Emissions Control Strategies from Ocean Going Vessels Effect on Black Carbon Emission Methods

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

UCR
UNIVERSITY OF CALIFORNIA, RIVERSIDE

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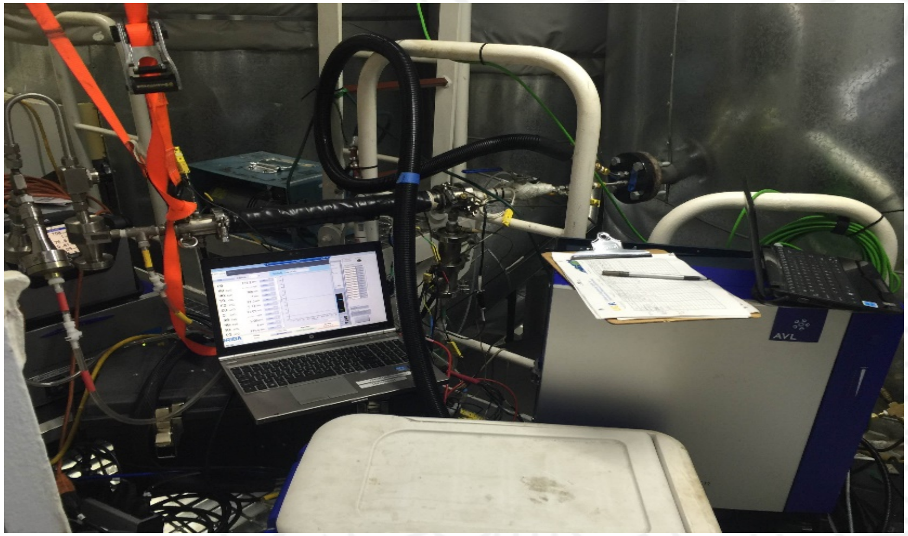
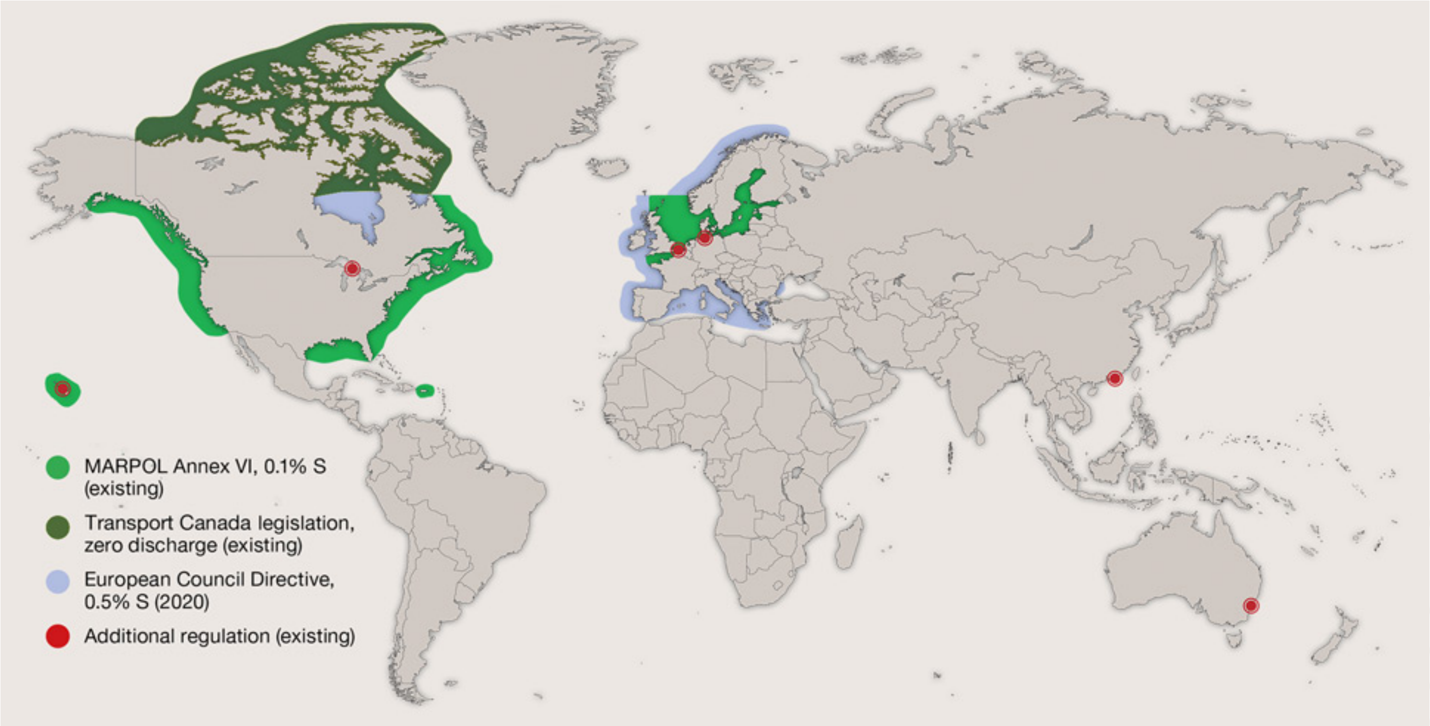
September 7th and 8th 2016
Vancouver, British Columbia, Canada

Outline

- ❑ **Background**
- ❑ **Objective**
- ❑ **Approach**
- ❑ **Results**
- ❑ **Discussions**



Emissions Control Areas (ECAs)



Sulfur Limits for Fuel in ECAs		Sulfur Limits in Other Sea Areas	
Before 1 July 2010	1.5% m/m	Before 1 July 2012	4.5% m/m
1 July 2010 – 1 January 2015	1.0% m/m	1 July 2012 – 1 January 2020	3.5% m/m
After 1 January 2015	0.1% m/m	After 1 January 2020	0.5% m/m

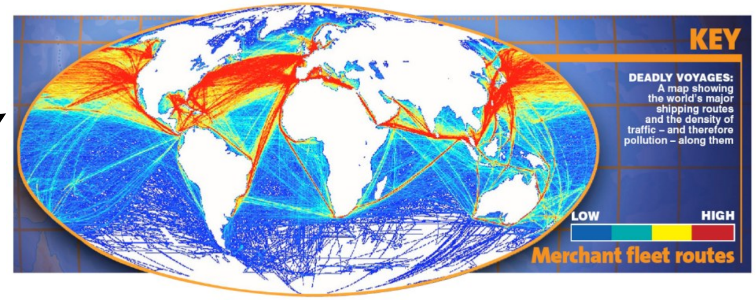
- ❑ MARPOL Annex VI is targeting 0.5% of sulfur in the fuel by 2020 internationally
- ❑ Strict sulfur limits are in place in ECAs, and potential of increase ECAs

Strategies to Control Sulfur Emissions

MARPOL Annex VI

Decision

Avoid ECAs



Switch to MGO

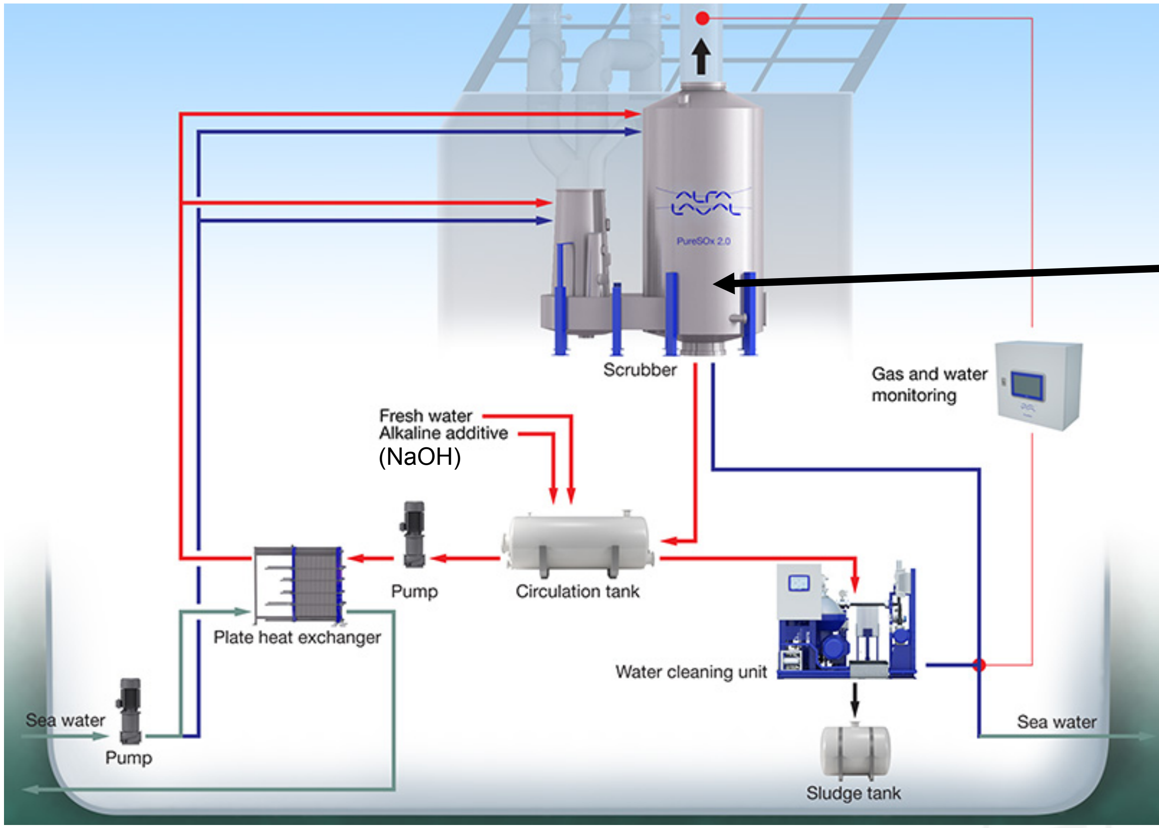
Bunker Prices ($/mt)	HFO	MGO
Global Average	277.50	546.50
Americas Average	280.00	588.50
APAC Average	287.50	551.00
EMEA Average	260.50	472.50

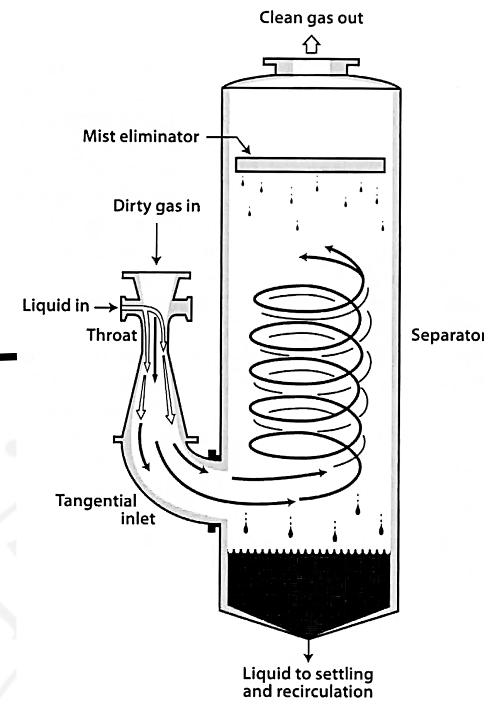
*mt stands for metric tons
*Information adopted from Ship&Bunker on Sep 1st

