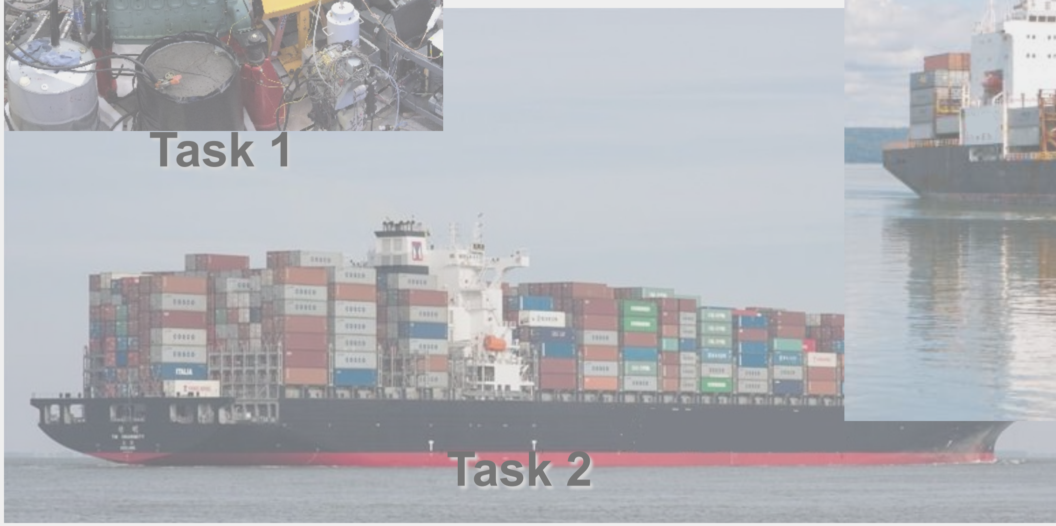
# Measure Marine Black Carbon Emissions
# Test Stand and Two On-Sea Campaigns

Task 1



Task 2

Task 3

Center for Environmental Research and Technology,
College of Engineering, University of California, Riverside

UCR UNIVERSITY OF CALIFORNIA, RIVERSIDE

ICCT Third Workshop on Marine Black Carbon Emissions
September 7th and 8th 2016
Vancouver, British Columbia Canada

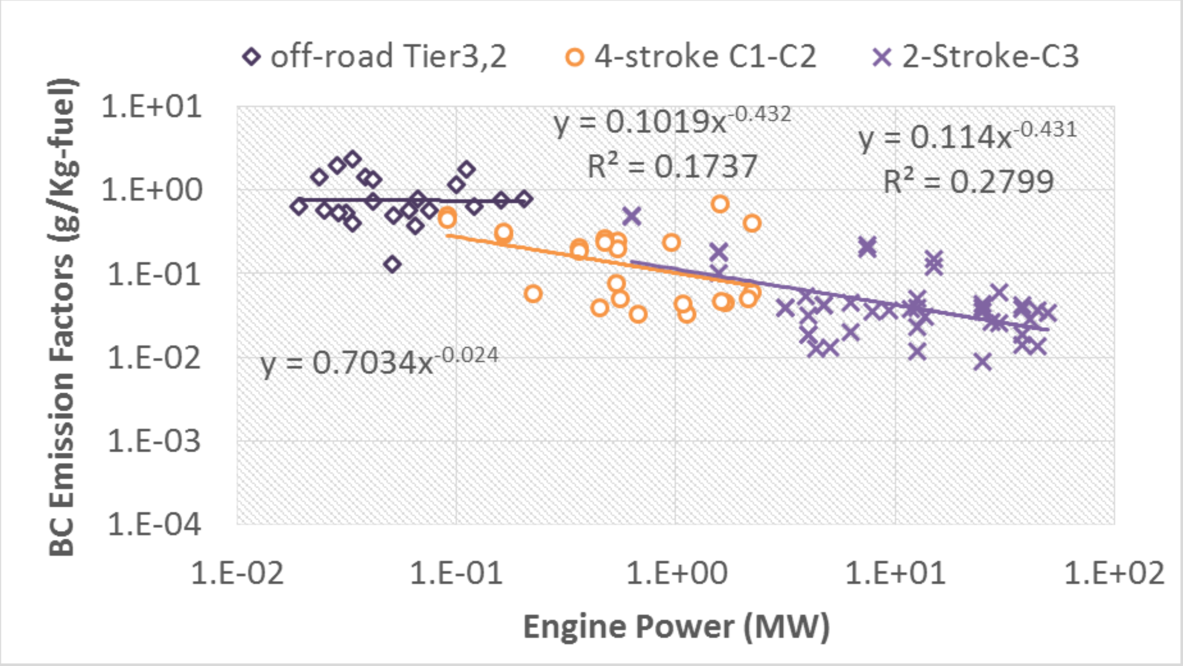
- **Motivation**
- **Background**
- **Approach**
- **Results**
- **Discussions**

# Project Motivation/Background

- International shipping has been reported at 2% of global BC emissions (Lack *et al.* 2012)
- Wide range (0.01-1 gBC/kg-fuel) of black carbon emission ratios in literature (Gysel *et al*., 2016, Lack *et al.* 2013, Kahn *et al* 2012, Petzold *et al*., 2010, Murphy *et al*. 2009, Agrawal *et al*. 2008)
- Different techniques used to estimate BC
  - Thermal/optical (EC/OC)
  - Laser induced incandescence (SP2, LII)
  - Light absorption-optical (MAAP, Aethalometer, FSN)
  - Light absorption-photoacoustic (MSS, PAS)

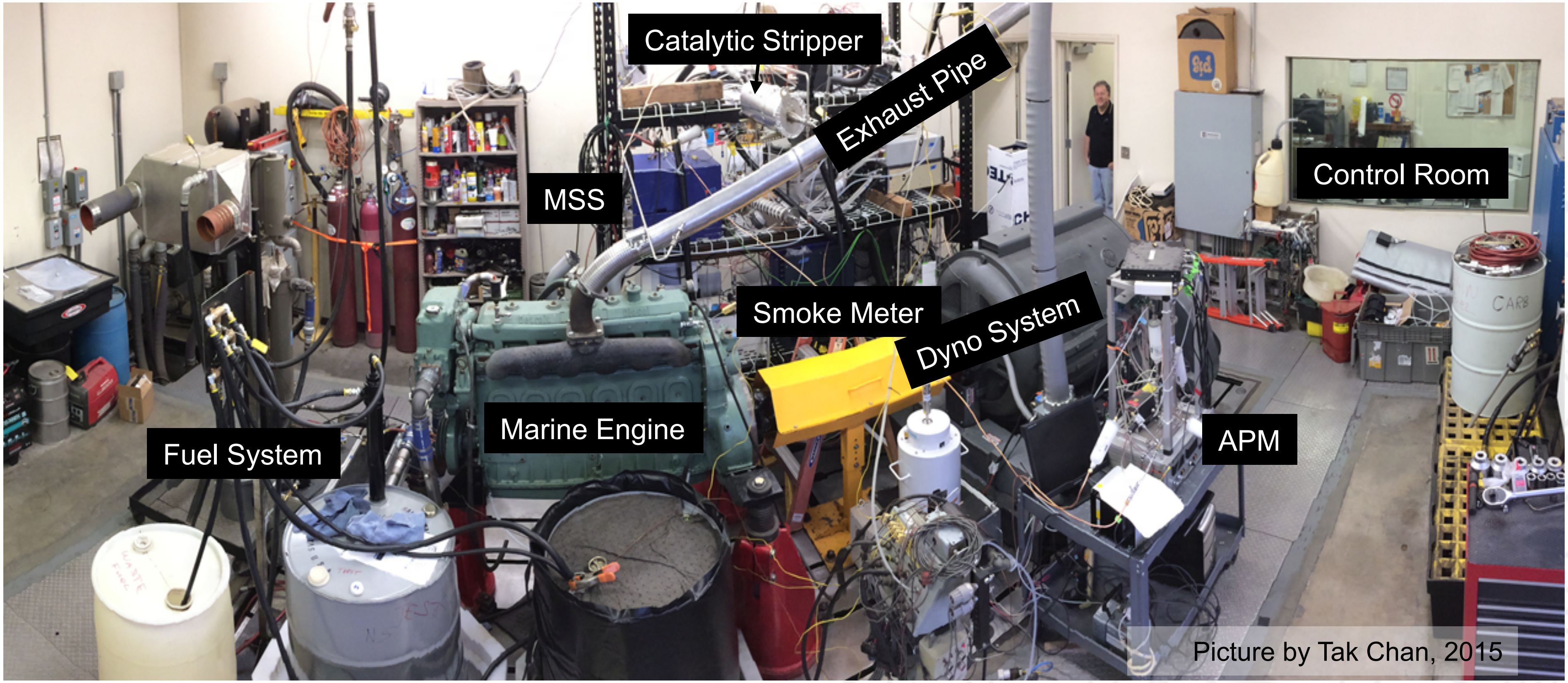
# Project Background

- UCR data shows wide BC EF range which appears to trend with engine size (photo acoustic method MSS-483)




- Is the wide range measurement method or some other cause?

