Phil Whitefield
- **ARI**: **Rick Miake-Lye**, Zhenhong Yu
- **EMPA**: **Lukas Durdina**, Jing Wang, Yeon Bahk, Jelena Buha
- **ETH**: Berko Sierau, Amewu Mensah, **Joel Corbin**, Manuel Abegglen
- **NRC**: **Greg Smallwood**, Kevin Thomson
- **FOCA**: **Theo Rindlisbacher**, Alice Suri
- **EPA:** **John Kinsey**
- **AVL**: Michael Arndt, Barouch Giechaskiel
- **SR Technics**: **Frithjof Siegerist (Ziggy)**, David Kaufmann

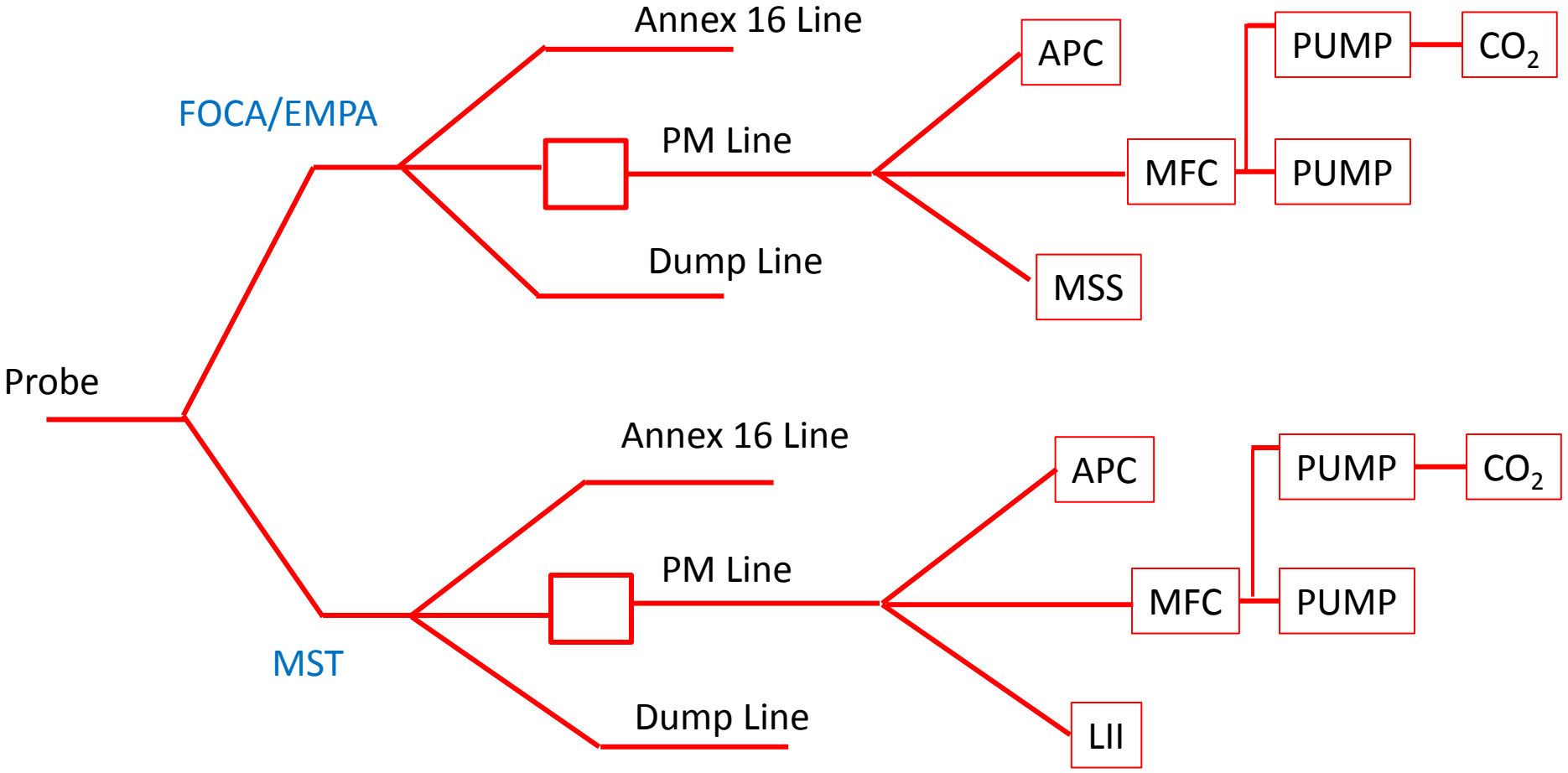
- **Observers:** Matthias Gantenbein* (FOCA), Simon Trauffer** (EFV), Doug Worsnop (ARI), Urs Baltensperger (PSI), Jay Slowik (PSI), Dave Lister (UK CAA), Wendy Bailey (TC), Mark Johnson (RR), Ulrike Lohmann (ETH)