Switch to LNG/Dual Engine

Install a Scrubber

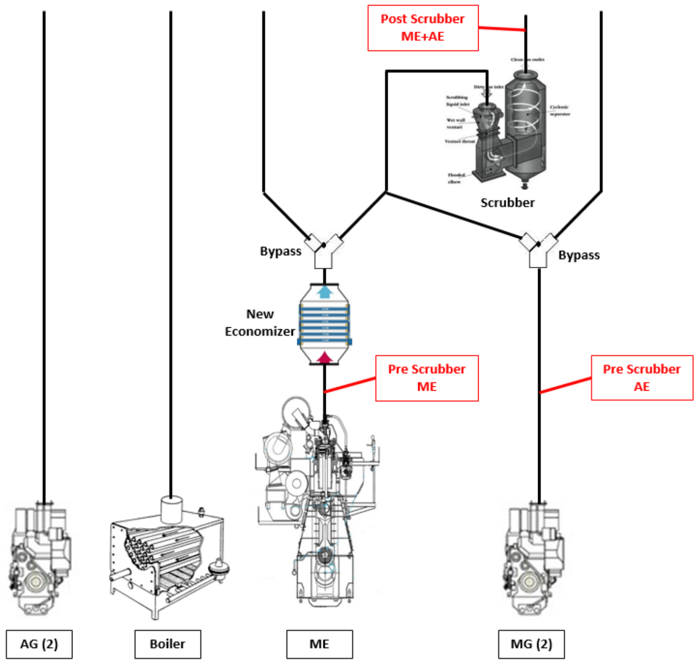
Scrubber System





- ❑ Both open and close loop System
- ❑ Typical Venturi scrubber and a cyclone separator
- ❑ Monitoring SO_2, CO_2, PH, PAH, and turbidity

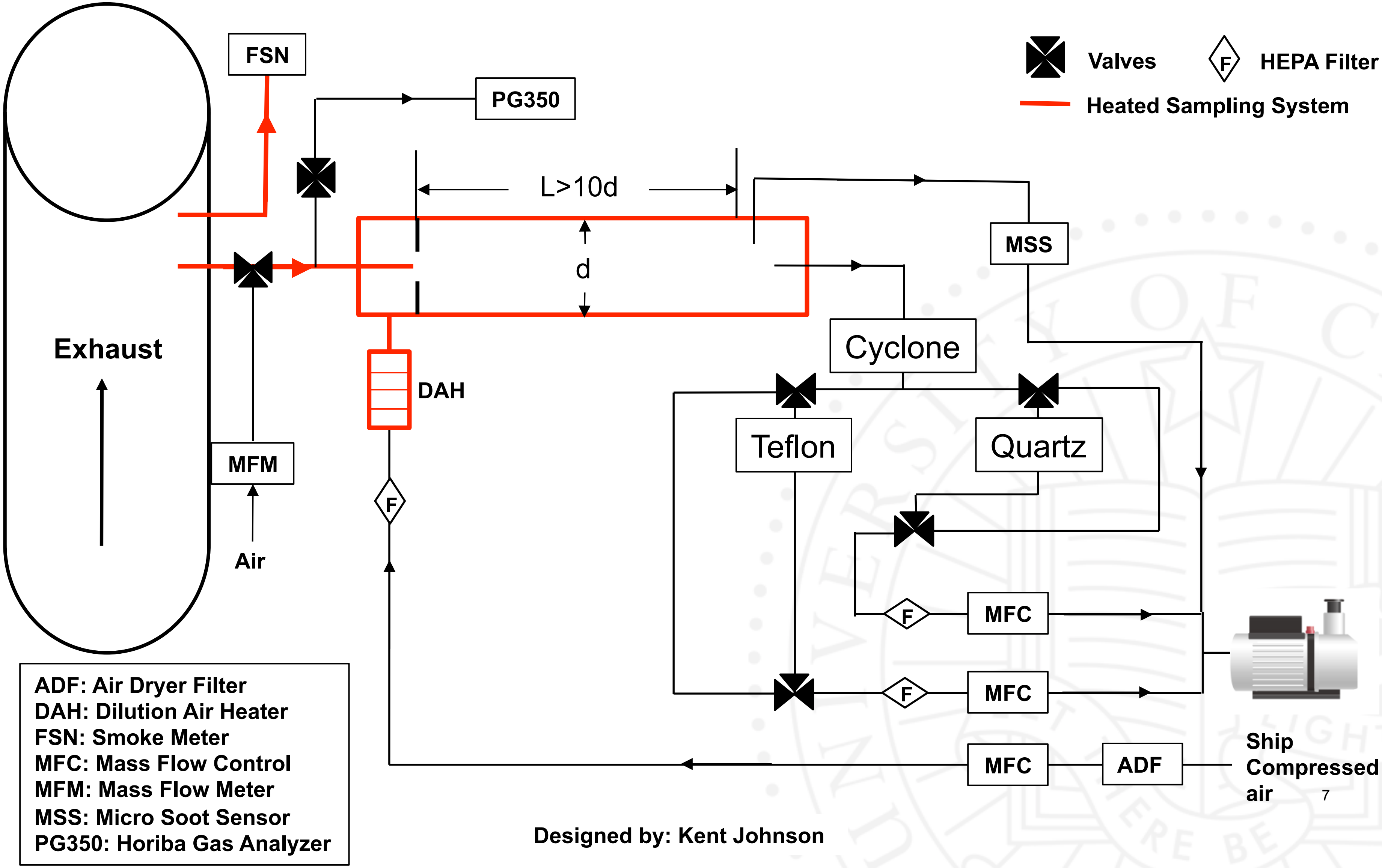
On Sea Scrubber Main and Auxiliary Engine



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

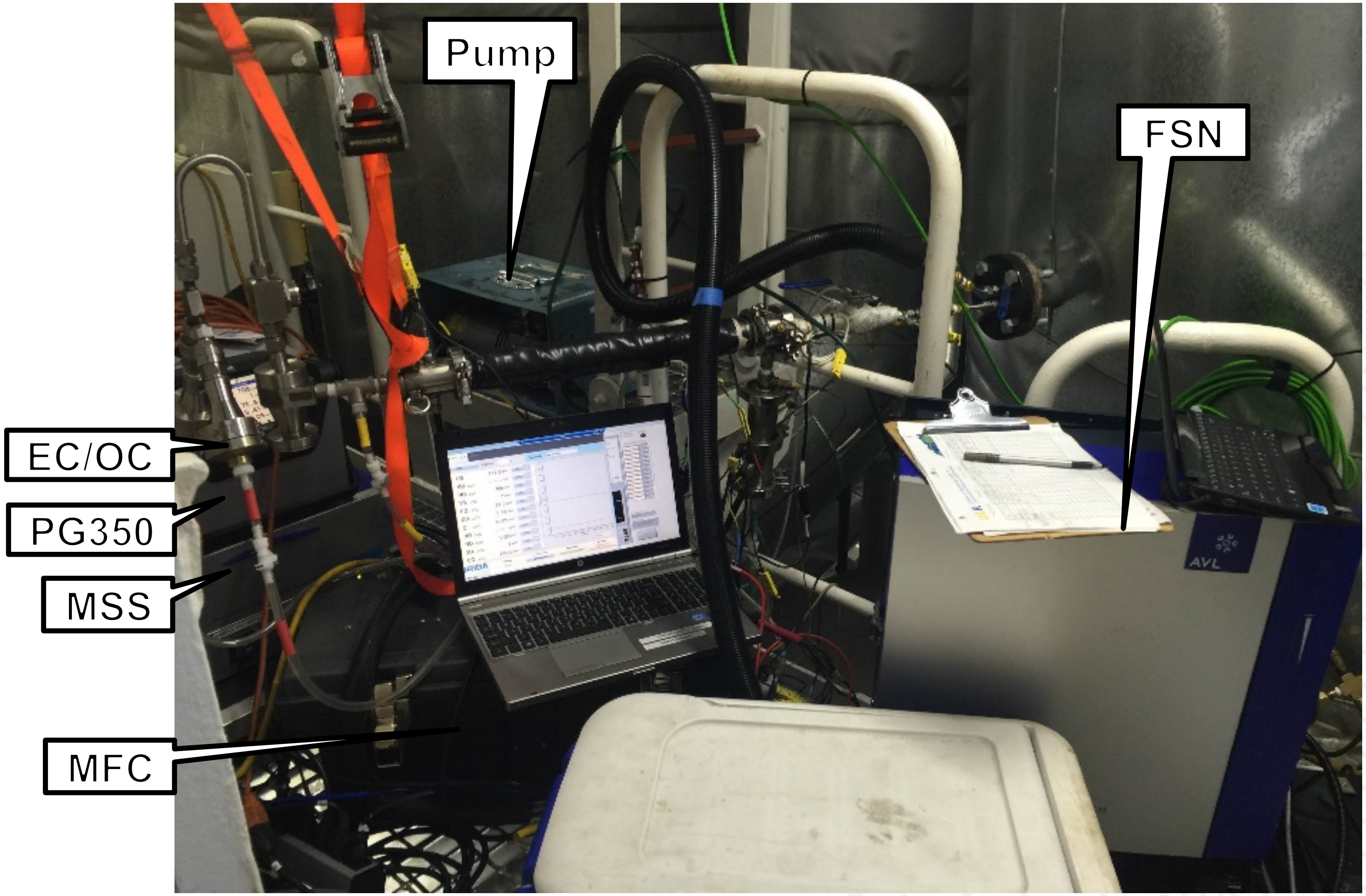
- ❑ Performed 4 loads on HFO fuel (1.9% S) pre and post scrubber
- ❑ Measured gaseous and PM emissions
- ❑ Measured BC via three methods
  - ❑MSS: Light absorption-photoacoustic
  - ❑FSN: Light absorption-optical
  - ❑ECOC: Thermal/optical