# Marine Test Stand Research

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# Engine Test Stand Details

| Engine Specifications and Test Setup | | | |
|---|---|---|---|
| Marine Engine | 2-Stroke | BMEP = 641 kPa | RPM (1100-2100) |
| 210 Hp@2100 RPM | 7.0 Liter | DDC 6-71N | |

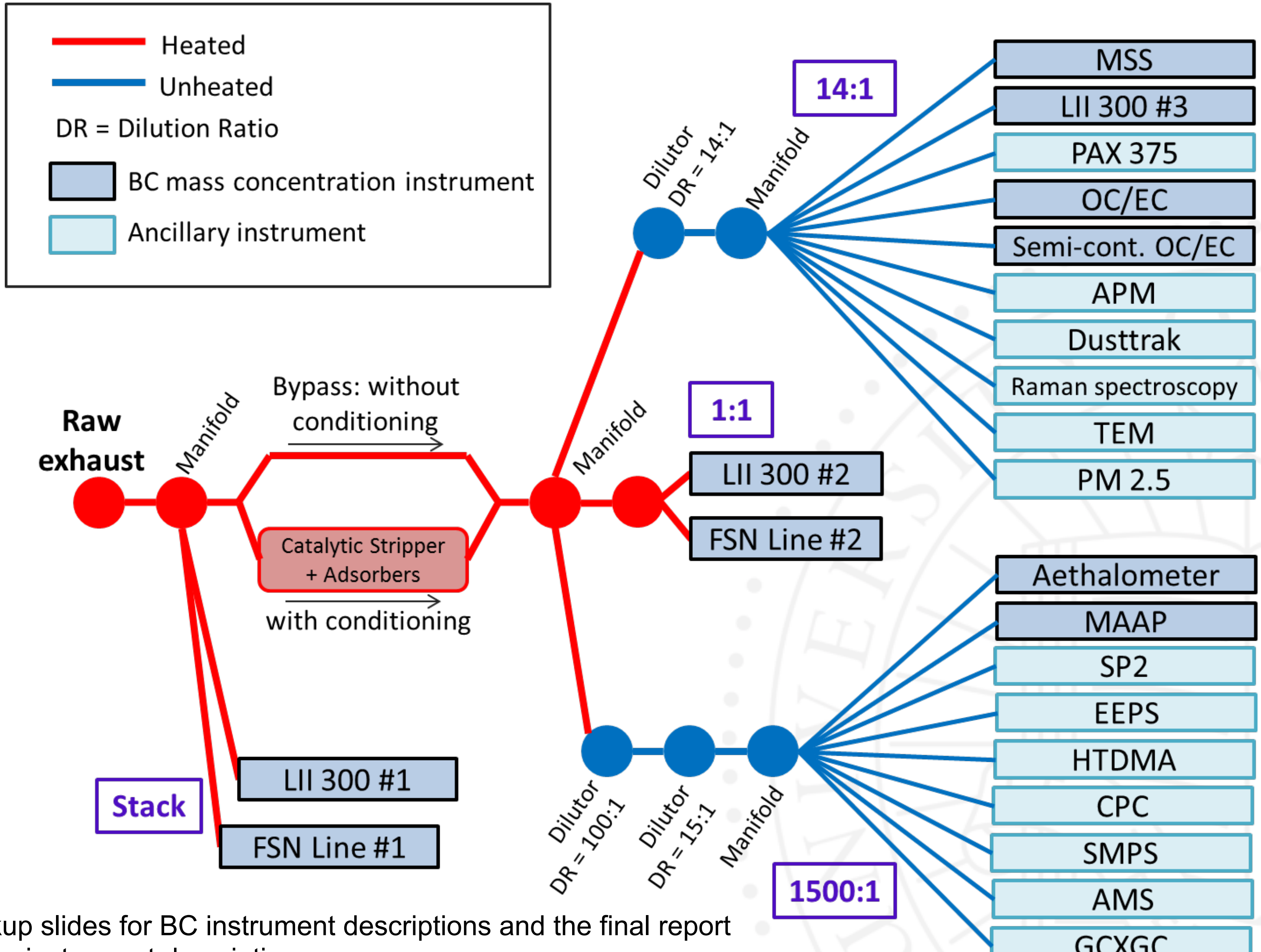
| Fuel Specs. | DMA | RMA-12 | RMG-380 |
|---|---|---|---|
| Sulfur % | 0.0013 | 0.0013 | 3.18 |
| Viscosity (cSt) | 2.69 | 13.7 | 358.9 |
| Density (g/mL) | 0.831 | 0.859 | 0.983 |

Sulfur ↑
Viscosity

| Test Modes | Speed (rpm) | Load | Conditoning[2] |
|---|---|---|---|
| Mode 1 | 1100 | 25% | CS and BP |
| Mode 2 | 1100 | 50% | CS |
| Mode 3 | 1100 | 75% | CS and BP |

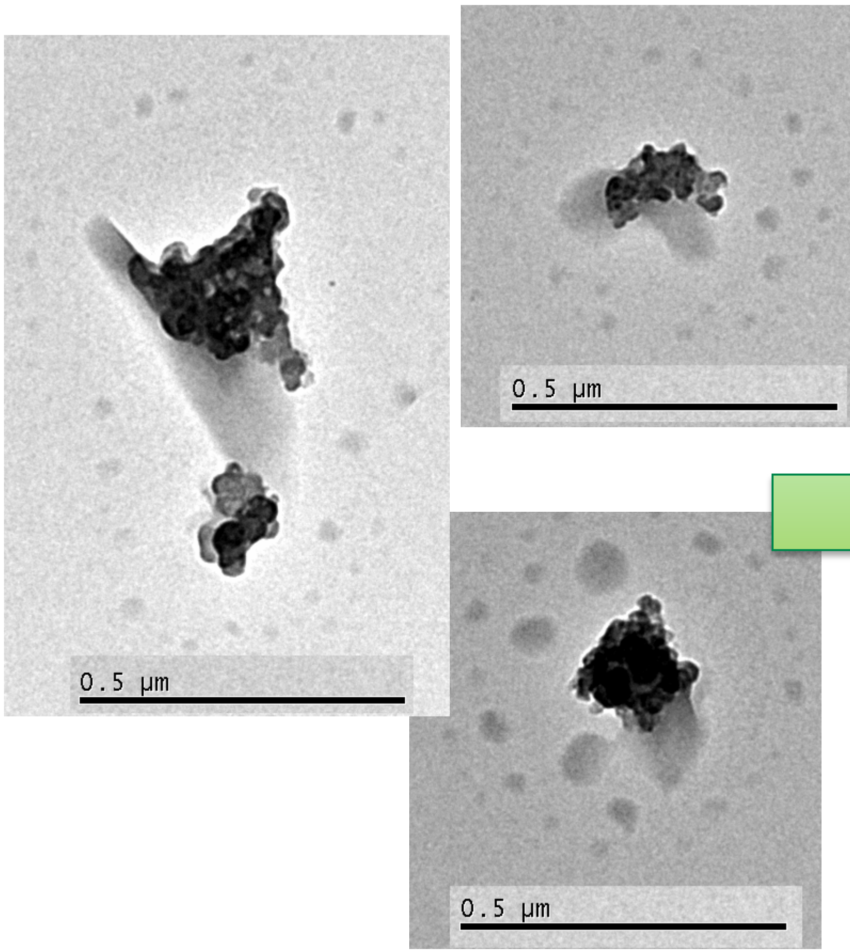
[1] CS stands for catalytic stripper and BP stands for bypass. Repeats for each of the three fuels.

# Experimental Design Comprehensive

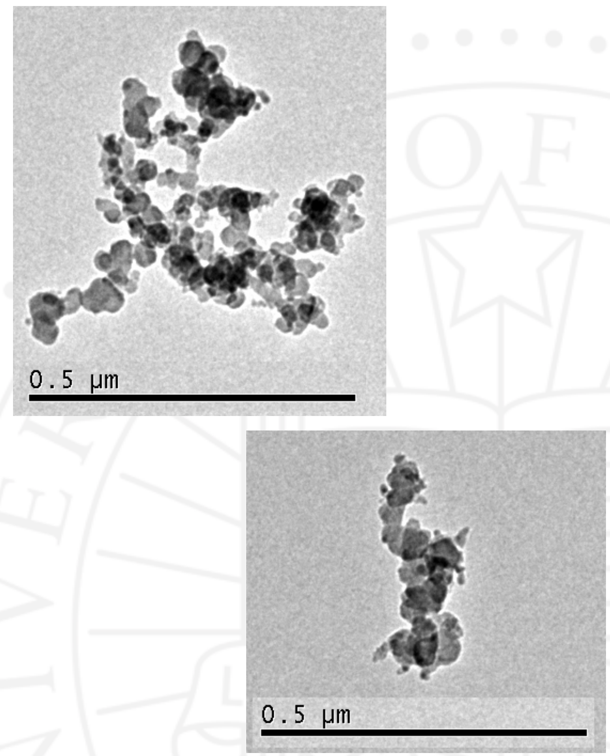



[1] See backup slides for BC instrument descriptions and the final report for other instrument descriptions