Team POCs

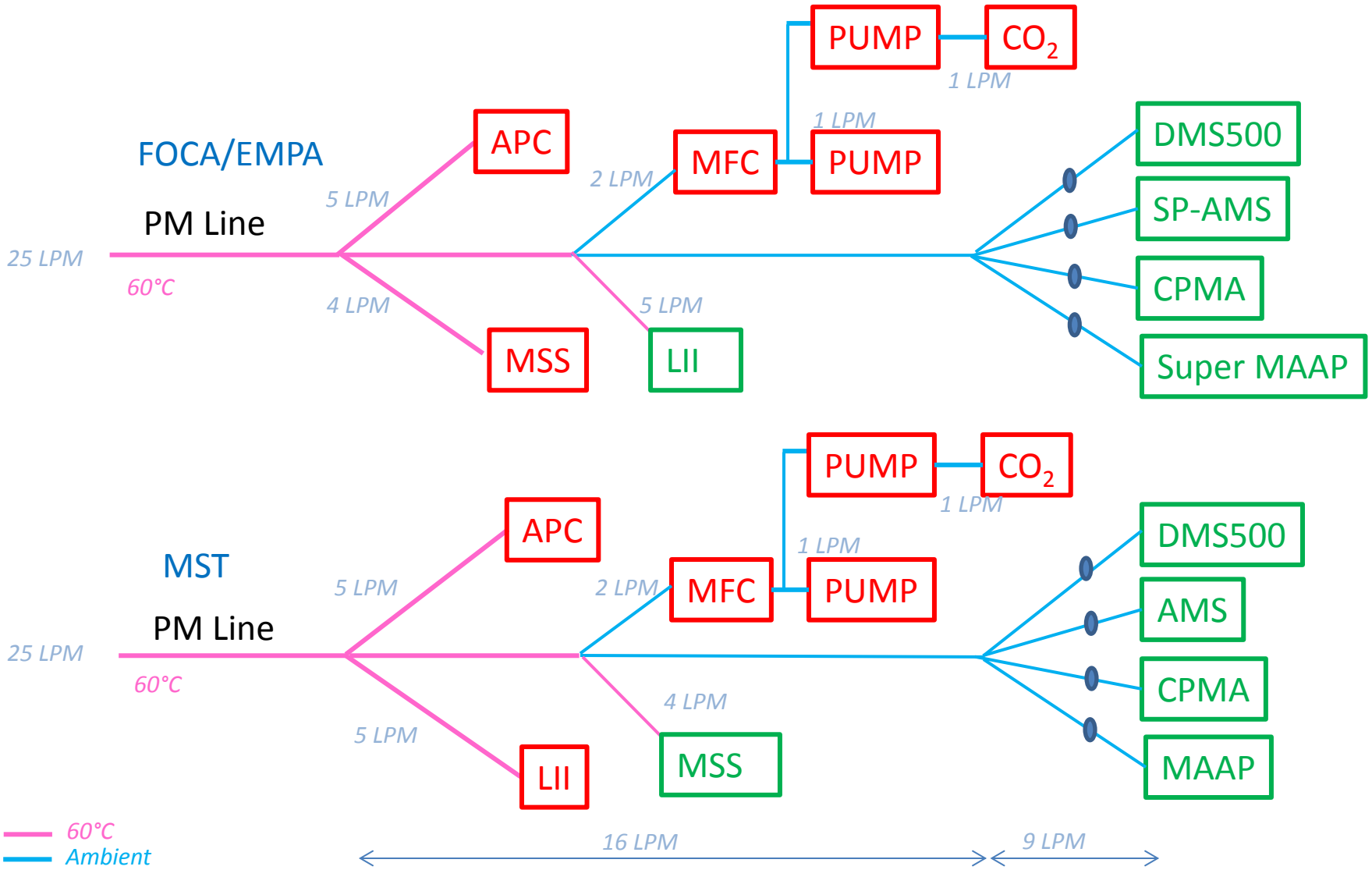
* *In charge of aviation fuel tax fund programs at FOCA*

** *Swiss Government Finance Department*

System Configuration
ARP instruments



System Configuration (ARP + ancillary instruments)

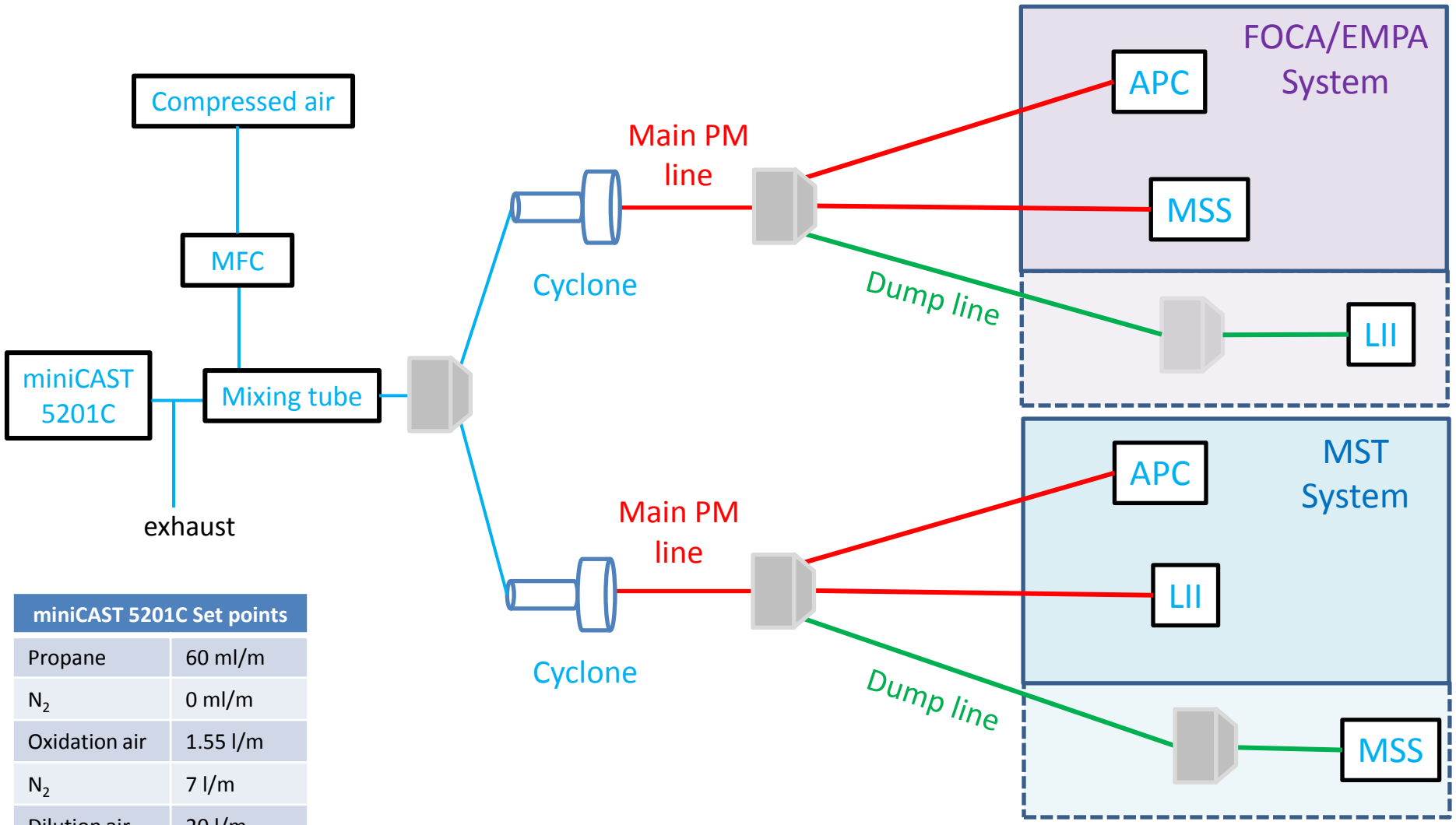


Instrument Intercomparisons

Instruments

- Mass instruments available for inter-comparison:
  - *FOCA/EMPA System*
    - MSS – from EMPA – on main FOCA/EMPA PM line
    - LII – from NRC – on FOCA/EMPA dump line
      - calibrated vs. NIOSH 5040 immediately prior to A-PRIDE 4 campaign
  - *MST System*
    - LII – from MST – on main MST PM line
      - calibrated vs. NIOSH 5040 immediately prior to A-PRIDE 4 campaign
      - Pre-campaign calibration factor: **0.802**; Post-campaign calibration factor: **0.798**
    - MSS – from AVL – on MST dump line
- Number instruments available for inter-comparison:
  - *FOCA/EMPA System*
    - APC – from EMPA – on main FOCA/EMPA PM line
  - *MST System*
    - APC – from MST – on main MST PM line