Emissions Sampling System



Designed by: Kent Johnson

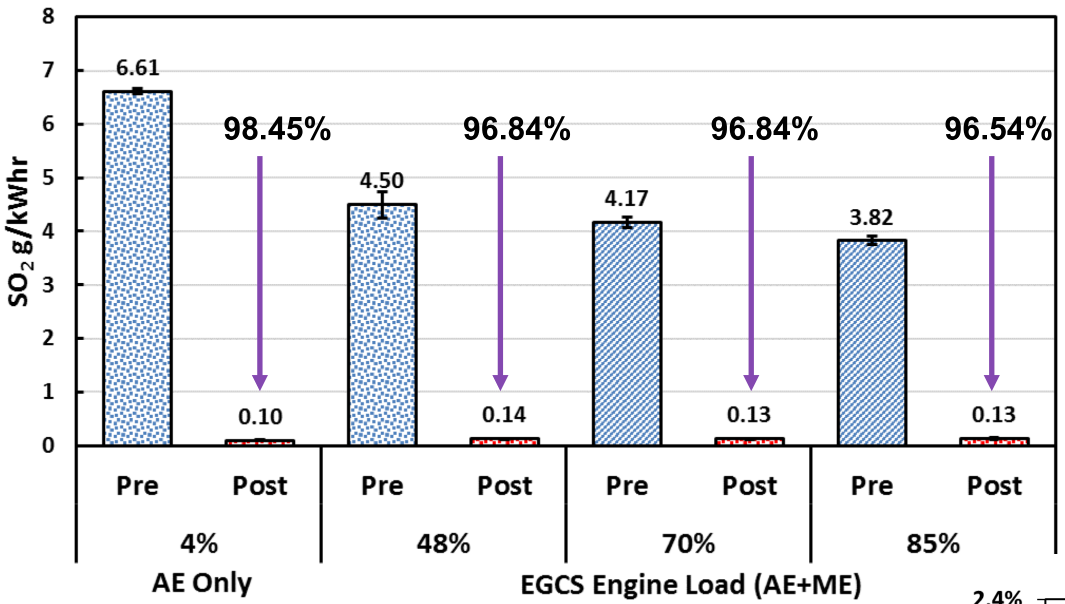
Post Scrubber Sampling



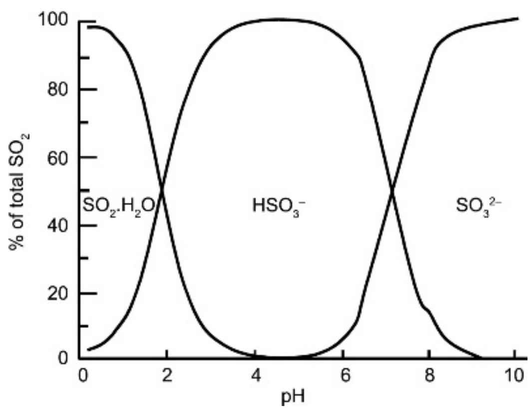
Test Sequence

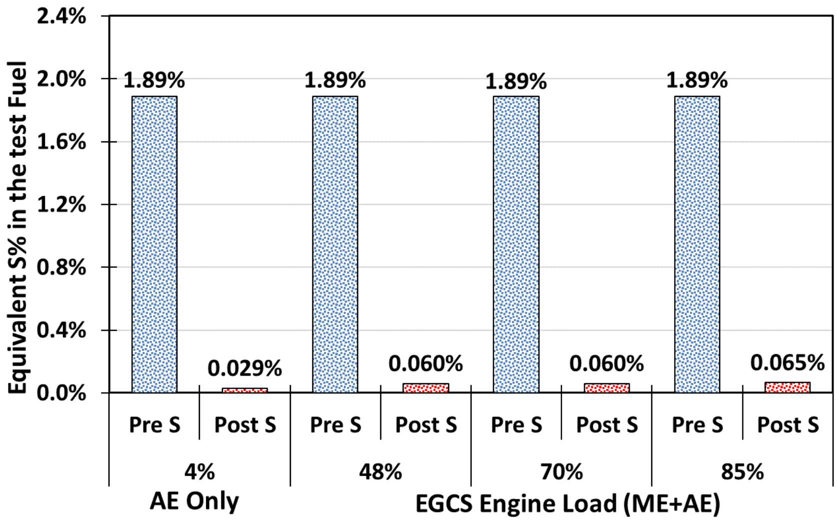
Day	Location	Special Notes [3]	Deck	Source	Scrubber	Mode	ME Load	AE Load
1	dock [1]	-	3	AE	Pre	4	0%	50%
2	at-sea	-	2	ME	Pre	3	50%	50%
2	at-sea	-	2	ME	Pre	2	75%	50%
2	at-sea	**High DR**	2	ME	Pre	2	75%	50%
2	at-sea	-	2	ME	Pre	1	92%	50%
3	at-sea	-	5	ME+AE	Post	1	92%	50%
3	at-sea	-	5	ME+AE	Post	2	75%	50%
3	at-sea	**High DR**	5	ME+AE	Post	2	75%	50%
3	at-sea	-	5	ME+AE	Post	3	50%	50%
3	at-sea	**No AE**	5	**ME-only**	Post	1	92%	50%
4	at-sea	**CL Mode**	5	ME+AE	Post	2	75%	50%
5	dock [2]	-	5	AE	Post	4	0%	50%

Preliminary Results: SO_2 Reduction

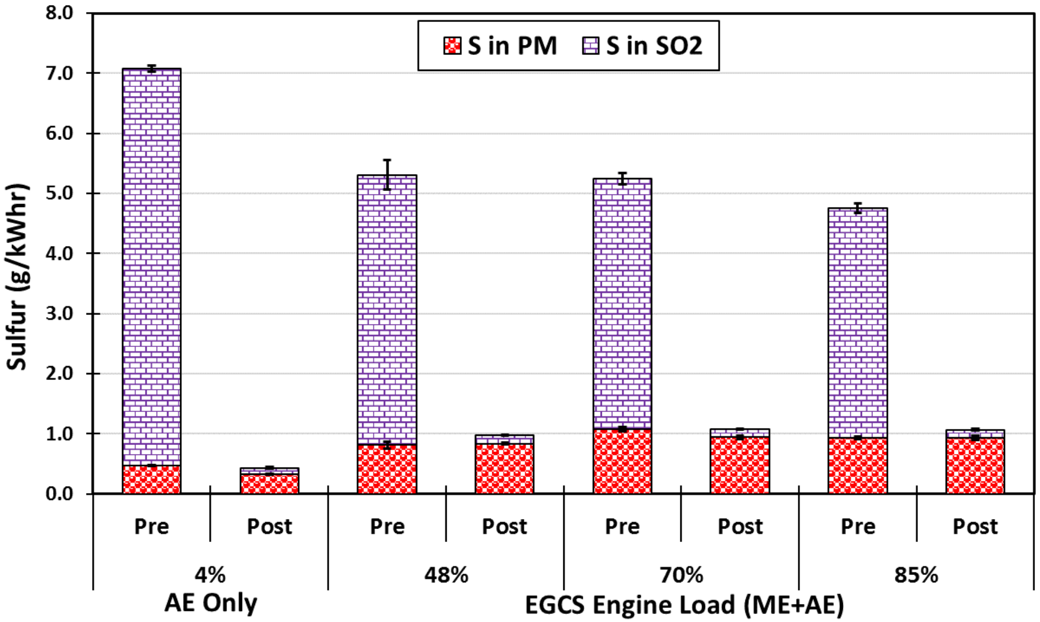


- ❑ 96-99% of the SO_2 reduction
- ❑ SO2/CO2 ratio < 4.3
- ❑ SO_2 emission reduction makes the fuel equivalent to 0.1% sulfur
- ❑ Fuel sulfur rule is being met with scrubber system (on a SO2 basis)





Preliminary Results: Overall Sulfur Reduction



	Engine Load (ME+AE)	SO4 µg/min*filter
Pre Scrubber	48%	64.60
	70%	131.47
	85%	158.73
Post Scrubber	48%	64.00
	70%	118.33
	85%	160.33

*Same dilution ratio at each load

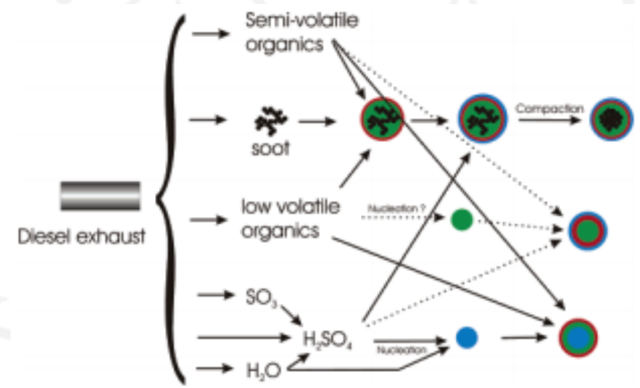


FIGURE 1. Schematic of the emissions and particle formation mechanisms in diesel exhaust. Solid lines indicate well-established processes, dotted lines indicate processes under discussion.

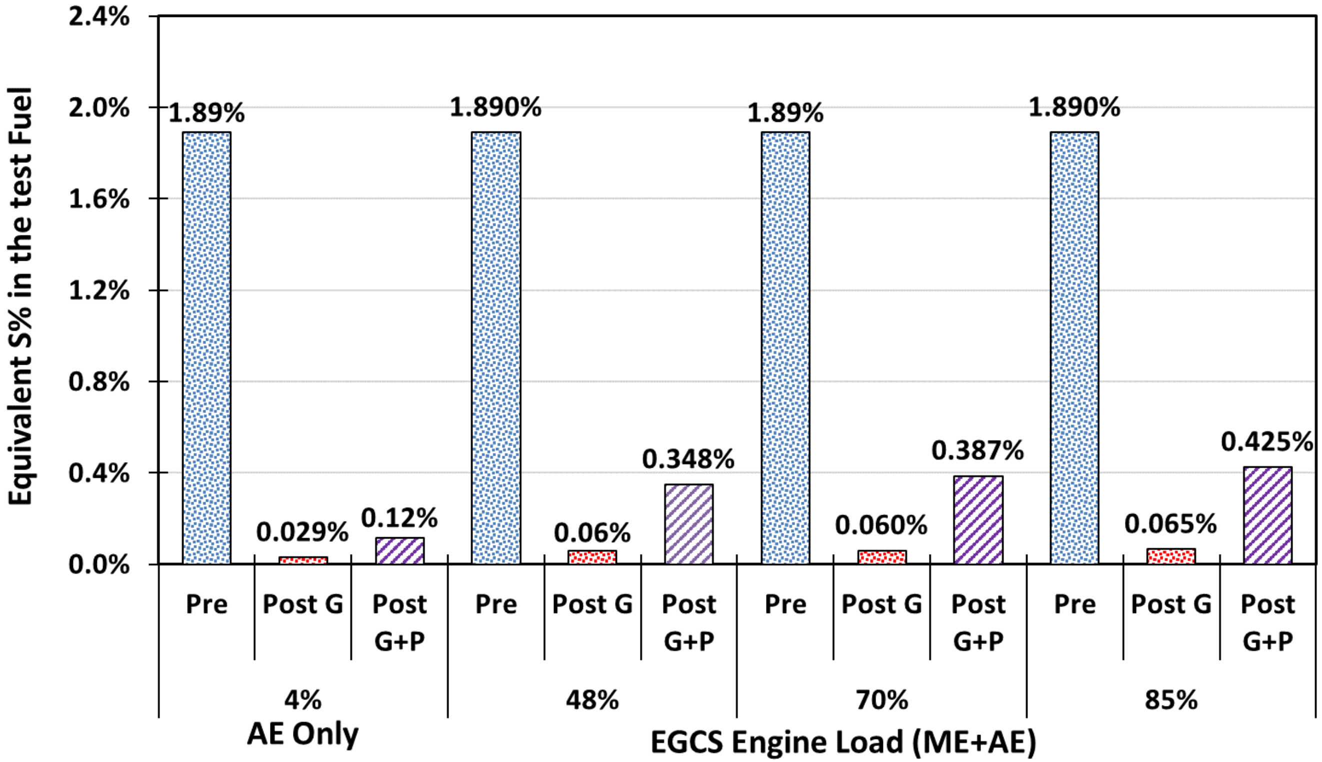
- ❑Study done by Schneider et al. (2005) explained - **Formation of nucleation mode particles from diesel exhaust occurs only under certain condition: high sulfur content and cooling effect.**

- ❑ Insignificant removal of the sulfur in the PM
- ❑ Health impact on the nanosize sulfuric acid particle is not clear

Schneider, J., Hock, N., Weimer, S., Borrmann, S., Kirchner, U., Vogt, R., & Scheer, V. (2005). Nucleation particles in diesel exhaust: Composition inferred from in situ mass spectrometric analysis. *Environmental science & technology*, *39*(16), 6153-6161.
Lemmetty, M., Pirjola, L., Mäkelä, J. M., Rönkkö, T., & Keskinen, J. (2006). Computation of maximum rate of water–sulphuric acid nucleation in diesel exhaust. *Journal of aerosol Science*, *37*(11), 1596-1604.