# Sample Conditioning did Change Particle Composition

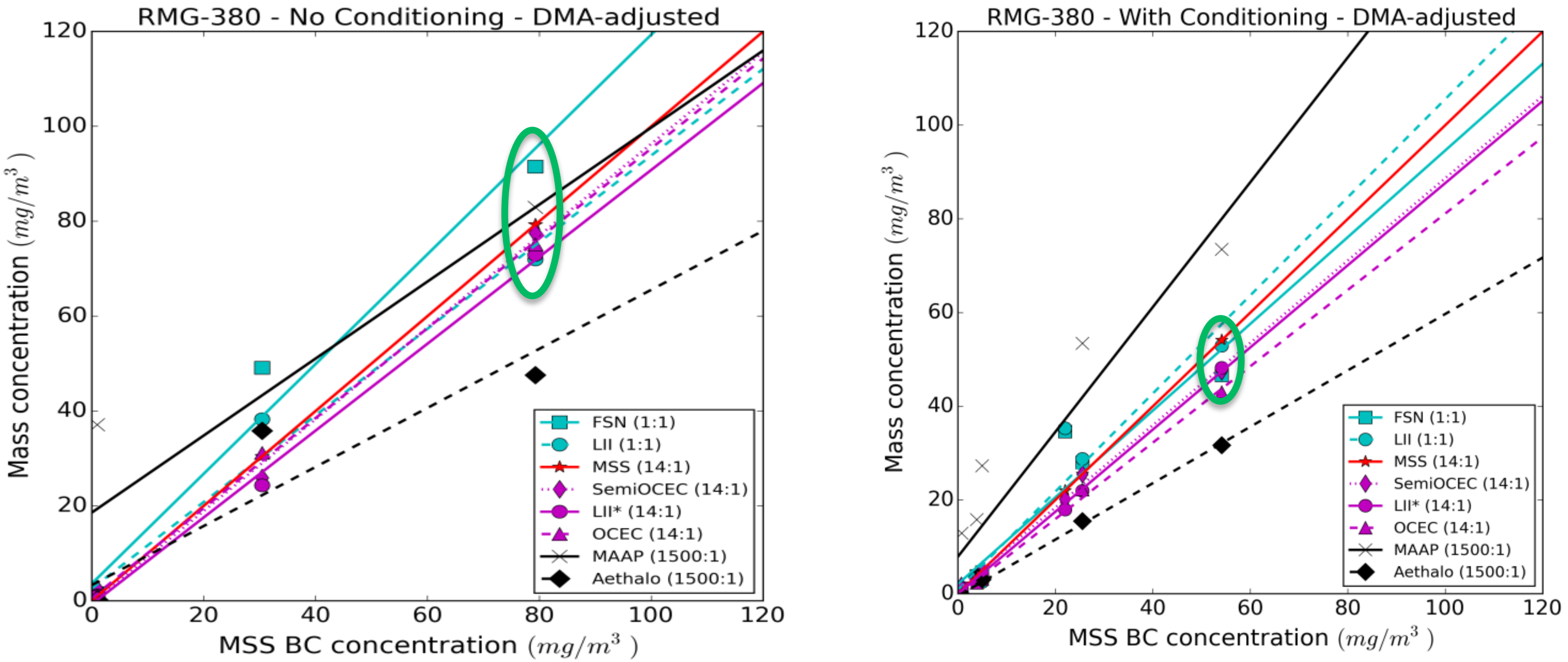



*No sample conditioning*




*With sample conditioning*

# Calibration improves some BC correlations




| | By Pass | | Sample conditioning | |
|---|---|---|---|---|
| **Fuel** | **No Calibration** | **Calibration** | **No Calibration** | **Calibration** |
| DMA | 23% | -- | 29% | -- |
| RMA-12 | 39% | 17% | 34% | 7% |
| RMG-380 | 29% | 12% | 40% | 12% |

[1] Since the fuels are calibrated based on the DMA fuel, DMA calibrated spreads are null. The calibration % are defined as the spread which is defined as the difference between the biggest and the smallest slope divided by the average of the two.

- Post-hoc calibration factors varied
  - Slopes from 1.13 to 0.53
  - Intercepts from 0.13 to 2.91

# Test Stand Conclusions

- Calibration improved BC results up to 75% level

- Sample conditioning improved the comparability of BC measurements up to 25% level, but PM losses confounded some results

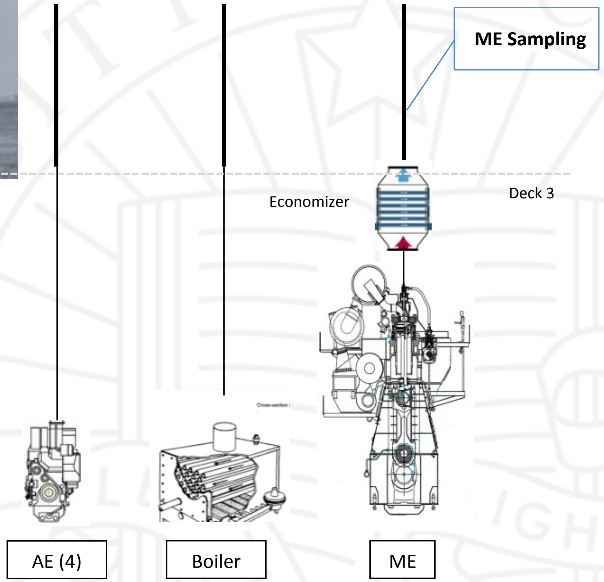
- BC Calibration is recommended, but sample conditioning showed small benefit

- BC reported measurement discrepancies (orders of magnitude) do not appear to be the result of BC measurement methods

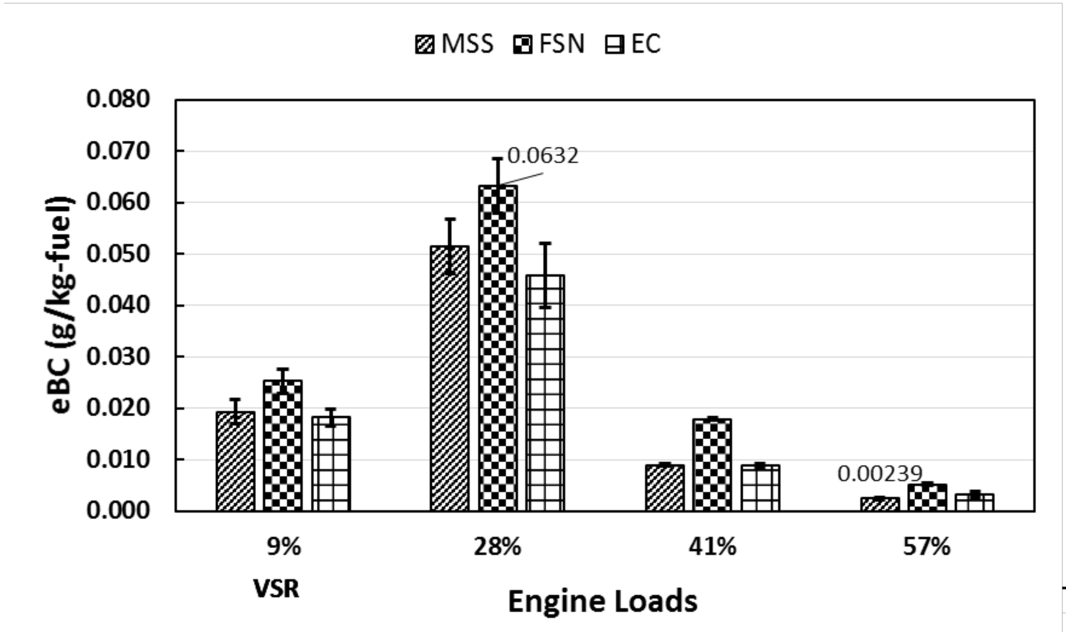
# Measured BC from ME: Meeting Tier 2 Stds.