System Configuration



miniCAST 5201C Set points	
Propane	60 ml/m
N_2	0 ml/m
Oxidation air	1.55 l/m
N_2	7 l/m
Dilution air	20 l/m

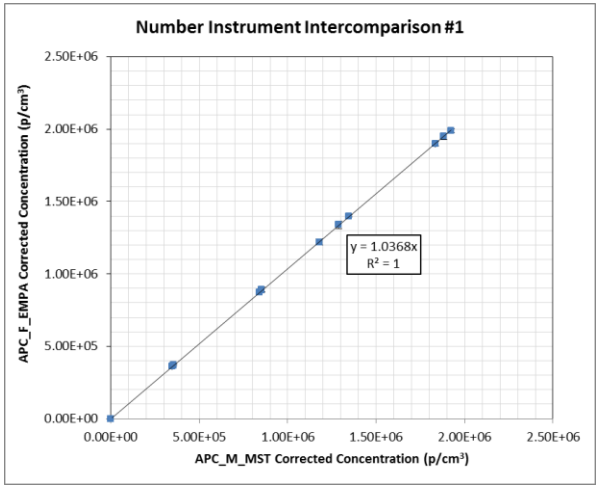
Experimental Procedure

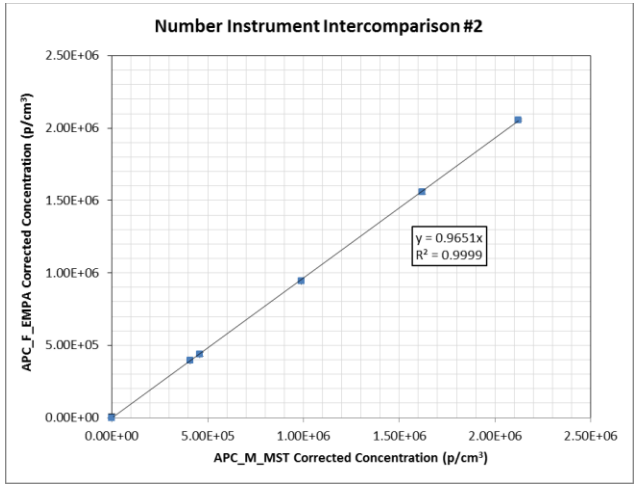
- Prior to the engine tests
  - once to determine the differences between instruments and to establish a normalization factor
  - a second time to verify the normalization factor
- Following the engine tests
  - to determine the drift (if any) in the instrument output
- The system for the inter-comparison study were configured as shown previously
- Equivalent line lengths were maintained between the splitters and instruments on both the FOCA/EMPA and MST systems
- All instruments were operational and recording data
- For each test point, after a stabilization period, each instrument recorded data for a period of 5 minutes
- Three sequences were conducted

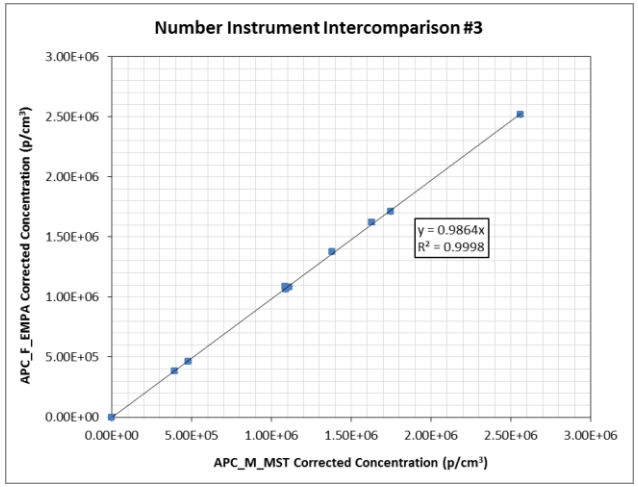
Test 1 (low to high)	Test 2 (random)	Test 3 (random)
0	500	500
250	250	1000
500	1000	250
750	750	0
1000	0	750