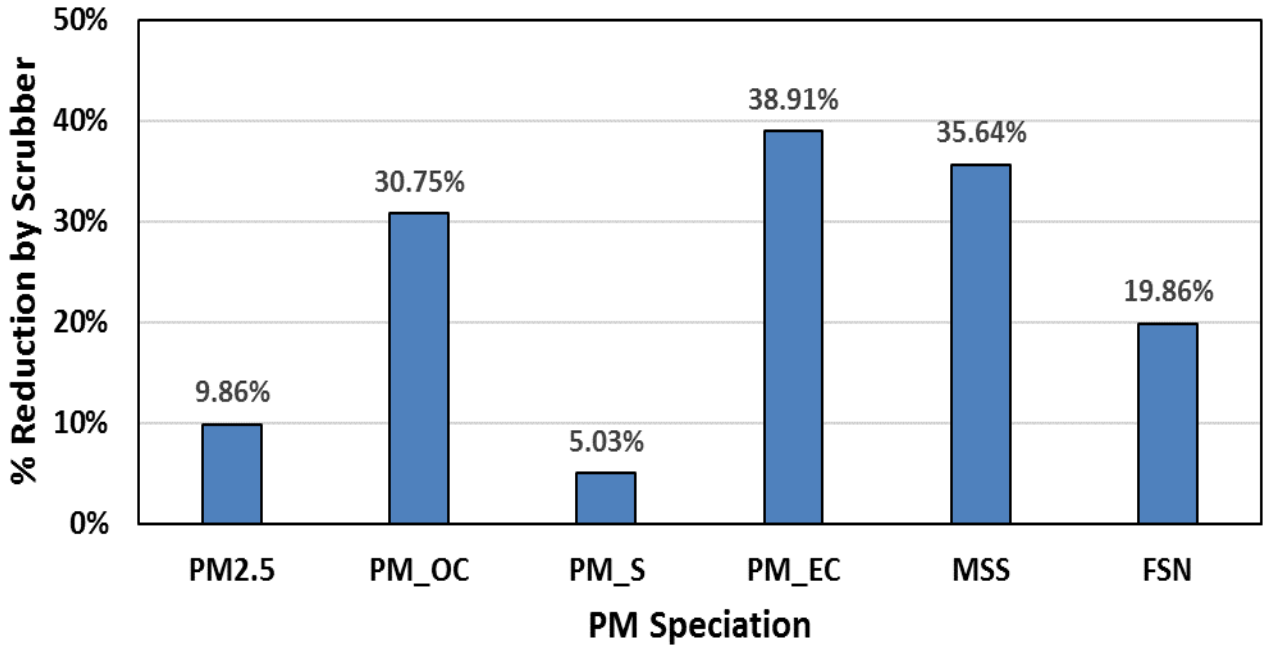
Exhaust Plume

Equivalent Sulfur in the Fuel (gas + particle)



❑ 79-93% of the overall sulfur content reduction.

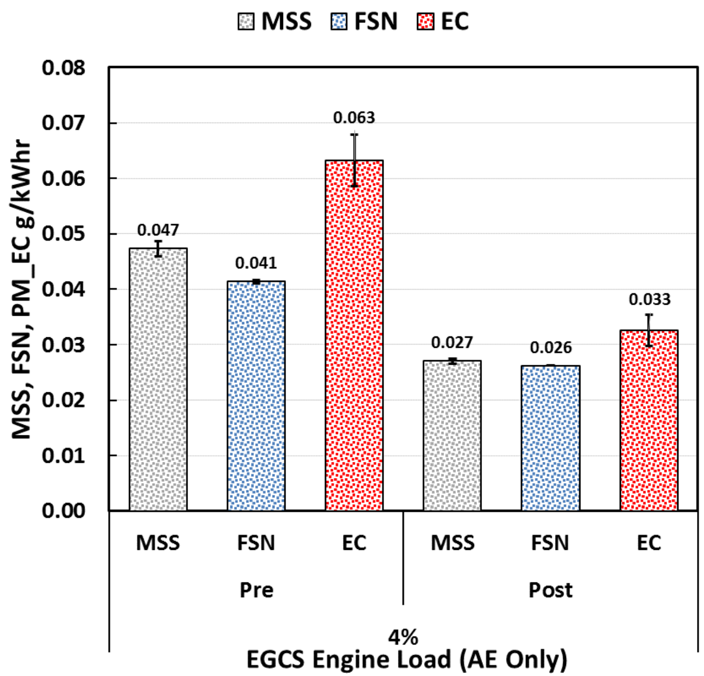
ISO Weighted Particle Reduction

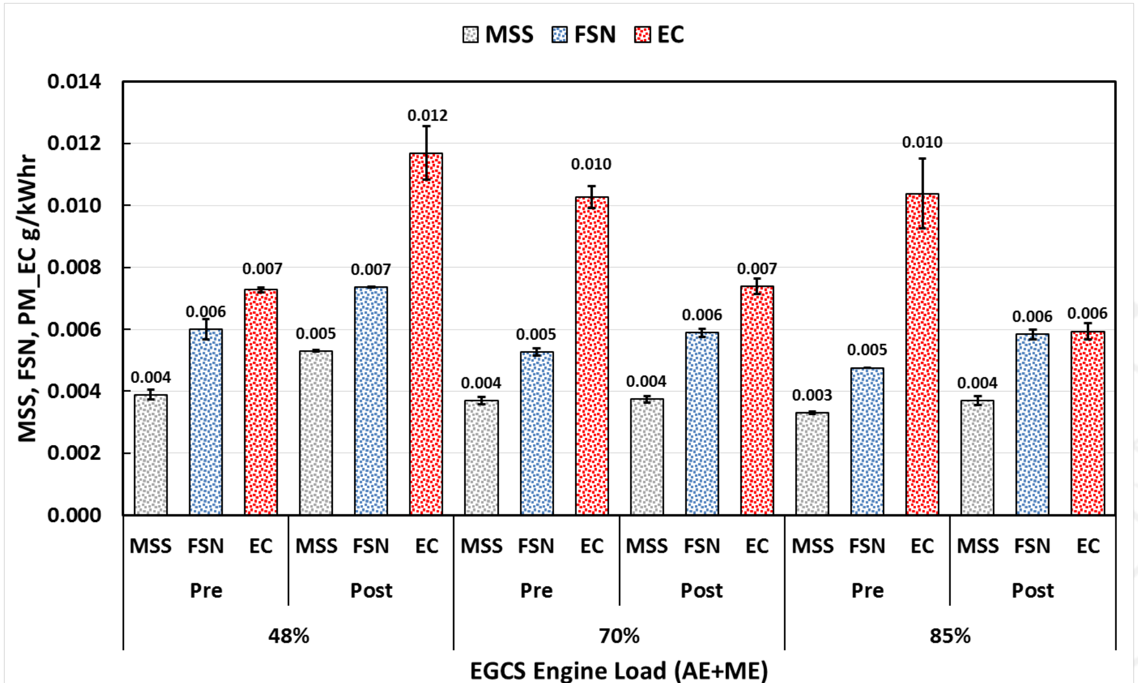


Combined Load (ME + AE)	Suggested Weighting Factor
85%	0.22
70%	0.52
48%	0.21
4%	0.05

- ❑ The scrubber is able to remove approximately 10% of the total PM, 30% on the OC, and 5% on sulfur PM.
- ❑ The reduction of the BC carbon varies on the measurement method has a range o 20-40% of reduction by scrubber.

BC Measurement EF Comparison



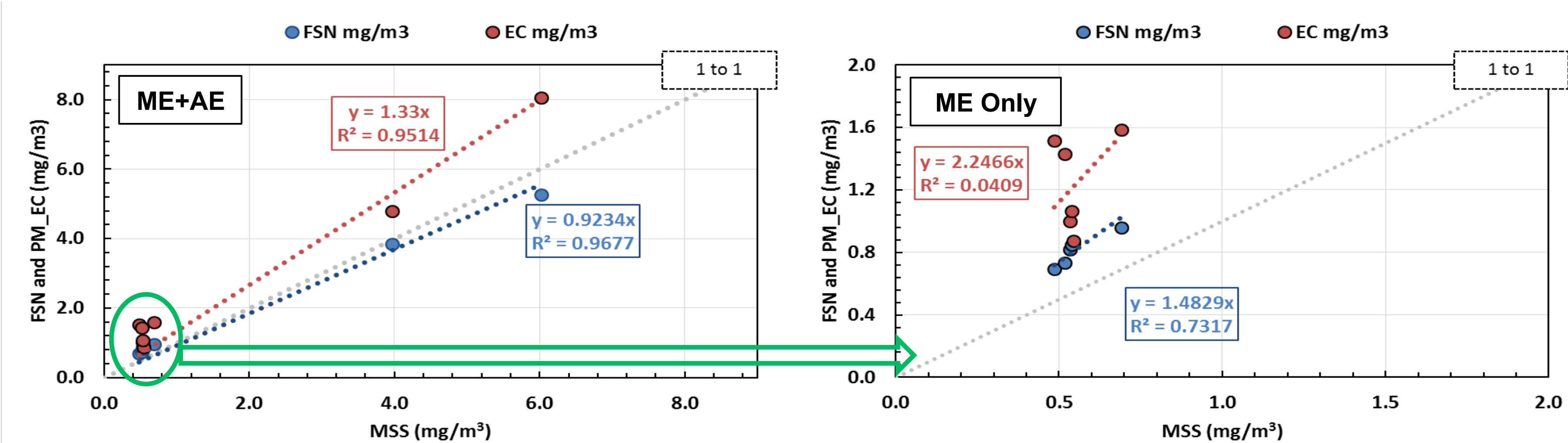


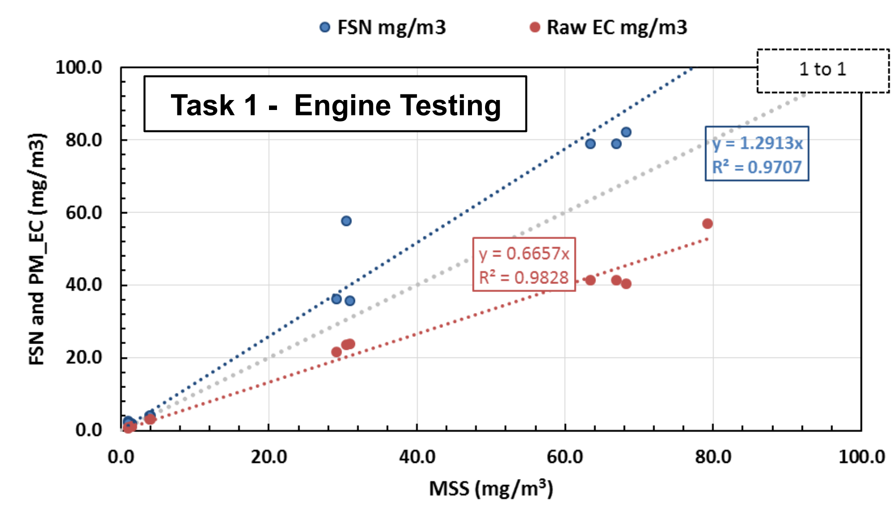
TTEST	MSS	FSN
MSS	x	x
FSN	0.8556	x
EC	0.2436	0.2740

*AE included

- ❑ AE trends to have more BC emissions rate (g/kWhr) than ME, 5-10 times
- ❑ Trend of BC emissions reduction by scrubber from AE, not ME
- ❑ FSN and EC trend to have higher BC results than MSS
- ❑ None of the instruments show a statistically difference