- ❑ Performed VSR and 3 other loads on MGO fuel (0.03% S)
- ❑ Measured gaseous and PM emissions
- ❑ Measured BC via three methods (MSS, FSN, and EC)
- ❑ Used ISO reference sampling methods

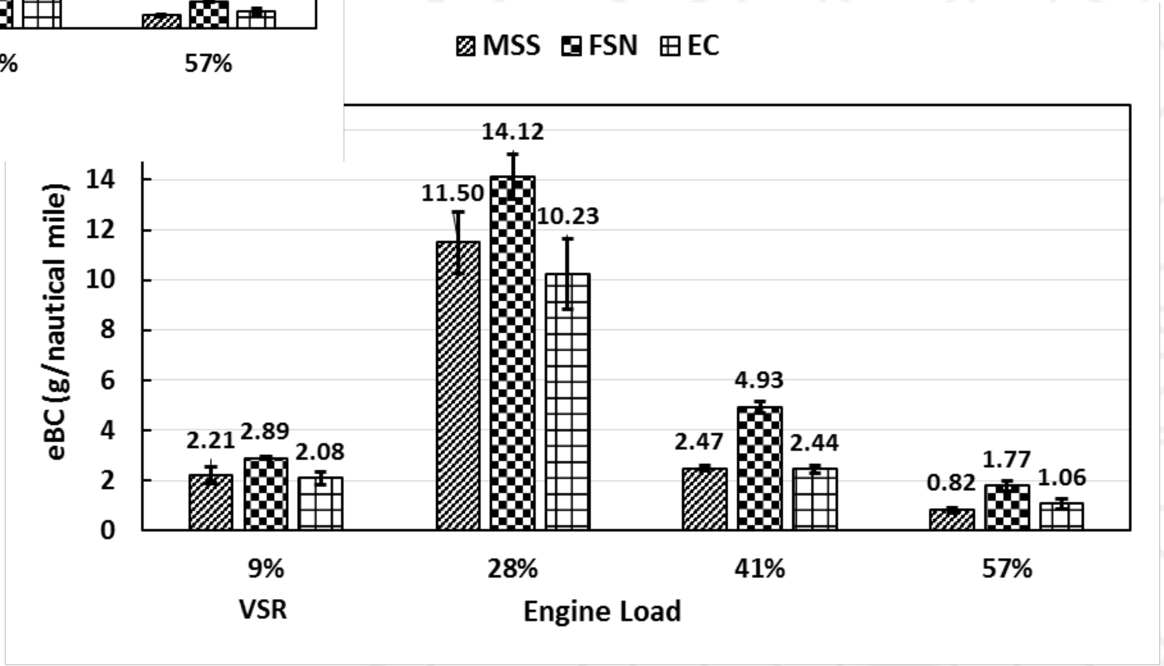
| Source | Engine Mfg. | MY and Model | Engine Power kW | Run Hours | EGCS |
|---|---|---|---|---|---|
| ME | Mitsui MAN B&W | 2011 12K98ME6.1 | 68,666 | 25,985 | no |
| AE1 | Daihatsu | 2011 8DC32e | 3,162 | n/a | no |
| AE2 | Daihatsu | 2011 8DC32e | 3,162 | n/a | no |
| AE3 | Daihatsu | 2011 8DC32e | 3,162 | 14,550 | no |
| AE4 | Daihatsu | 2011 8DC32e | 3,162 | n/a | no |
| Boiler | Alfa-Laval | 2011 n/a | n/a | n/a | no |



# BC Emission Factor Very Low for Tier 2 Engine

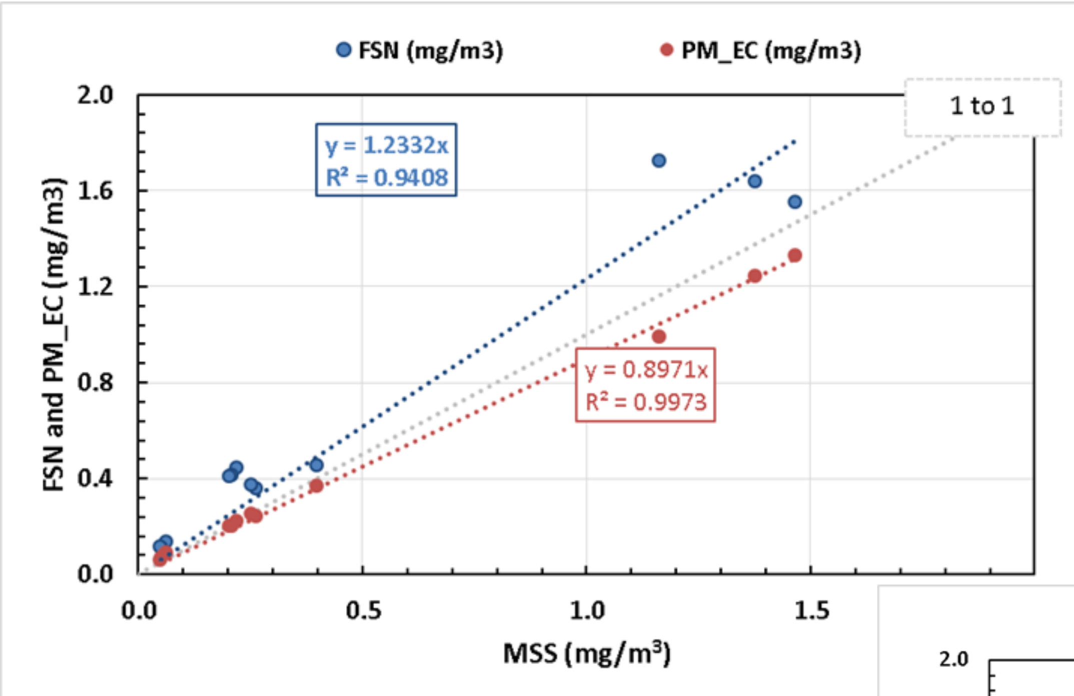



- ❑BC emissions very low at 57% load (0.0024 g/kg-fuel)
- ❑BC emissions highest at 28% load not VSR even on a per nm basis.
- ❑BC emission factor possibly lower at higher loads
- ❑ The Tier 2 BC EF at 57% load are 5 times lower than other UCR tested vessels (Tier 1 and Tier 0)

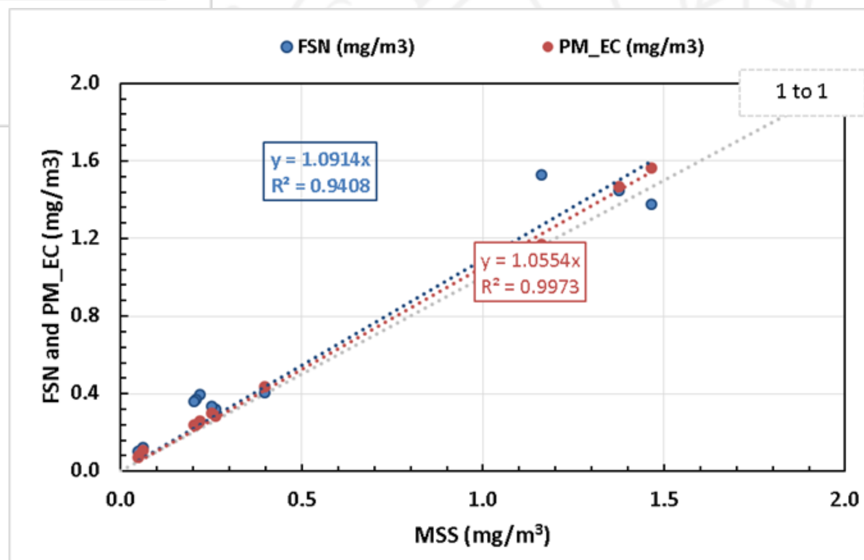



[1] All engine loads are a percent of maximum continuous rating (MCR)

# BC Measurement Methods Correlated Well

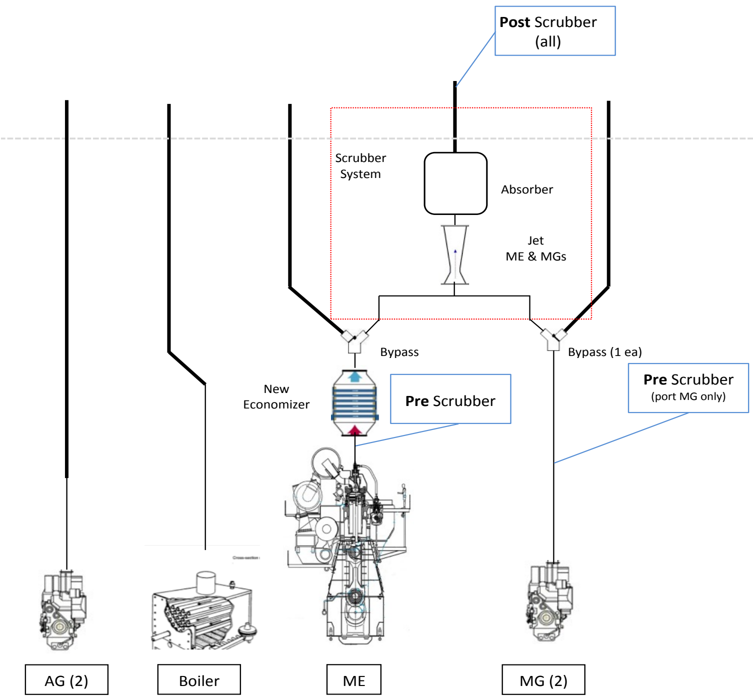



- ❑ BC concentration varied from 0.06 mg/m3 to 1.5 mg/m3
- ❑ $R^2$ is high for both methods at > 0.94
- ❑ FSN is response higher than MSS and EC is lower (similar to test stand)
- ❑ Same test stand calibration improves correlation
  - FSN slope from 1.23 to 1.09
  - EC slope from 0.90 to 1.06




[1] Tier 2 engine MSS eBC concentrations varied from 0.06 to 1.5 mg/m³ , and test stand ranged from 0.4 to 80 mg/m3 (no conditioning