Concentrations in $\mu g/m^3$

Pre-test PM number instrument Inter-comparison

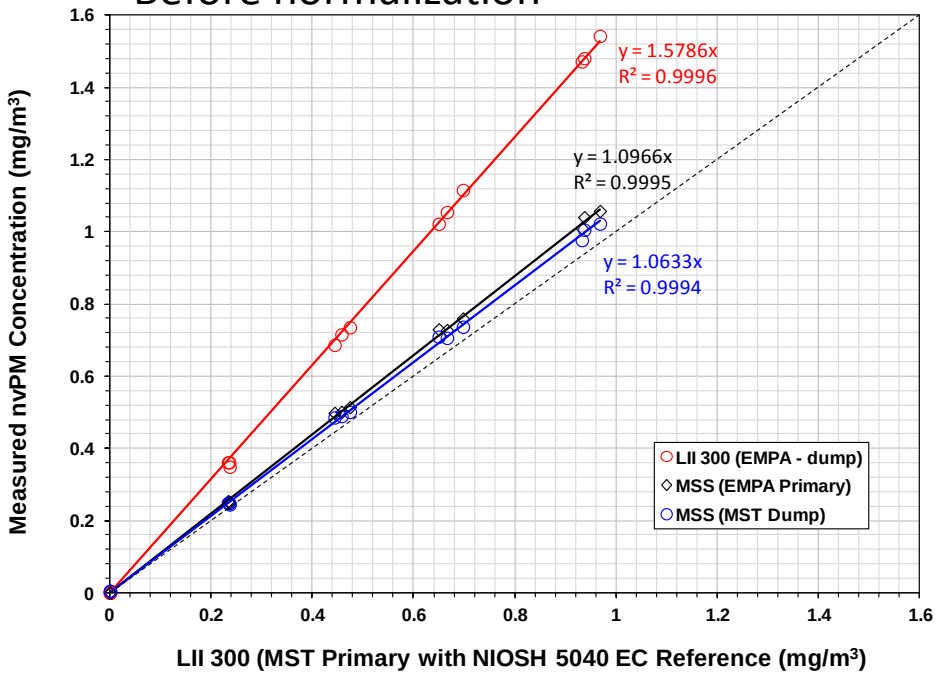




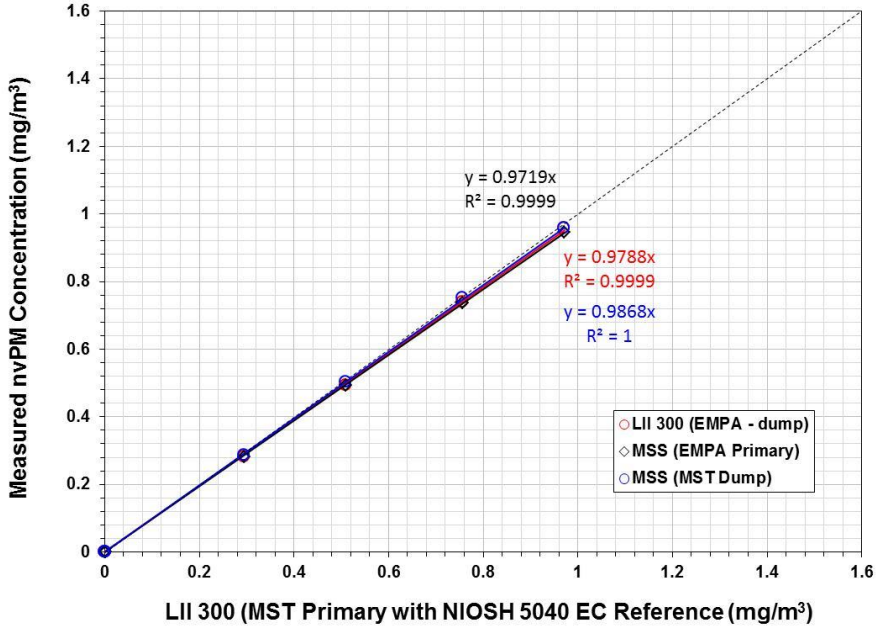


Pre-test PM mass instrument Inter-comparison

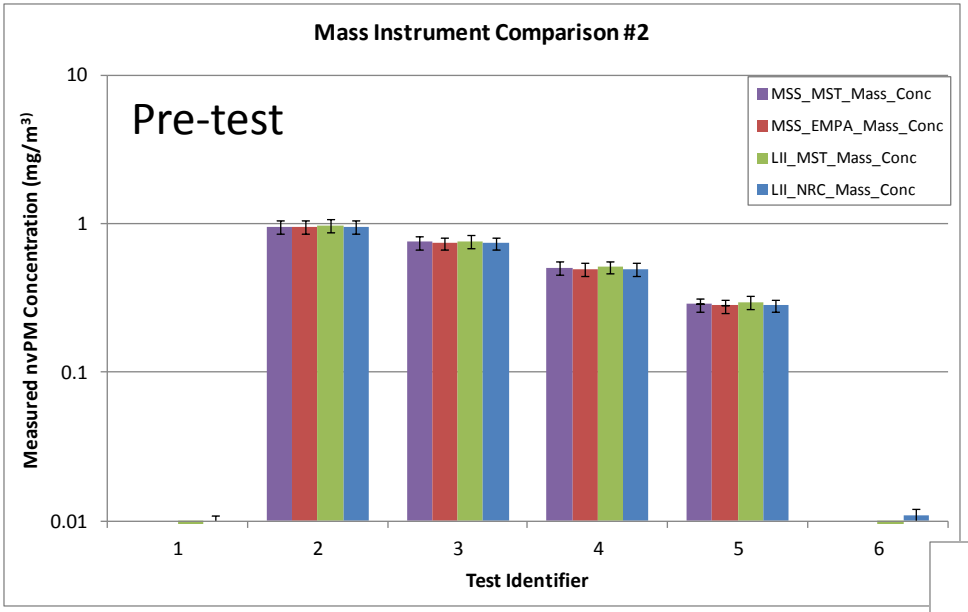
Before normalization

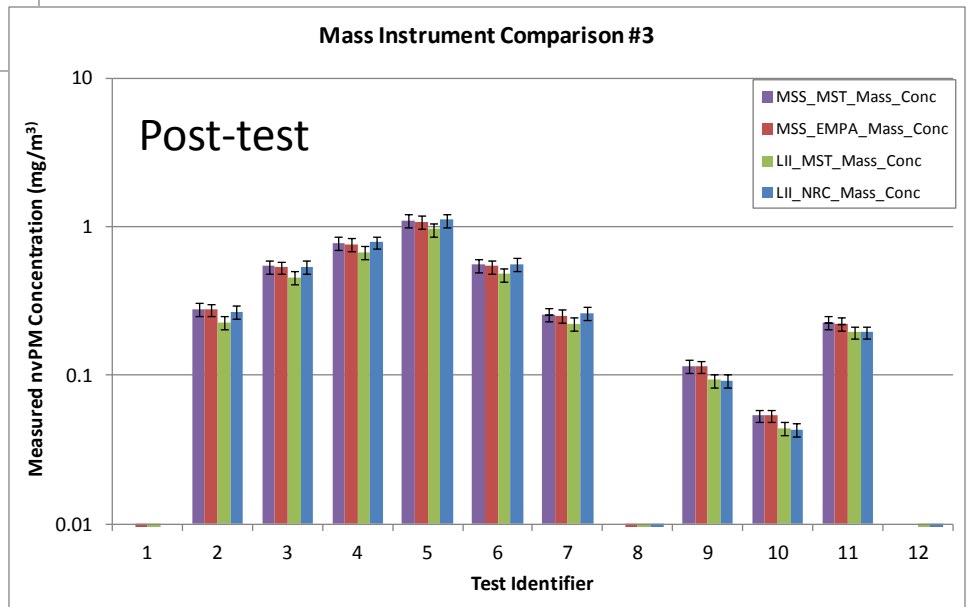


After normalization



PM mass instrument Inter-comparison





Engine Tests

Engine Test Details

Date	Test #	Start Time	Stop Time	Engine	Test Details
10/11/12	1	18:59	20:30	CFM56-5B4/2P	Shakedown Test
11/11/12	2	14:46	17:57	CFM56-5B4/2P	Dedicated Engine Test
12/11/12	3	14:40	17:45	CFM56-5B4/2P	Dedicated Engine Test
13/11/12	4	09:59	10:48	CFM56-7B24/3	Piggy Back Test (Seal Test)
14/11/12	5	12:26	13:21	PW4168A	Piggy Back Test (Seal Test)
15/11/12	6	08:56	12:29	CFM56-5B4/2P	Dedicated Engine Test
16/11/12	7	17:34	23:00	CFM56-7B24/3	Piggy Back Test (Seal + Trim balance Test)
18/11/12	8	11:12	15:28	CFM56-5B4/2P	Dedicated Engine Test