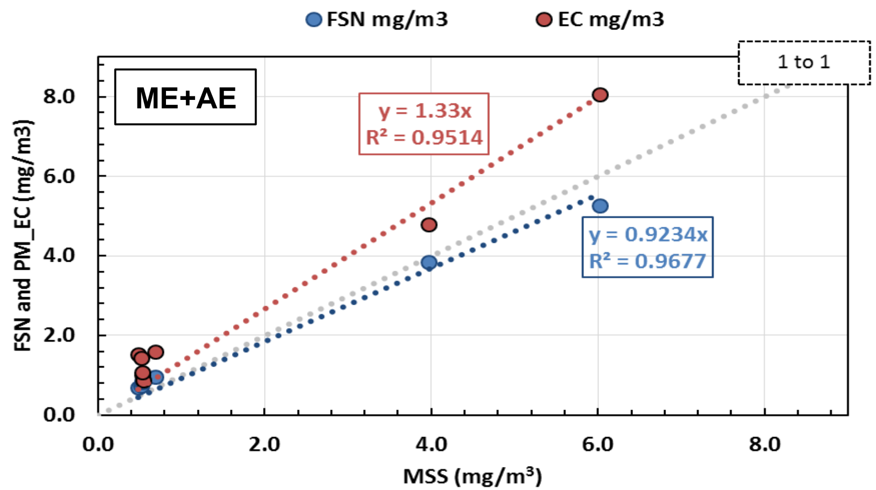
BC Measurement Comparison – FSN vs MSS

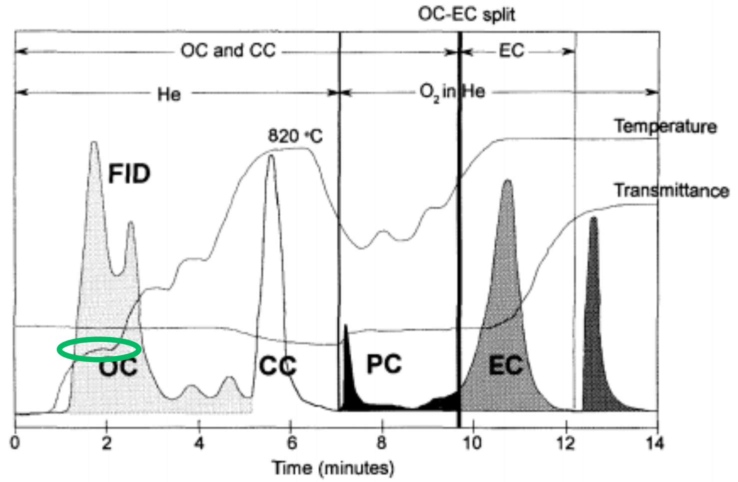


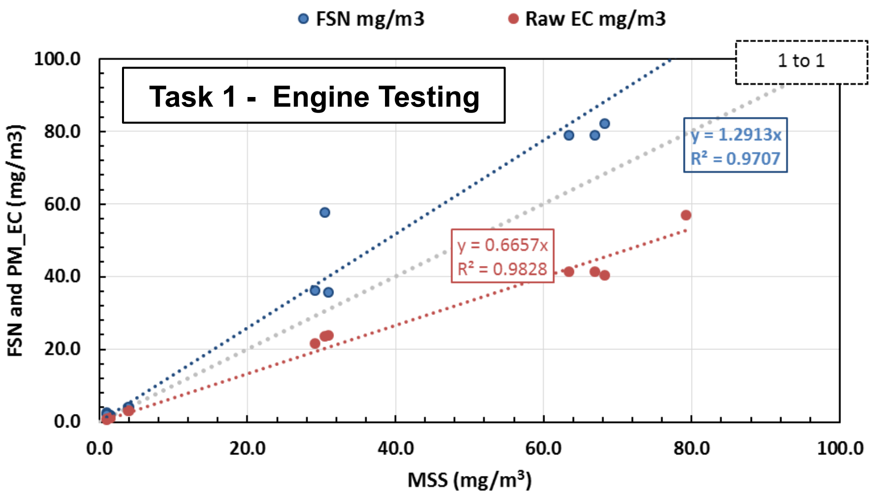


- ❑ Sample Range has a big effect on correlation curve
- ❑ ME+AE data shows a high R2 and good slope
- ❑ ME only shows a poor R2 and low slow and high offset

BC Measurement Comparison – EC vs MSS





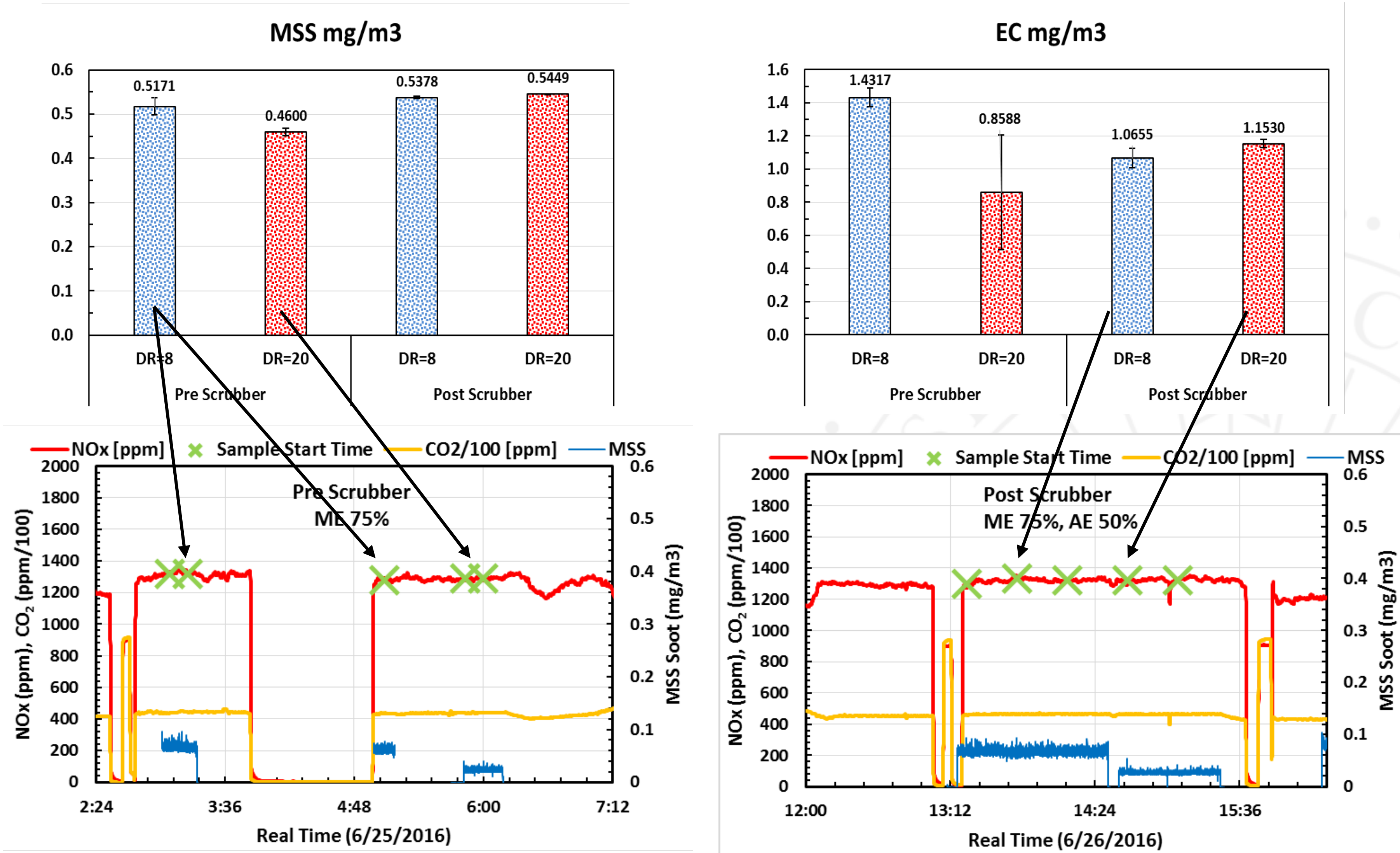


Particles (µg/filter)	Task 1	Task 3
EC	2 - 476	2 - 79
OC	5 - 515	54 - 498
SO4-	1 - 100	102 - 3380

- ❑Lower EC element in a higher sulfur filter, 150 times lower than task 1
- ❑ High sulfur content on the quartz filter made the pyrolyzation of the OC happens at low temperature, change OC-EC split point

Birch, M. E., & Cary, R. A. (1996). Elemental carbon-based method for monitoring occupational exposures to particulate diesel exhaust. *Aerosol Science and Technology*, *25*(3), 221-241.

Dilution Effect on BC Sampling



Summary and Conclusion

- ❑ Nucleation mode sulfuric acid particles were formed in high sulfur fuel and cooling effect, which is not able to be removed by scrubber system. Scrubber system is not as effective as the fuel sulfur rule when considering the sulfur in the particle phase.
- ❑ Quartz filter based ECOC shown higher EC results when high amount of sulfur on the filter due to the pyrolyzation at low temperature effect the ECOC split point.
- ❑ MSS and FSN shown comparable correlation with task 1.
- ❑ Scrubber system able to meet SO_2/CO_2 (ppm_v/%_v) ratio less than 4.3, which corresponds to a 0.1% sulfur fuel.