# Task 3: BC Control with Sea Scrubber for ME and AE

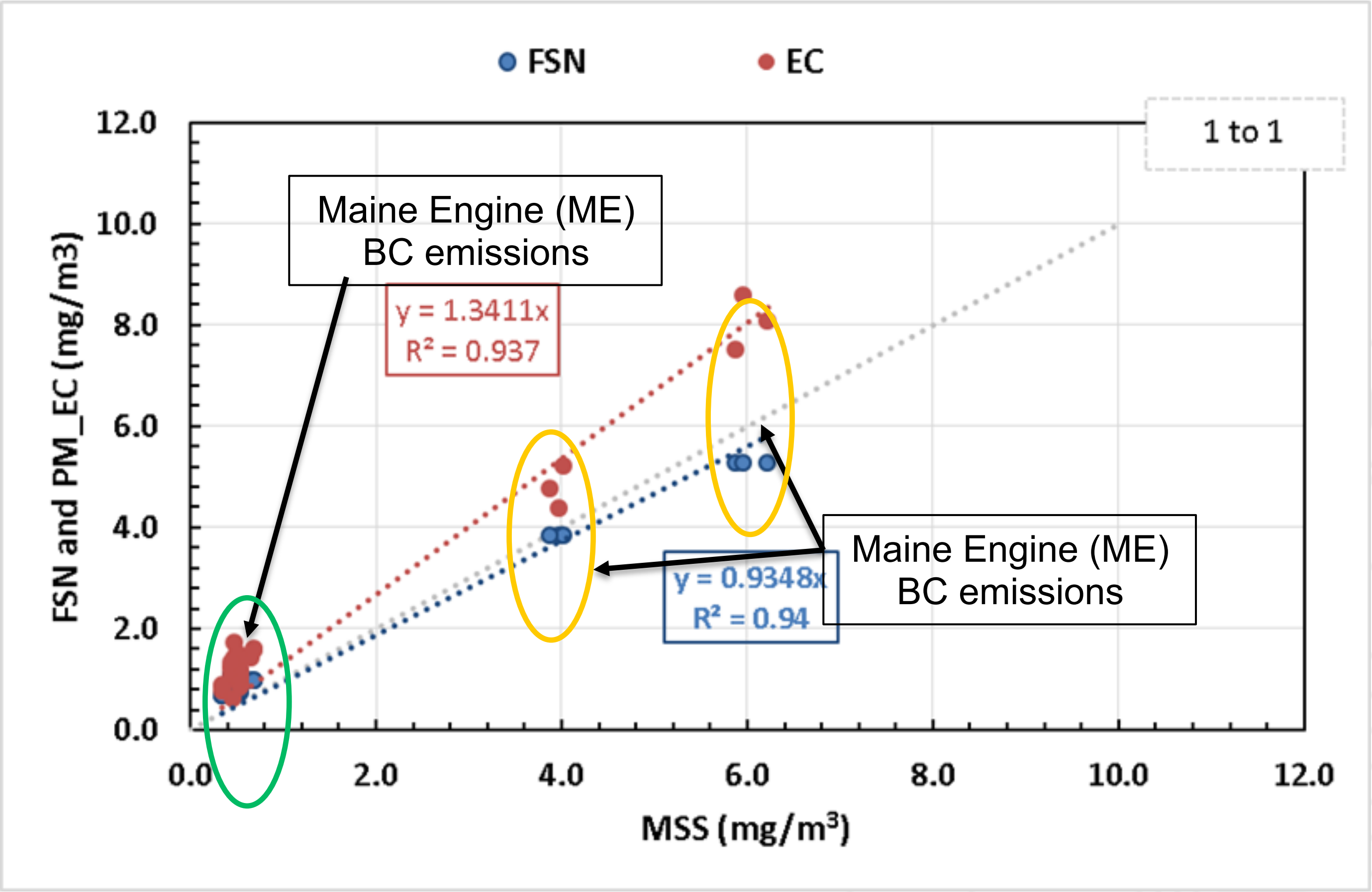




| *Source* | *Engine Mfg.* | *Model* | *Engine Power kW* | *Run Hours* | *EGCS* | *Exhaust Fraction*[2] |
|---|---|---|---|---|---|---|
| ME | Mitsui B&W | 7L70 | 16,578 | 177,962 | yes | 93% |
| AE_1s | Wartsila | 6R32D | 2,105 | 70,096 | yes | 0% |
| AE_1p | Wartsila | 6R32D | 2,105 | 79,020 | yes | 7% |
| AE_2s | Wartsila | 4R32BC | 1.263 | 63,211 | no | n/a |
| AE_2p | Wartsila | 4R32BC | 1.263 | 55,067 | no | n/a |
| Boiler | n/a | n/a | n/a | | no | n/a |

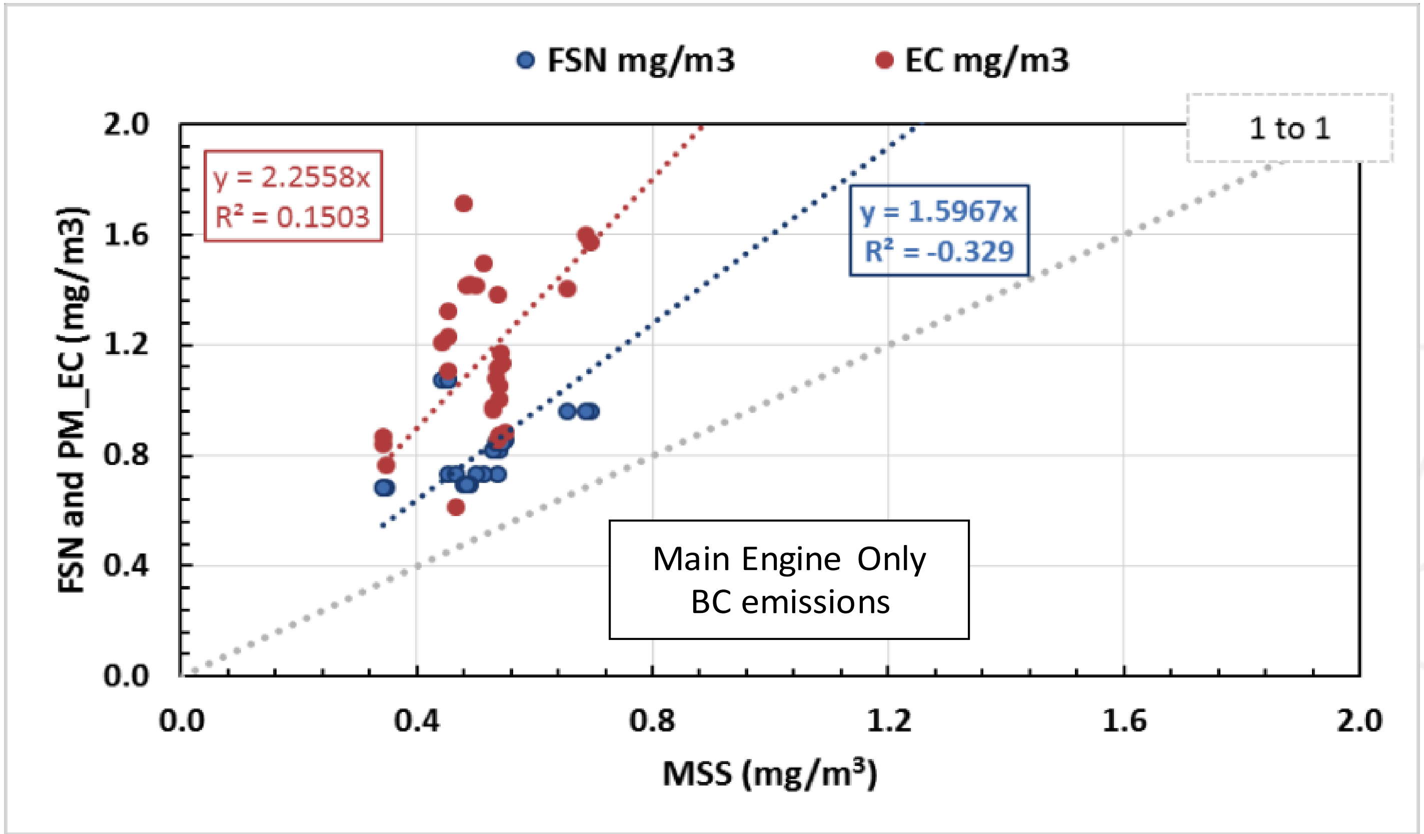
- ❑ Performed 4 loads on HFO fuel (1.9% S) pre and post scrubber
- ❑Measured gaseous and PM emissions
- ❑ Measured BC via three methods (MSS, FSN, and EC)
- ❑ Measured emissions with updated sampling system (post-scrubber design)