Test Matrix for Dedicated Engine Tests

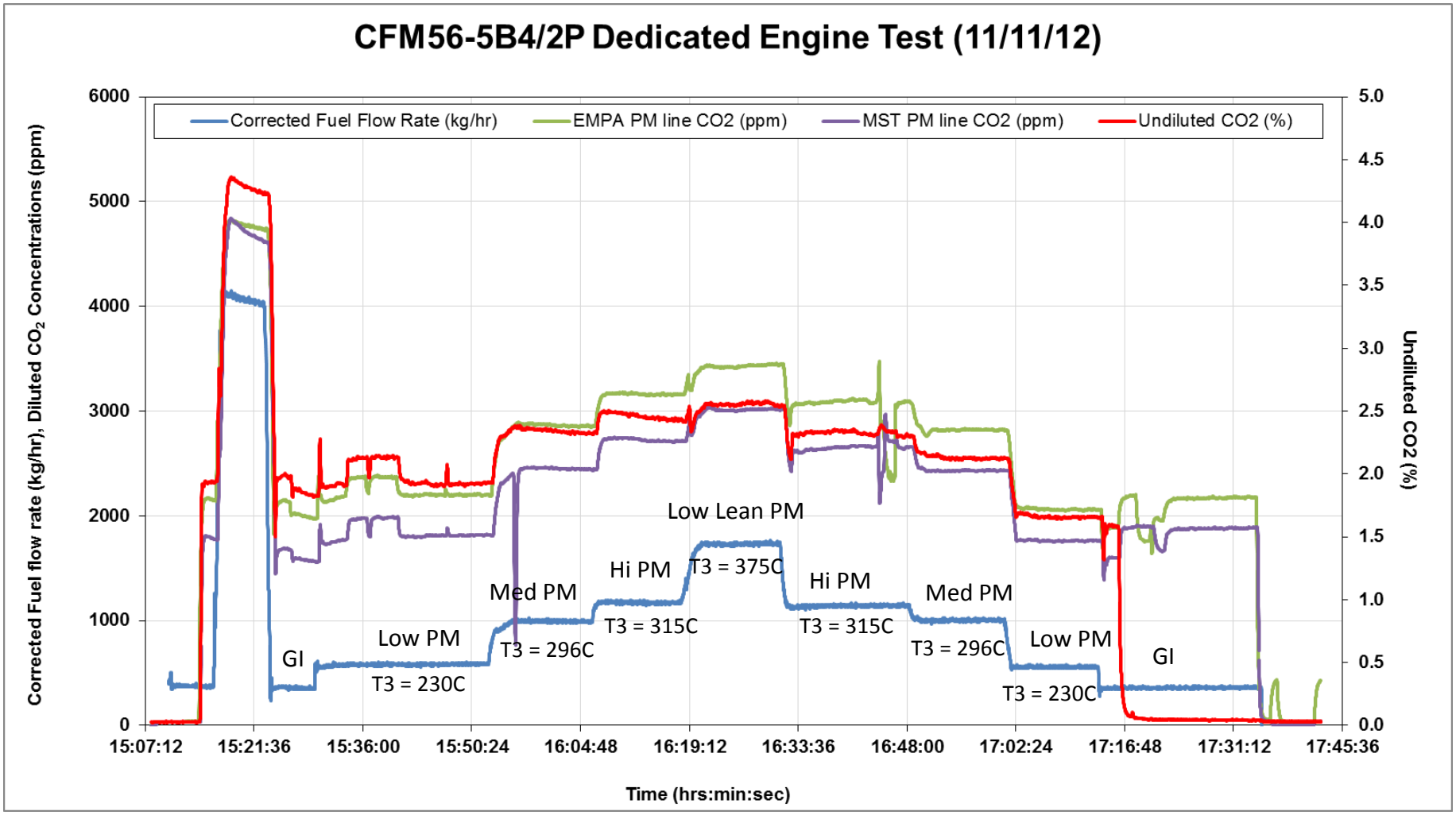
- Test points for A-PRIDE 4
  - Low PM [T3=230°C]
  - Med PM [T3=296°C]
  - Hi PM [T3=315°C]
  - Lean Low PM [T3=375°C]