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AVL: Monica Tutuianu

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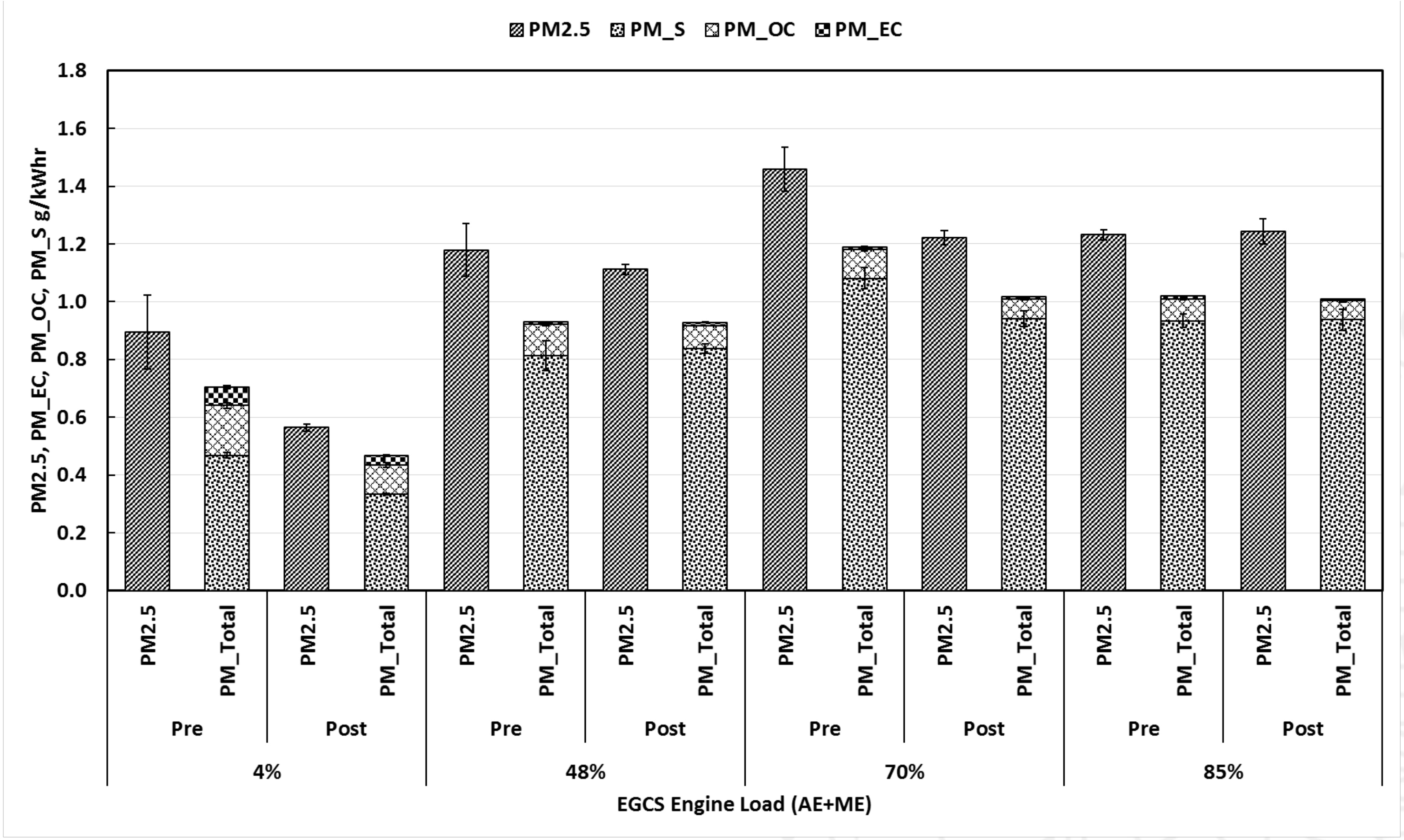
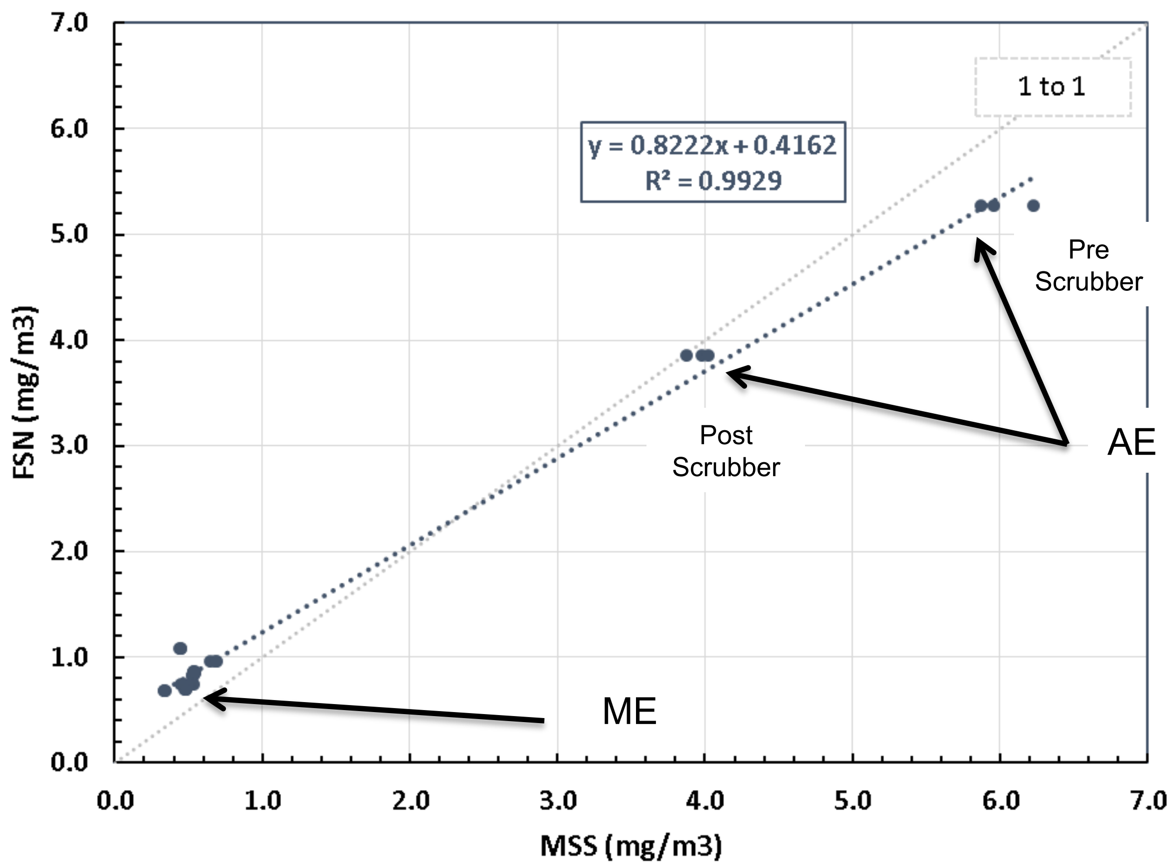
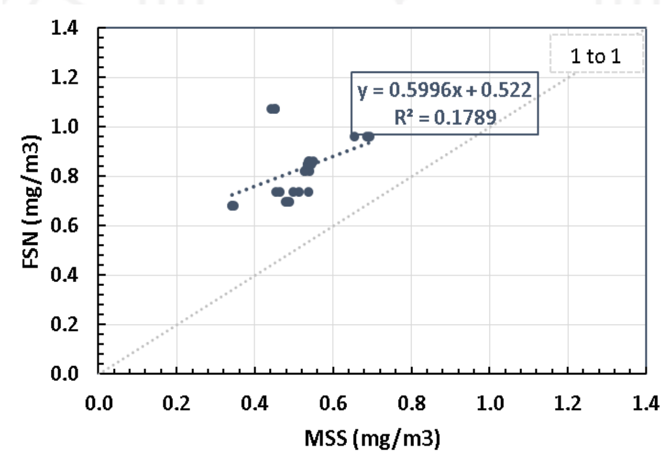
Thank You for Your Attention


PM2.5
PM_S
PM_OC
PM_EC
PM2.5, PM_EC, PM_OC, PM_S g/kWhr
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
PM2.5
PM_Total
Pre
Post
4%
48%
70%
85%
EGCS Engine Load (AE+ME)

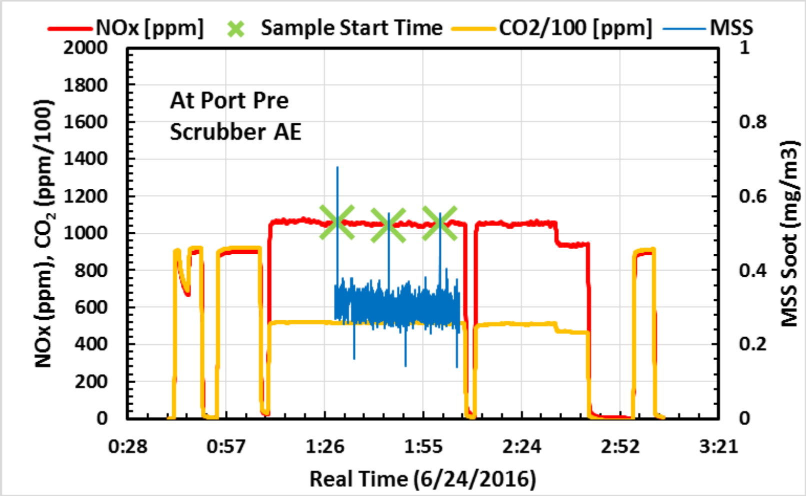
Preliminary BC Comparisons look good

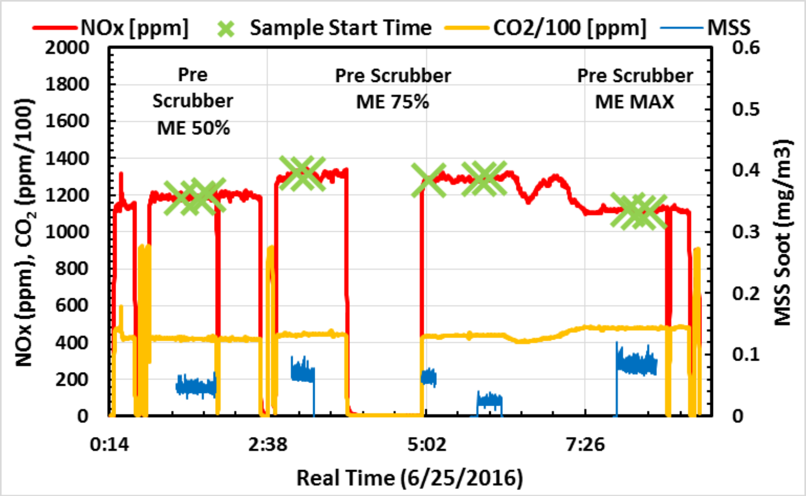


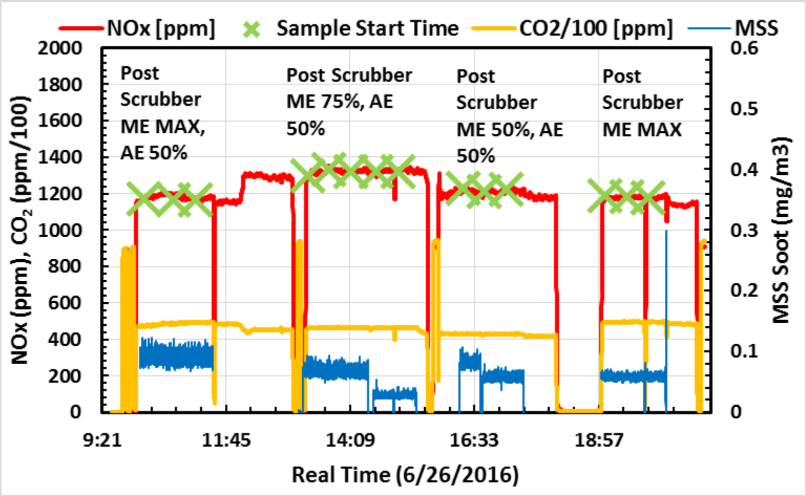
- ❑ Concentrations very high for BC on AE engine (8x)
- ❑ ME+AE data shows a high R2 and good slope (0.82)
- ❑ ME only shows a poor R2 and low slow and high offset
- ❑ Concentrations for Scrubber vessel much higher than the Tier 2
- ❑ Prelim data suggest scrubber is reducing BC emissions.