# BC Measurement Methods Relatively Poor Correlation



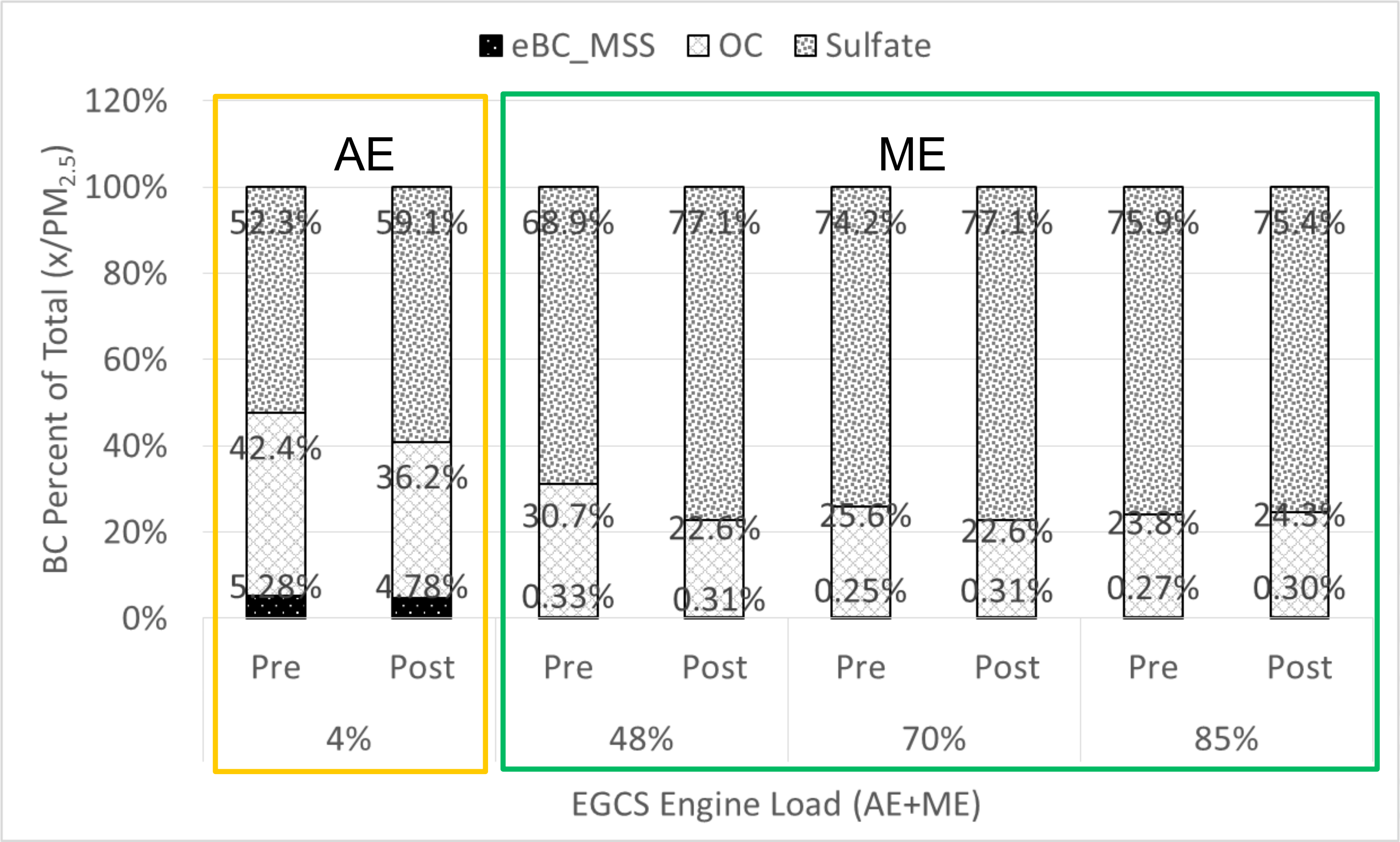

- ❑BC emission factor for the weighted loads was 0.038 g/kg-fuel (post scrubber)
- ❑Correlation shows good $R^2$ and good slopes (1.34 to 0.93). Very similar trend and magnitude as Task 1 and 2 (for like instruments)
- ❑ ME results lower left corner, AE results upper right corner. What if data AE's is removed?

# BC Measurement Methods Relatively Poor Correlation for ME




- ❑ ME results show EC and FSN slopes of 2.26 and 1.60 (much further away from 1 than task 1 and 2)
- ❑ $R^2$ was poor and below 0.2 for both methods (mostly likely a result of the small data spread)
- ❑ Post-hoc calibration improved FSN slope from 1.60 to 1.40, but the EC method showed a worse slope (2.97 vs 2.26)

# What Caused the Correlation to go from Good to Poor?



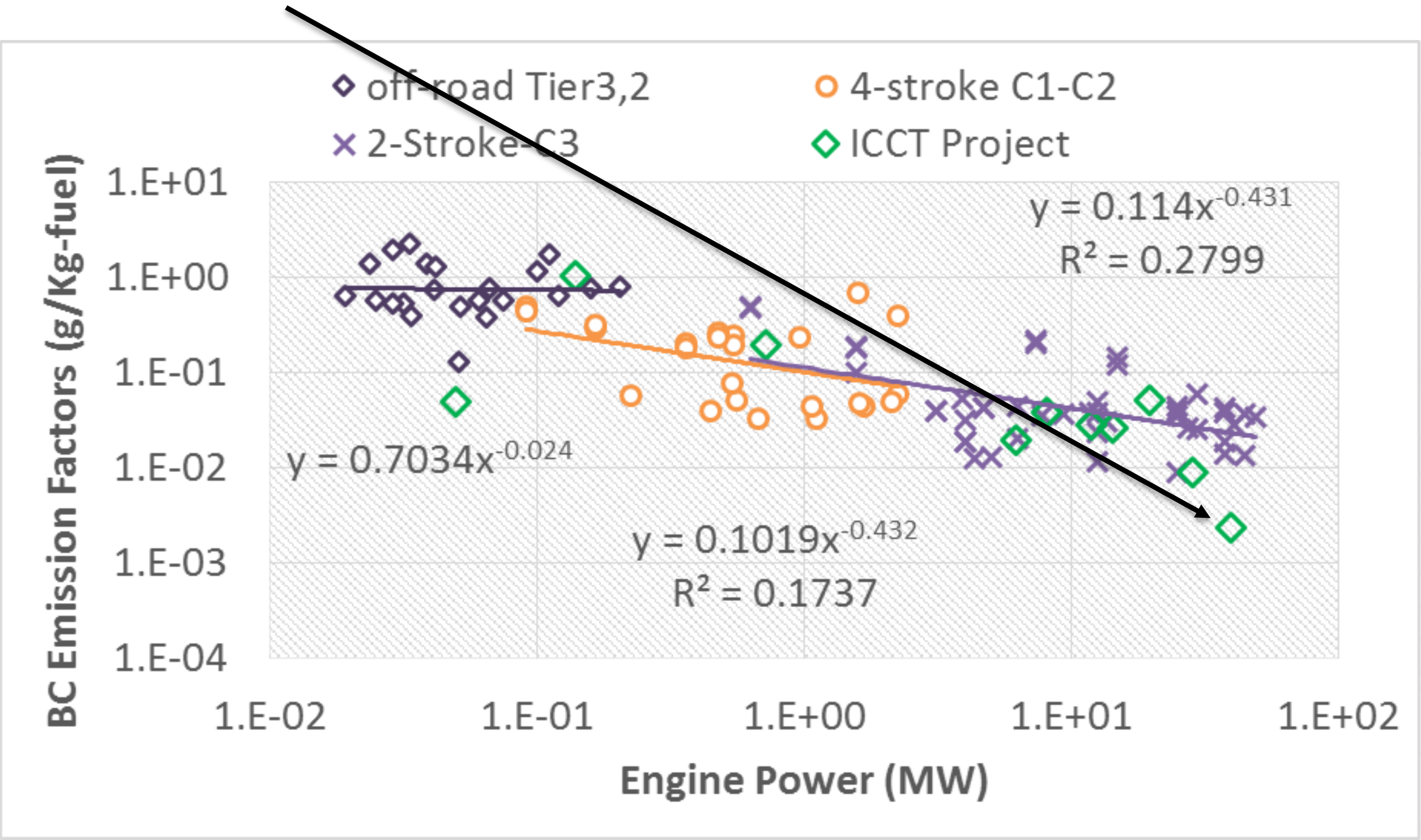

The PM fraction changed from AE to ME:

- ❑ Sulfate fraction was about the same (slightly higher)
- ❑ Organic carbon fraction was about the same (slightly lower)
- ❑ BC fraction changed significantly from 5% to ~ 0.3% (eBC/$PM_{2.5}$)

# Overall BC Measurement Method Conclusions

- Calibration improvements mixed (FSN, EC, and MSS)
  - Test stand and Tier 2 at-sea improved
  - At-sea PM scrubber got worse
- BC method agreement ranged from 5% to a factor of 2.9
- BC Measurement methods seem to be sensitive to BC concentration as a fraction of total PM ($PM_{2.5}$)
- In general BC reported measurement discrepancies (orders of magnitude) do not appear to be the result of BC measurement methods

# ICCT BC EF agree with observations and Tier 2 engine shows possible factor of 10 reduction in BC EF (0.002 g/kg-fuel)



# Acknowledgment

**Funding:**

- International Council for Clean Transportation (ICCT)
- United States Maritime Administration (MARAD)