Test points for SAMPLE III.2

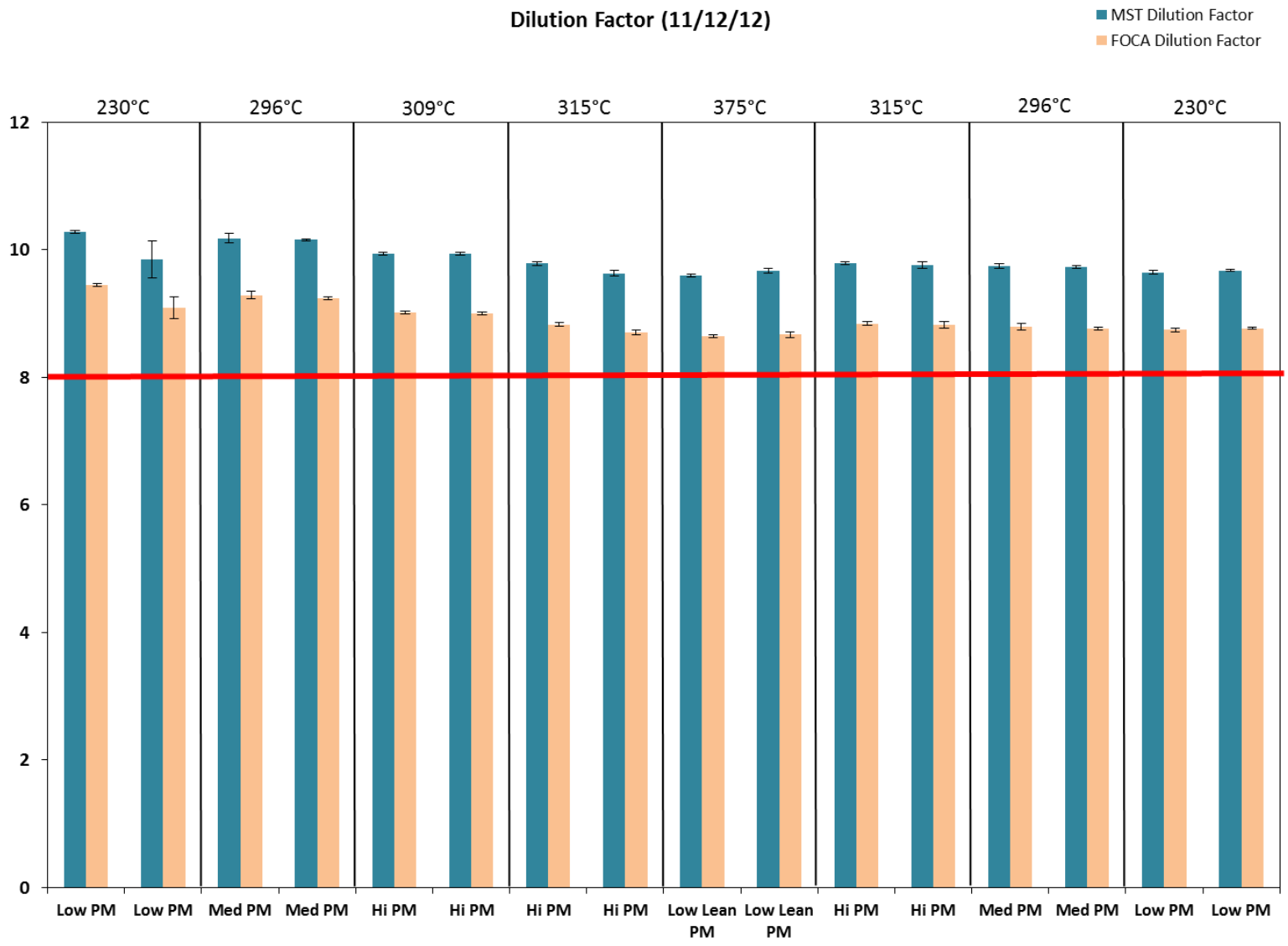
- ML [T3=230°C]
- MH[T3=296°C]
- H[T3=340°C]
- L [T3=375°C]

- Typical run times
  - 5 mins at ground idle to start
  - 5 + 10 to16 mins per test point (7 total test points)
    - 5 mins to set T3
    - 5-8 mins with main systems and DMS500
    - 5-8 mins with main systems and MAAP
  - 5 mins at ground idle to end