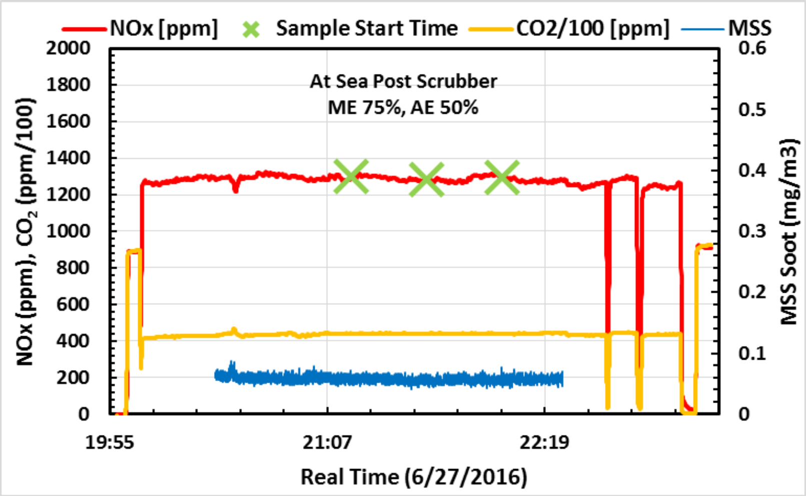


Real Time Evaluation





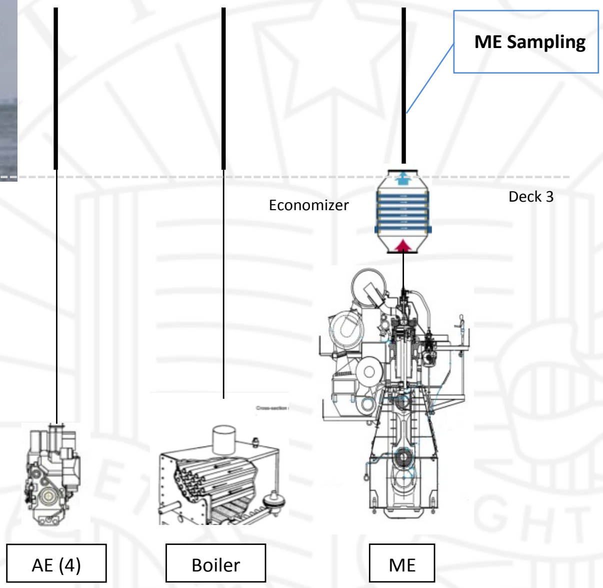




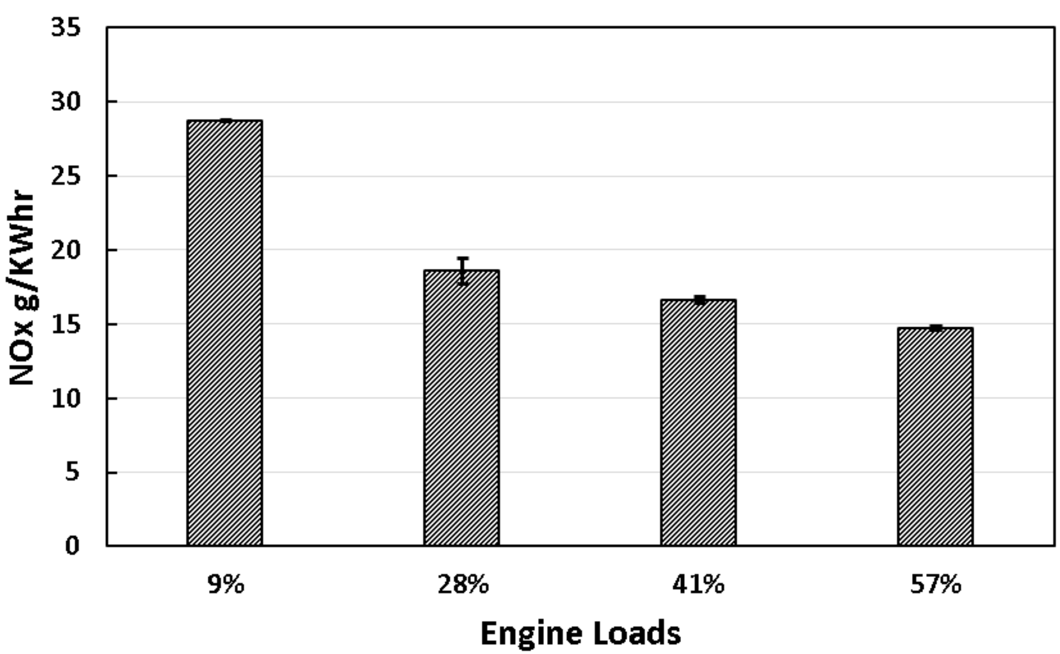
First Ever Tier 2 Main Engine Tested

- ❑ 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

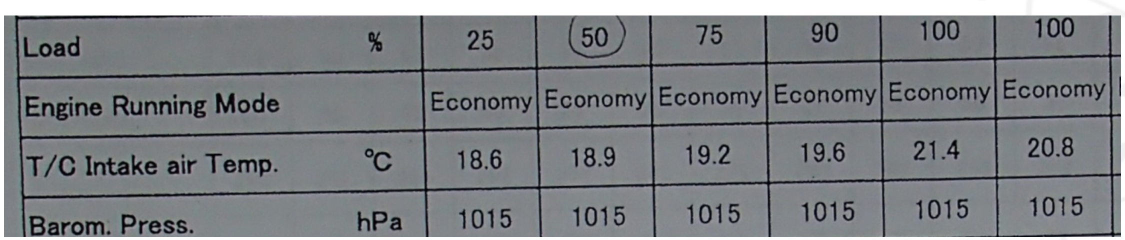
Source	*Engine Mfg.*	*MY and Model*	*Engine Power kW*	*Run Hours*	*EGCS*
ME	Mitsui MAN B&W	2011 12K98ME6.1	68,666	25,985	no
AE1	Daihatsu	2011 8DC32e	3,162	n/a	no
AE2	Daihatsu	2011 8DC32e	3,162	n/a	no
AE3	Daihatsu	2011 8DC32e	3,162	14,550	no
AE4	Daihatsu	2011 8DC32e	3,162	n/a	no
Boiler	Alfa-Laval	2011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



NOx Emissions in Compliance

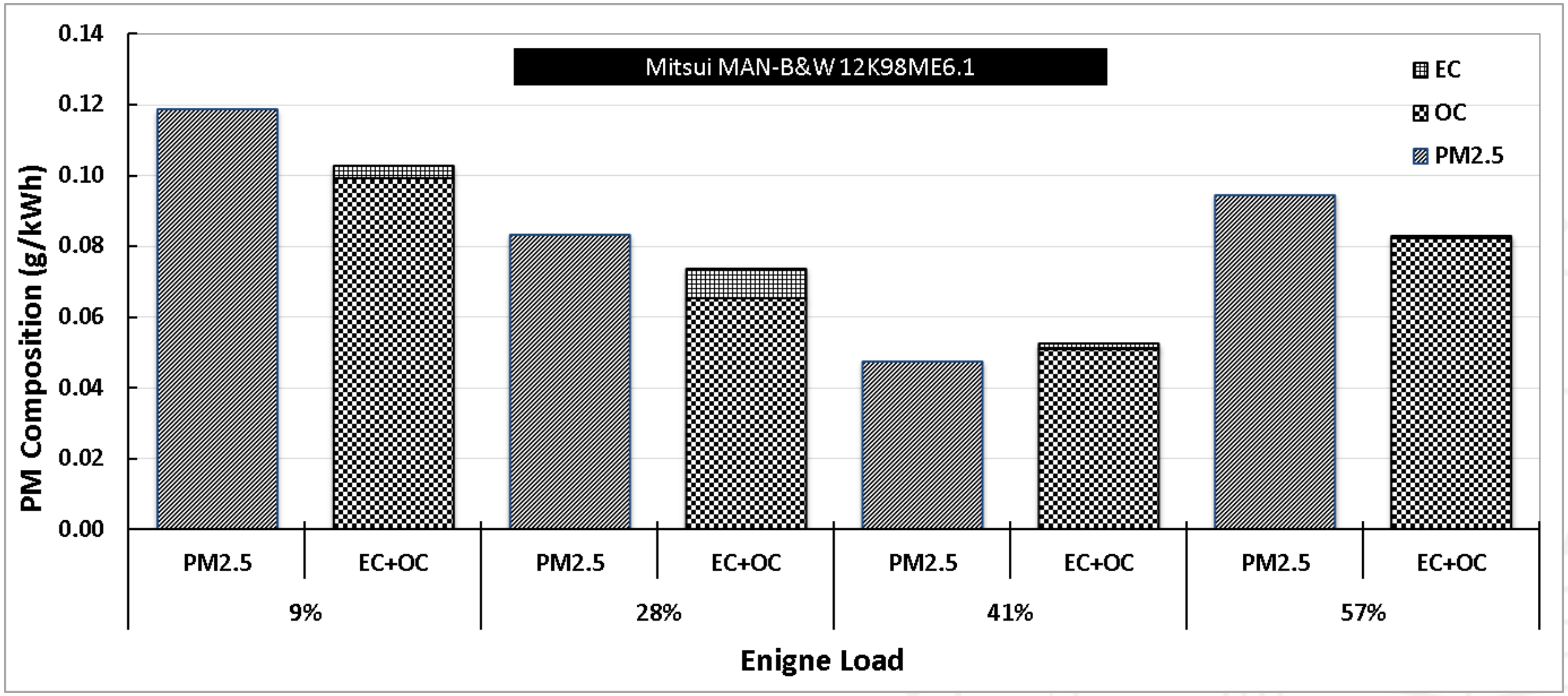


- ❑ Vessel operated in "TC Cut Out" mode
- ❑ Shop trial performed in "Economy" mdoe
- ❑Estimated ISO weighted NOx value of 15.5 g/kWhr
- ❑ ISO Cat 3 standard is 14.4 g/kWhr (dif of 7%)
- ❑ Engine is in compliance



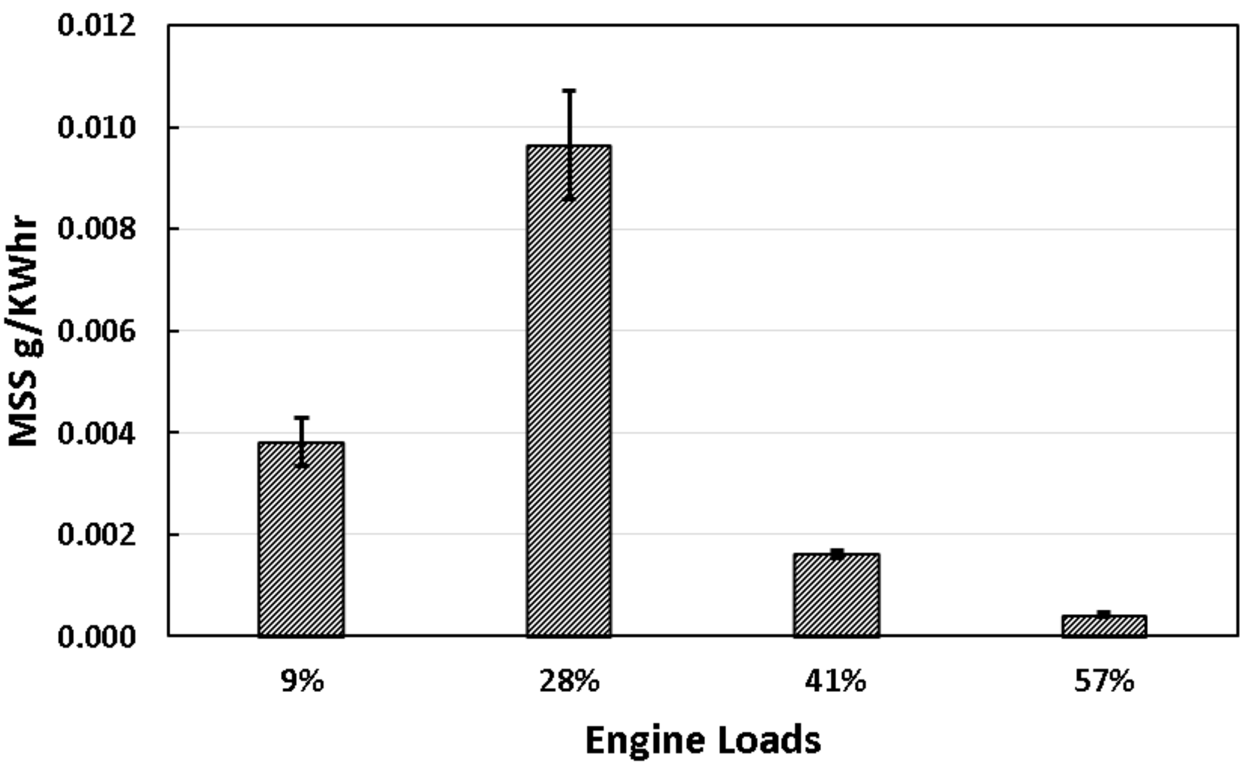
Load	%	25	50	75	90	100	100
Engine Running Mode		Economy	Economy	Economy	Economy	Economy	Economy
T/C Intake air Temp.	℃	18.6	18.9	19.2	19.6	21.4	20.8
Barom. Press.	hPa	1015	1015	1015	1015	1015	1015