**Equipment in-kind loans Task 1**

- AVL Filter Smoke Number (FSN) **Task 1-3**
- SunSet Labs SemiCont EC/OC
- South Coast Air Quality Management District (SC-AQMD) Aethalometer
- National Resource Canada, Two (2) LIIs, RAMAN, TEM analysis
- Environment and Climate Change
- Canada, LII, Rotating disk dilutor, CPC
- UC Riverside, GC by GC, AMS, SMPS, CPC, PAX 375 nm, HTDMA, MAAP
- California Air Resources Board EEPS
- NTK-Sparkplugs Stack OBD $NO_X$ /PM/PN Sensor

# Acknowledgment Cont. Task 1

**Faculty, Technical Support, and Graduate Students**

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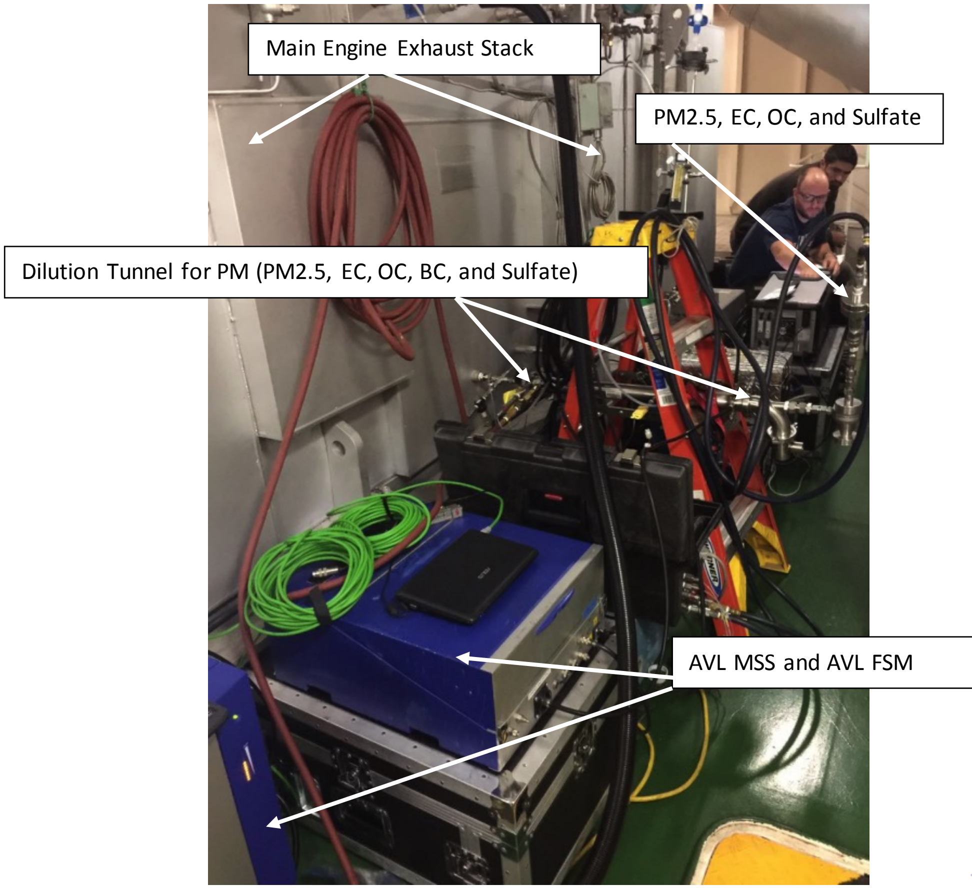
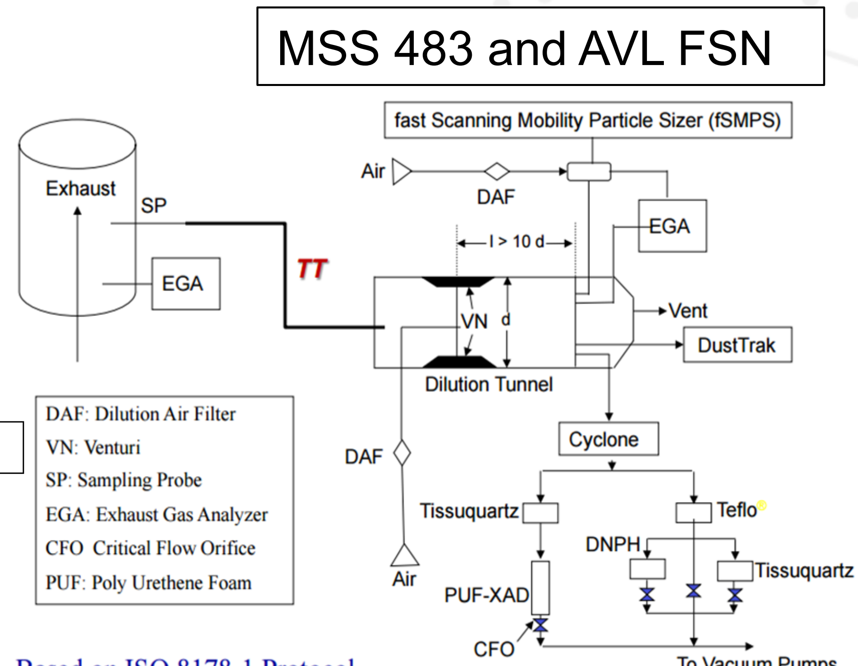
# Back up Slides