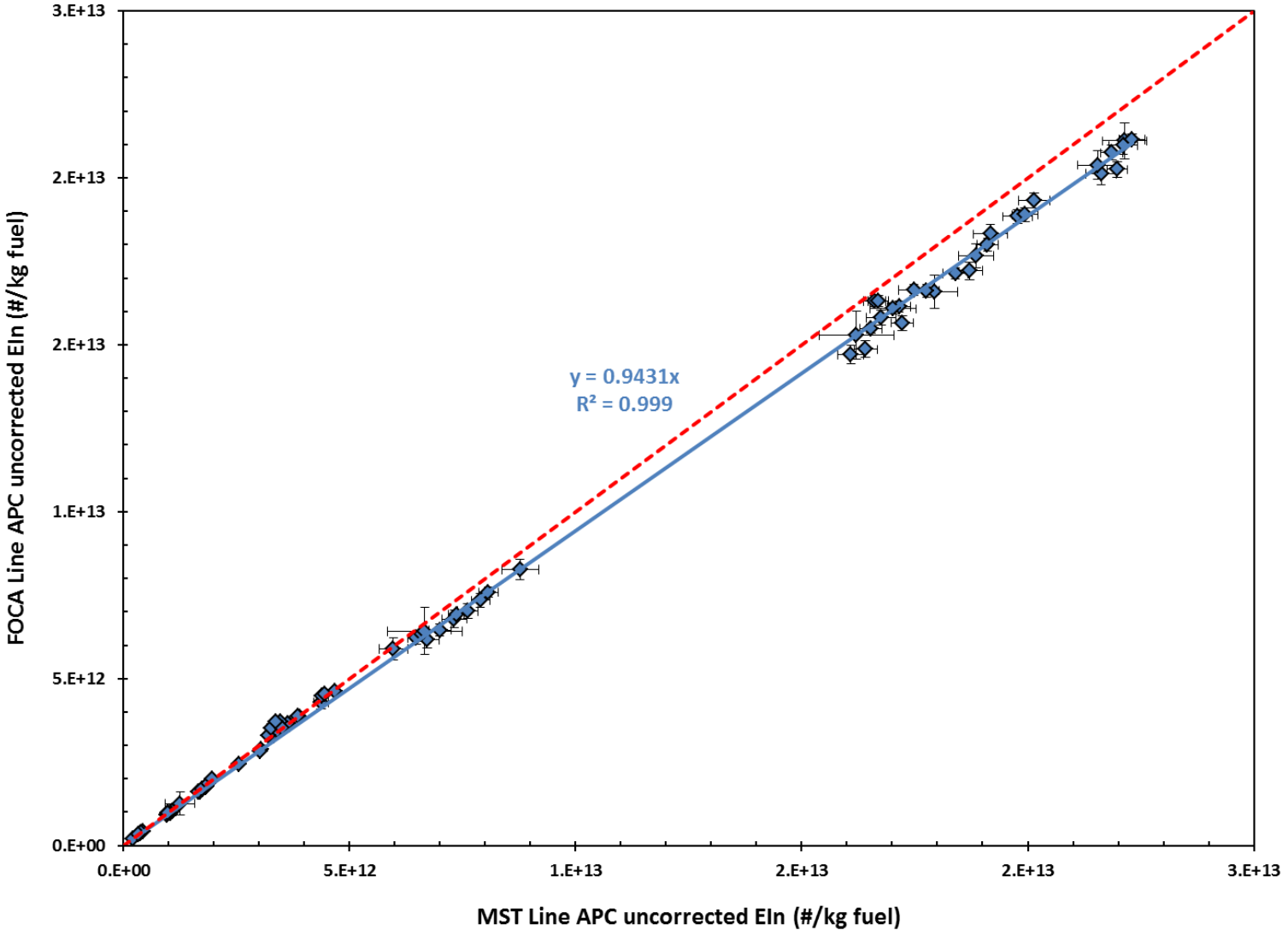
Time Series for Test #2



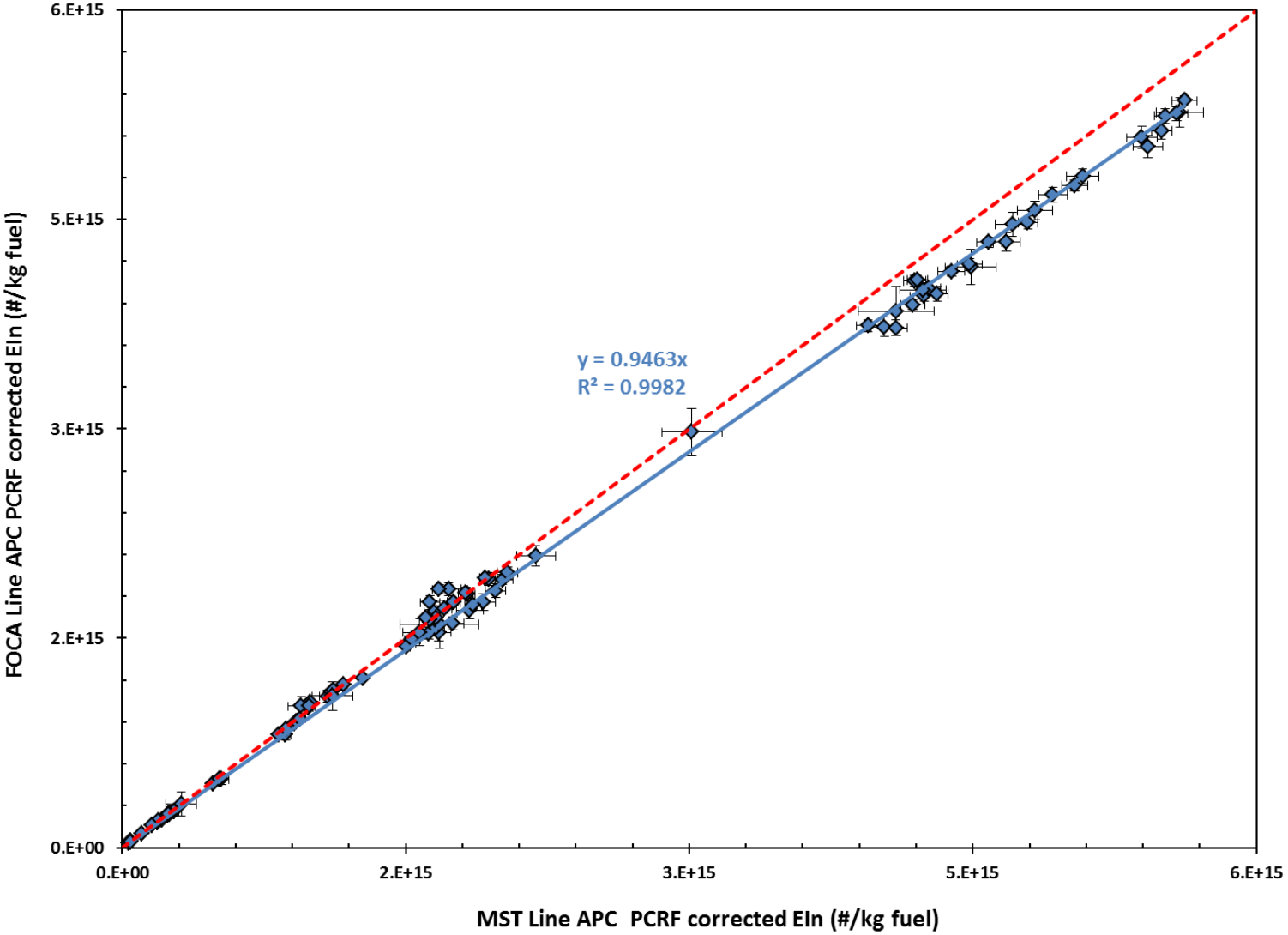
Dilution Factors



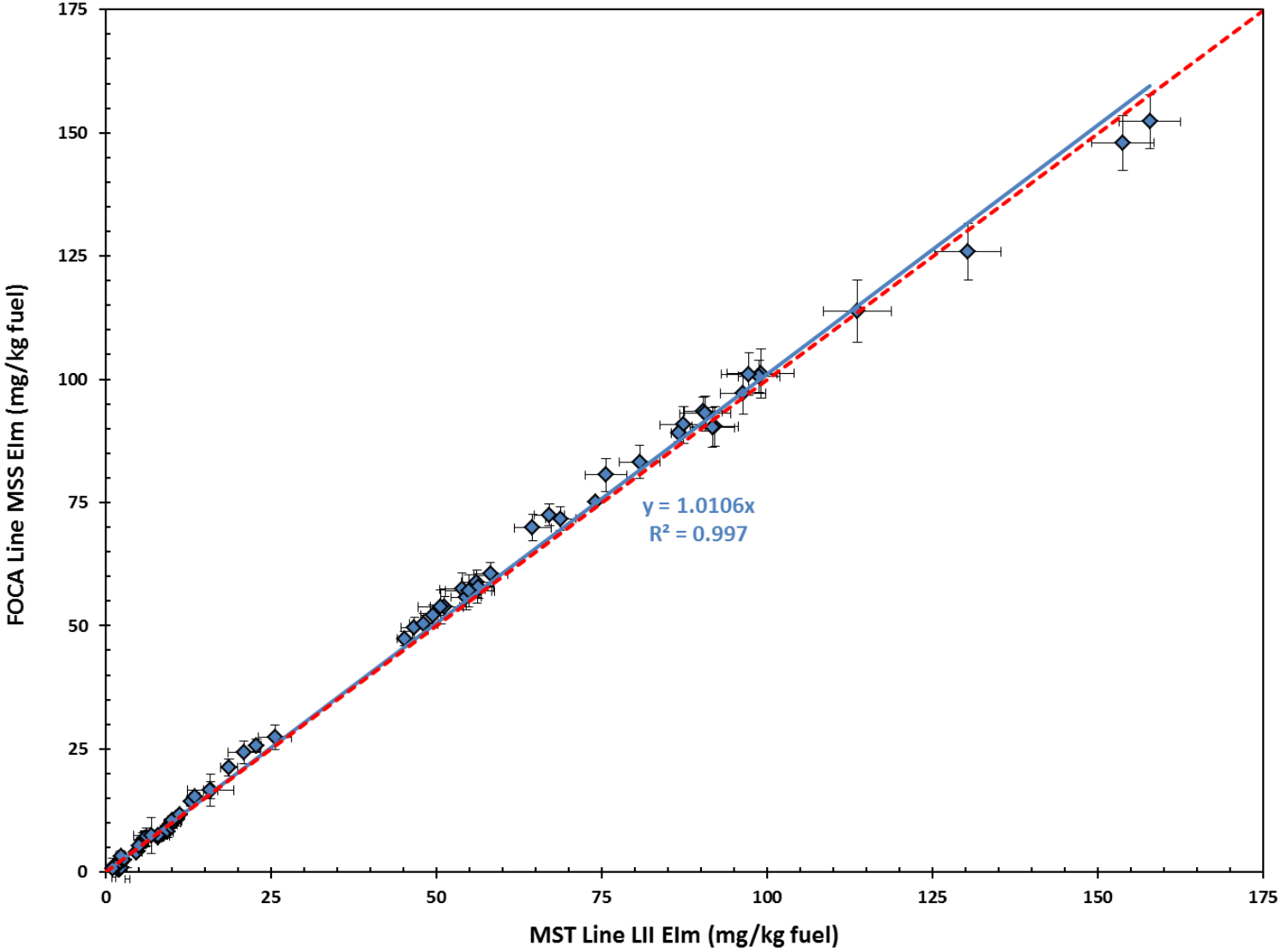
PM Number – Overall (uncorrected)