PM Emissions Lowest at 40% Load



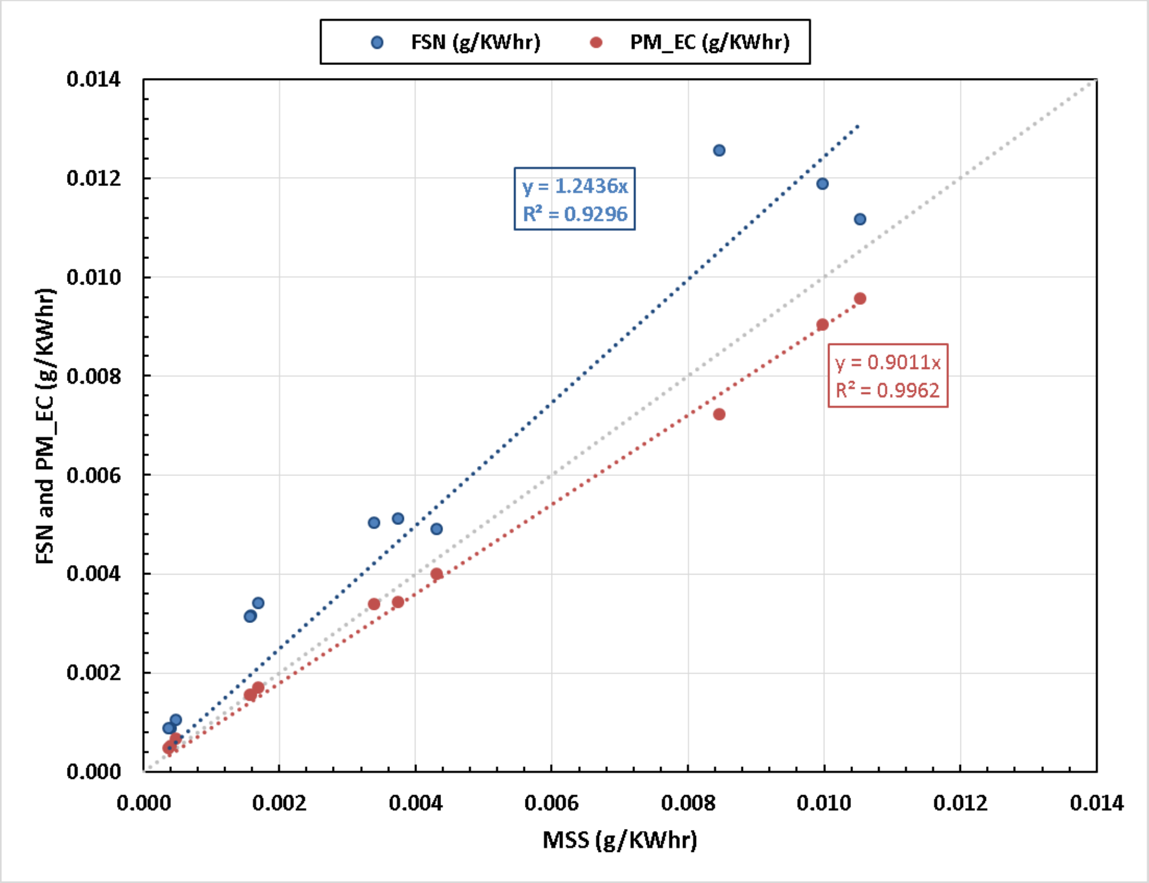
- ❑ PM emissions highest at VSR (~ 0.12 g/kWhr)
- ❑ Most of the PM is organic with some little BC
- ❑ Organic PM follows the trend of total PM
- ❑ Sulfate estimated at “tbd”

BC Emissions Lowest at high load and possibly stilll dropping

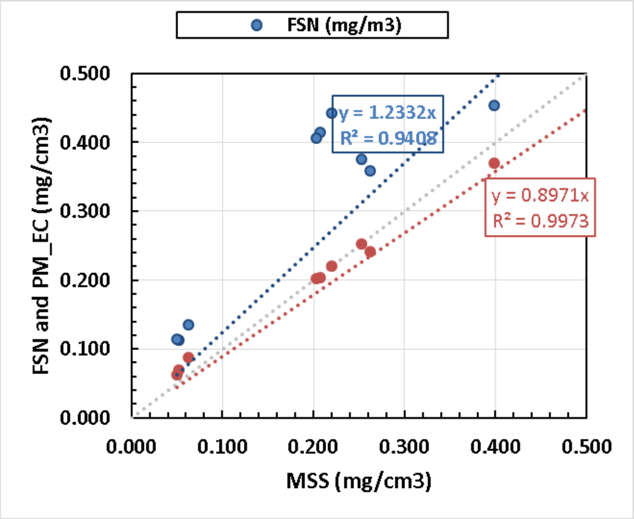


- ❑ BC emissions highest at 28% load
- ❑ BC emissions very low at 57% load
- ❑ Emission Factors at 57% load were 0.001 g/kWhr
- ❑ The Tier 2 BC EF at 57% load are 10 times lower than other tested (Tier 1 and Tier 0 vessels)

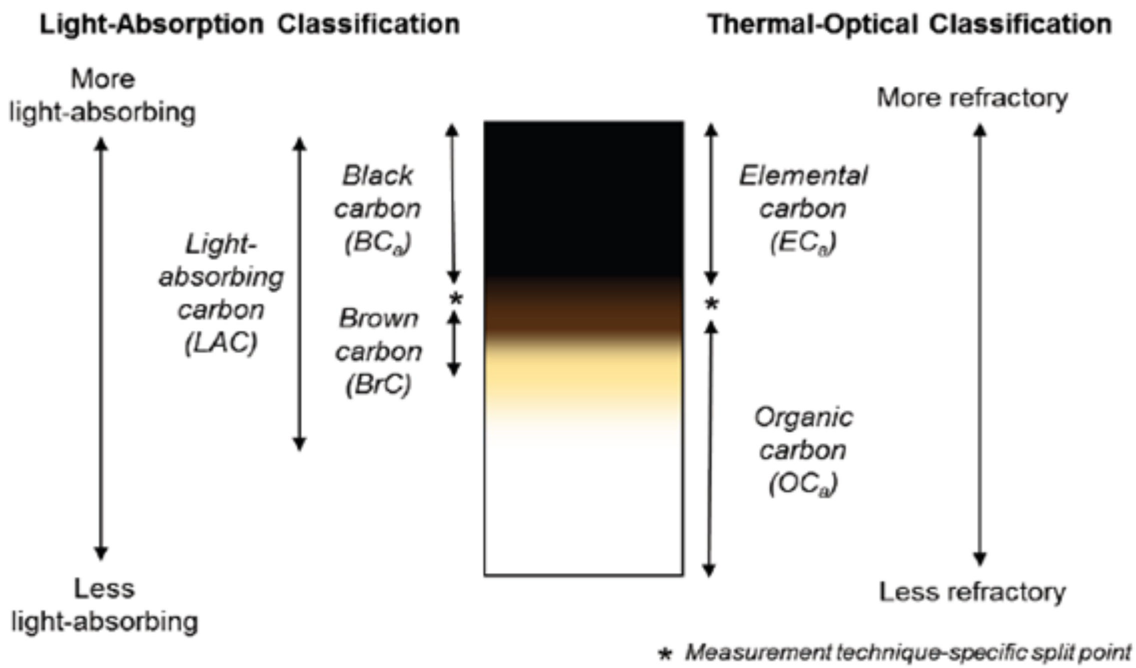
BC Measurement Methods Correlated Well



- ❑ R2 is high for both methods at 0.9 or greater
- ❑ FSN is higher than MSS and EC is lower.
- ❑ Raw stack concentrations very from 0.06 to 0.46 ug/m3



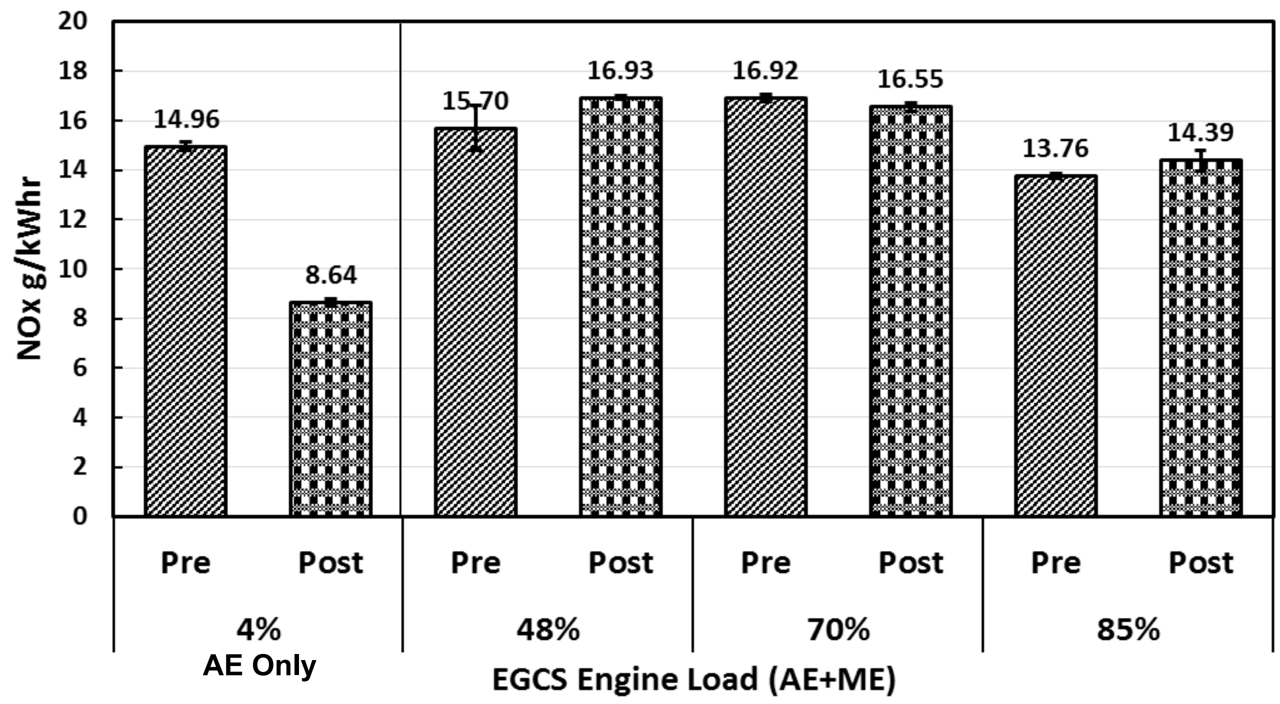
Project Background



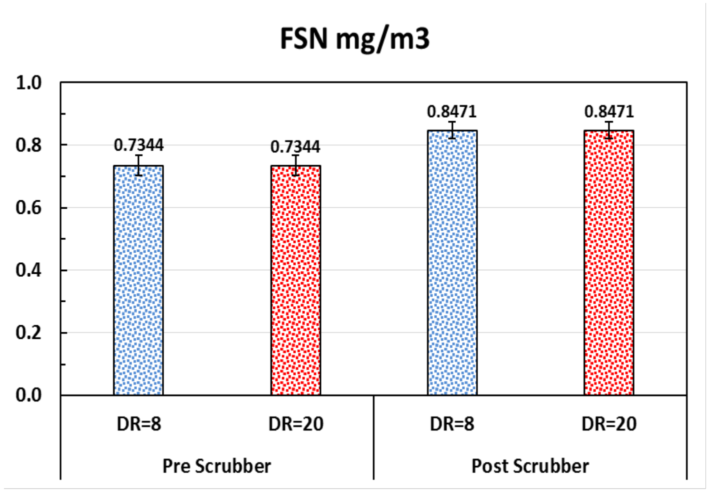
- BC Measuring methods
  1) Light-absorbing property --- often referred to as BC
  2) Thermal or thermal/optical technique --- referred to as EC

Figure 1-1 Measurement of the Carbonaceous Components of Particles (SOURCE: EPA)

Preliminary Results: NOx Emissions



Dilution Effect on BC Sampling



- ❑ Dilution ratio has an larger effect at pre scrubber (exhaust temperature)
- ❑ Filter based EC has a larger derivation than MSS
- ❑ lower EC element in a higher S filter

Scrubber Operation Effect on BC Emissions