# ISO 8178 Sampling Method



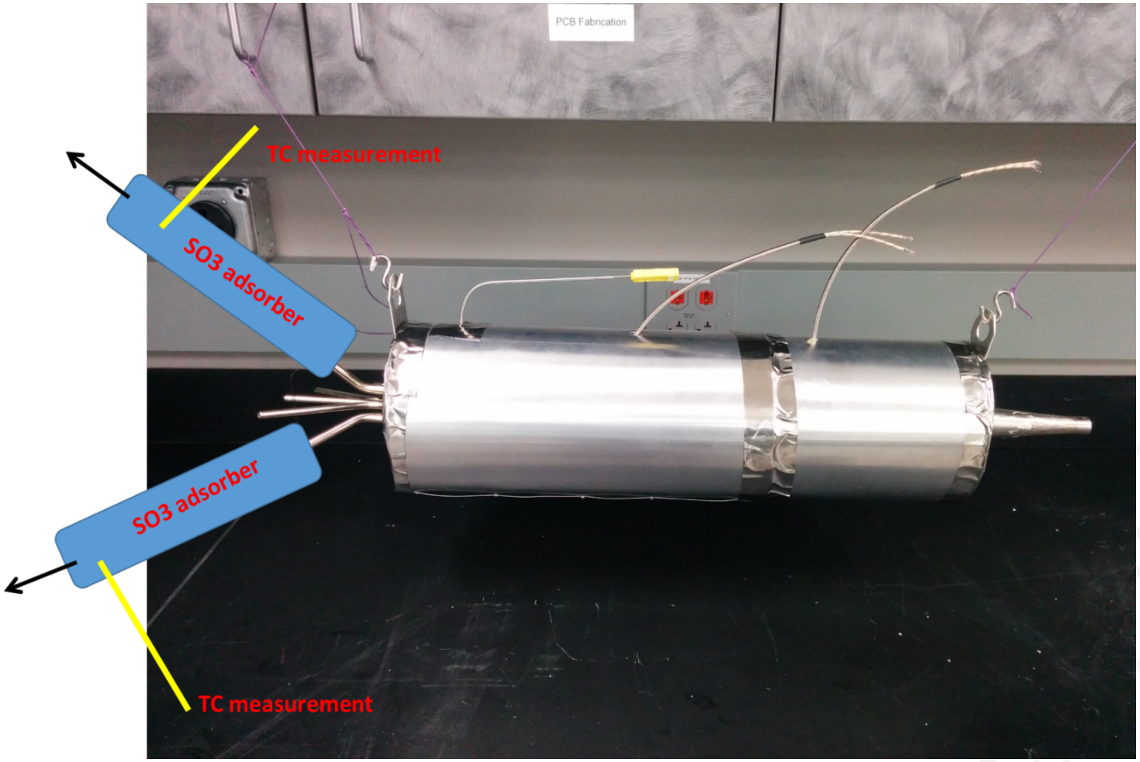




Based on ISO 8178-1 Protocol

# Key BC Mass Concentration Instruments

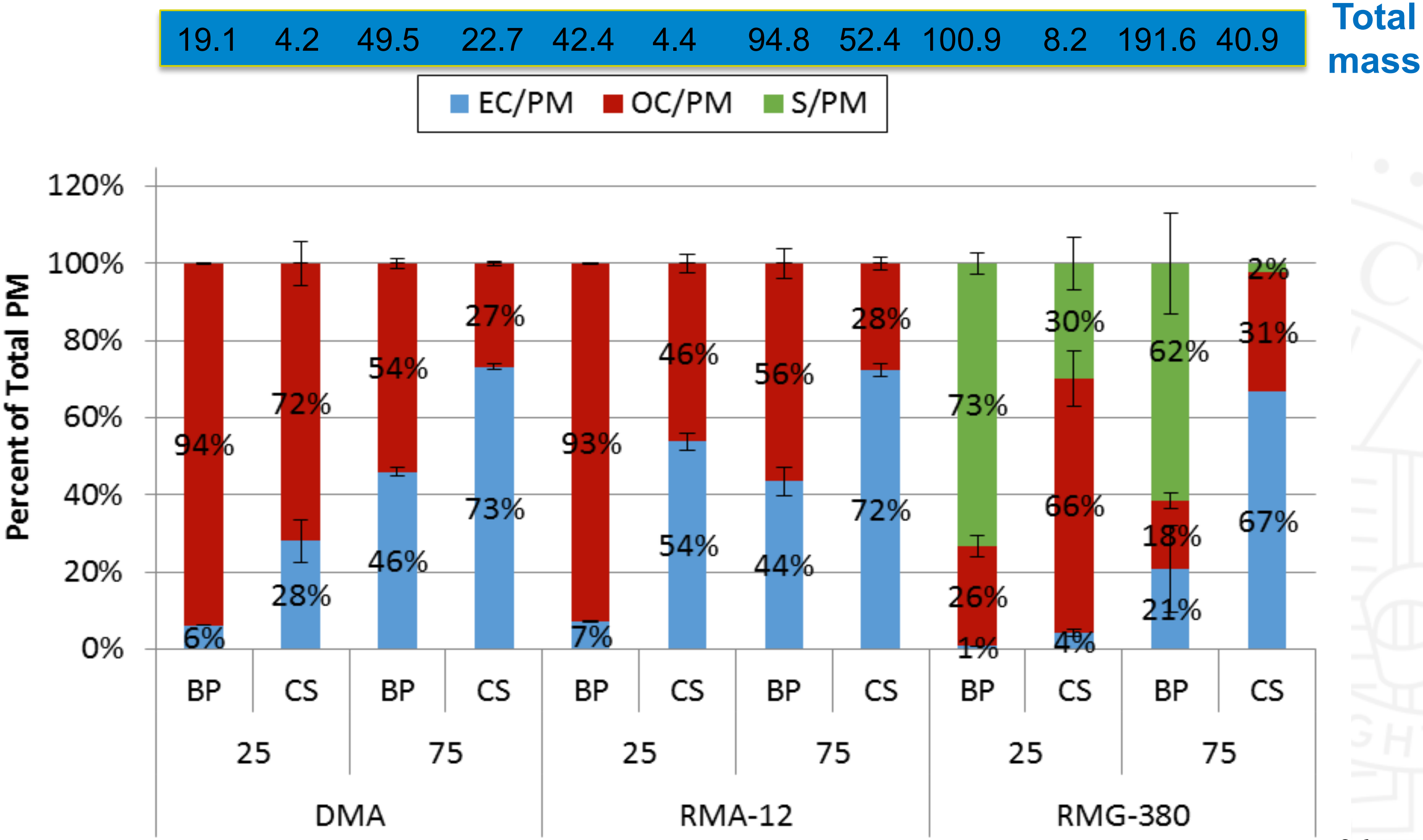
| Instrument | Manufacturer | Model | Abbreviation | Measurement Principle | Reported As |
|---|---|---|---|---|---|
| **Semi-continuous Organic Carbon/ Elemental Carbon** | Sunset Laboratories | | SemiOCEC | thermal-optical | EC |
| **Batched Organic Carbon/Elemental Carbon** | Sunset Laboratories | | OCEC | thermal-optical | eBC |
| **Laser Induced Incandescence** | Artium | 300 | LII | thermal radiation | rBC |
| **Micro-Soot Sensor** | AVL | 483 | MSS | light absorption (photoacoustic) | eBC |
| **Smoke Meter** | AVL | 415SE | FSN | light absorption | eBC |
| **Multi-Angle Absorption Photometer** | Thermo Scientific | 5012 | MAAP | light absorption and scattering | eBC |
| **Aethalometer** | Magee Scientific | AE21 | Aethalo | light absorption and scattering | eBC |

# Test Stand: Catalytic stripper and Sulfur adsorber

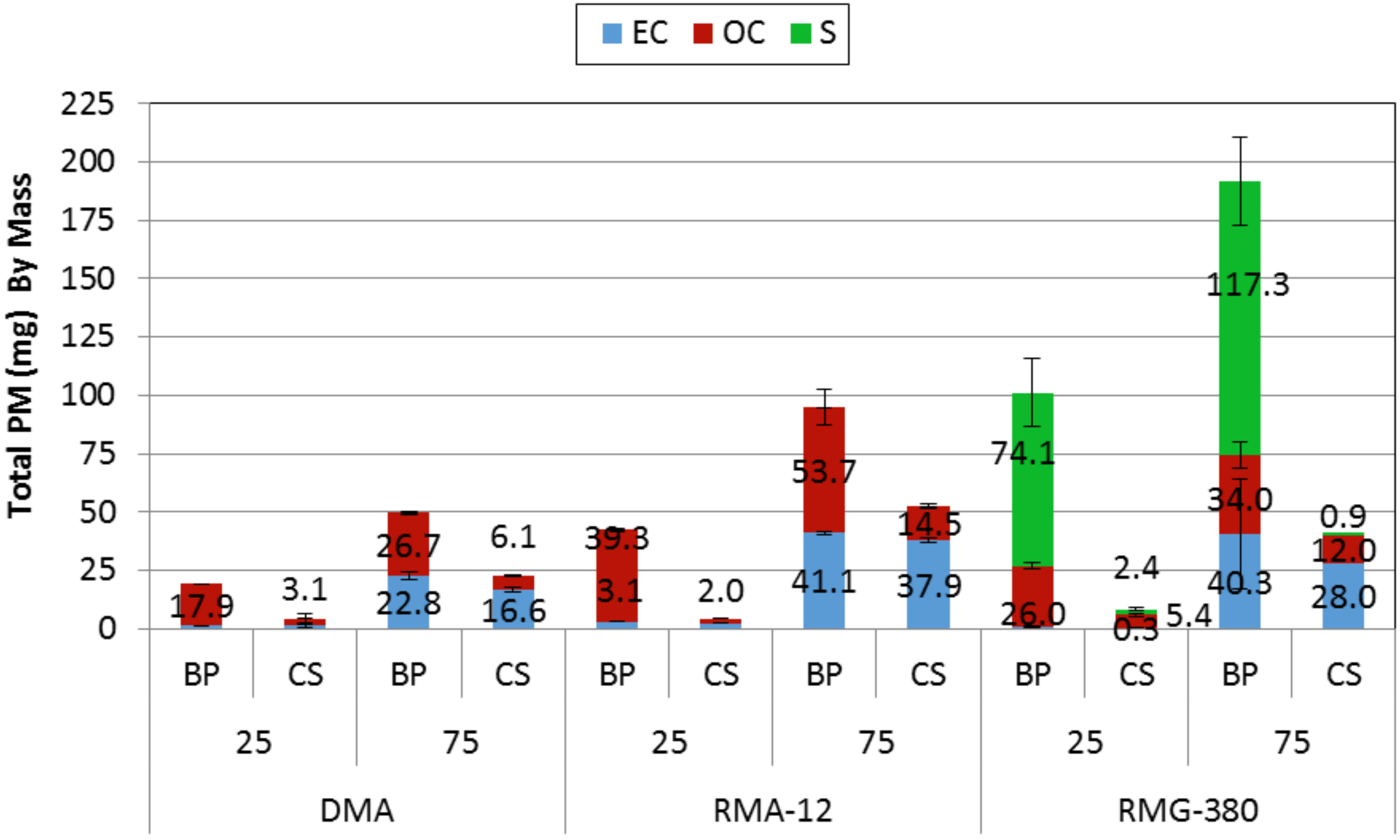



- Flow-through ceramic monoliths for organic PM reduction
- platinum and palladium based wash coats
- 40 liter/minute maximum flow
- Catalyst operation: 350 ºC to 400 ºC
- Two sulfur adsorbers designed for $SO_3$ oxidation at 150 ºC

# Test Stand: Percent of total PM Composition



# Test Stand: Total PM Mass Composition (mg/m3)



# Test Stand: Post-Hoc Calibration Factors Obtained

| | By Pass (BP) | | Conditioning System (CS) | |
|---|---|---|---|---|
| **Instrument** | **Slope** | **Intercept** | **Slope** | **Intercept** |
| FSN (DR 1:1) | 1.13 | 0.13 | 1.30 | 0.00 |
| LII (DR 1:1) | 1.22 | -0.83 | 1.56 | -1.16 |
| MSS (DR 14:1) | 1.00 | 0.00 | 1.00 | 0.00 |
| SemiOCEC (DR 14:1) | 0.89 | -0.01 | 0.88 | -0.09 |
| LII (DR 14:1) | N/A | N/A | N/A | N/A |
| OCEC (DR 14:1) | 0.76 | 0.03 | 0.85 | 0.15 |
| MAAP (DR 1400:1) | 0.53 | 3.24 | 0.42 | 2.91 |
| Aeth (DR 1400:1) | 1.25 | 2.93 | 1.14 | 2.53 |

The DMA fuel was used as the calibration source so that fuel will not have a calibration correction