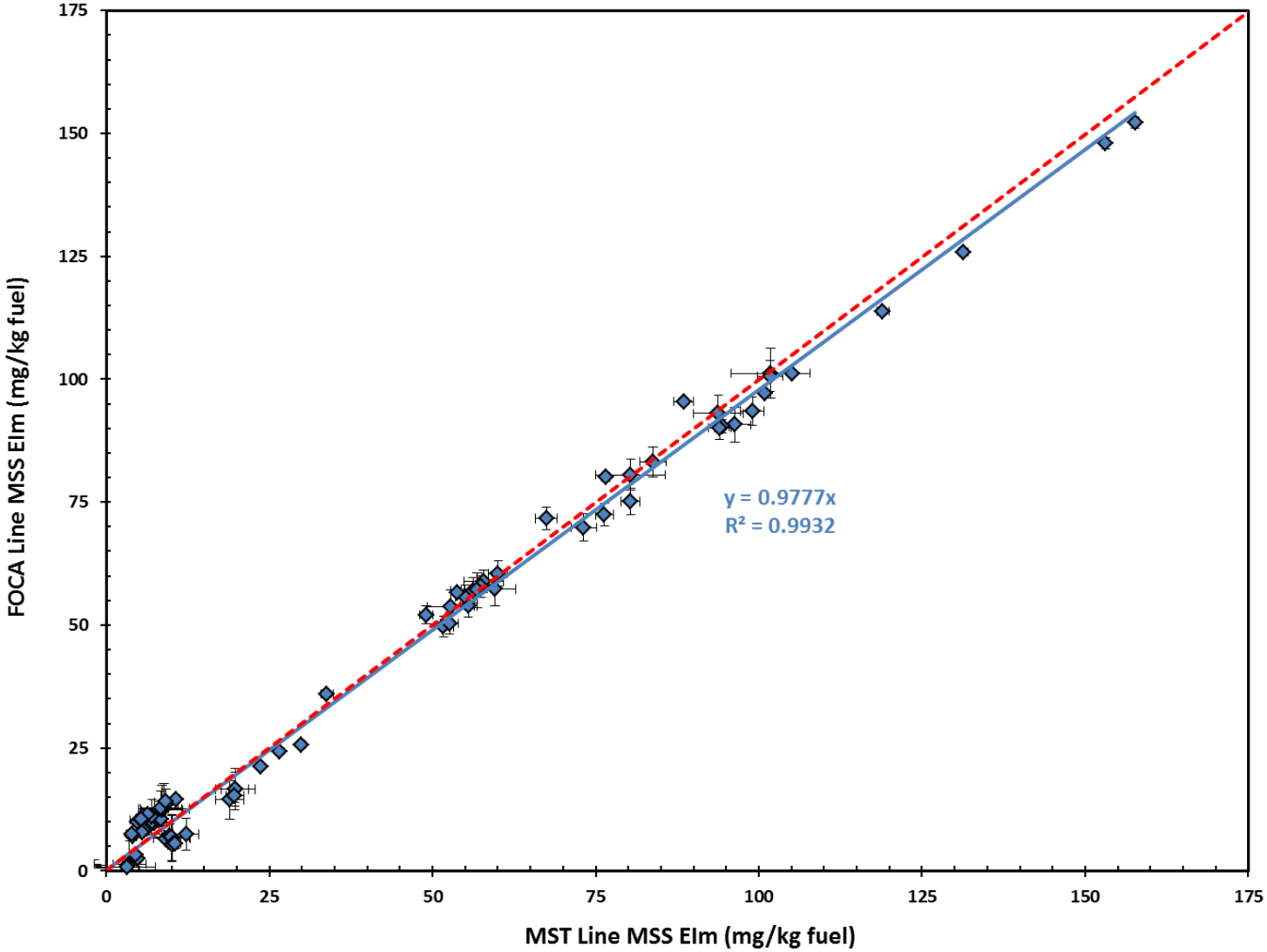
PM Number – Overall (PCRF corrected)



PM Mass – Overall (Primary mass instruments)



PM Mass – Overall (MSS instruments)



Conclusions

- Use of NIOSH 5040 provided a robust calibration for the mass instruments
- Pre-test calibration to NIOSH 5040 EC was the same as the post-test calibration factor (within 0.5%)
  - calibration to NIOSH 5040 is repeatable and reproducible
- Performance evaluation of two identically assembled, DWD compliant systems was successfully performed
- The FOCA/EMPA and MST system agreement in terms of
  - PM number was ~5%
  - PM mass was ~ 1%

A-PRIDE 4 Team

Acknowledgments

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