Marine Scrubber Efficiency and NOx Emission from Large Ocean Going Vessels

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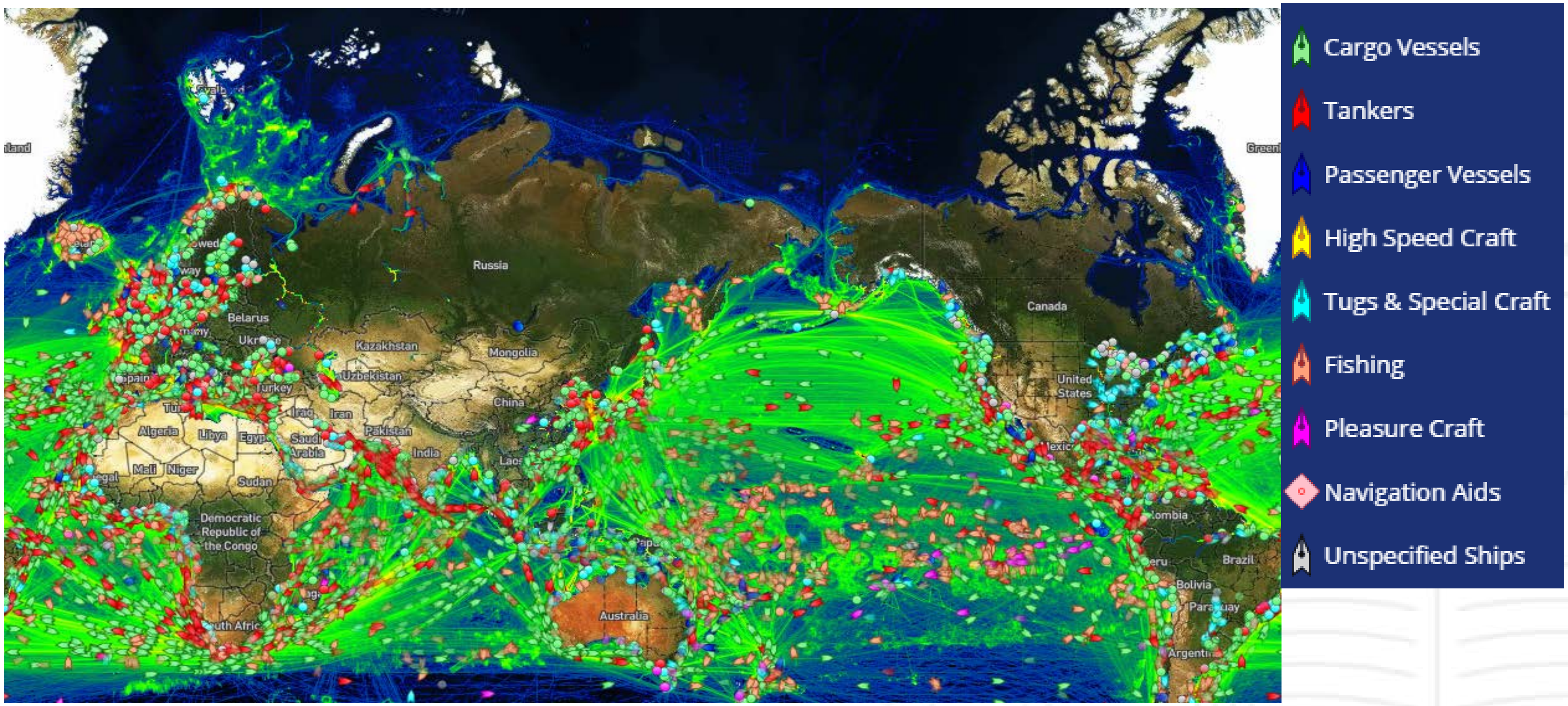
Baltimore, MD

Outline

- **Background**
- **Marine Emissions Policy, Control Strategy and Challenge**
  - Sulfur Emission
  - Oxides of Nitrogen (NOx) Emission
- **Conclusion**

Marine Vessels and Global Shipping

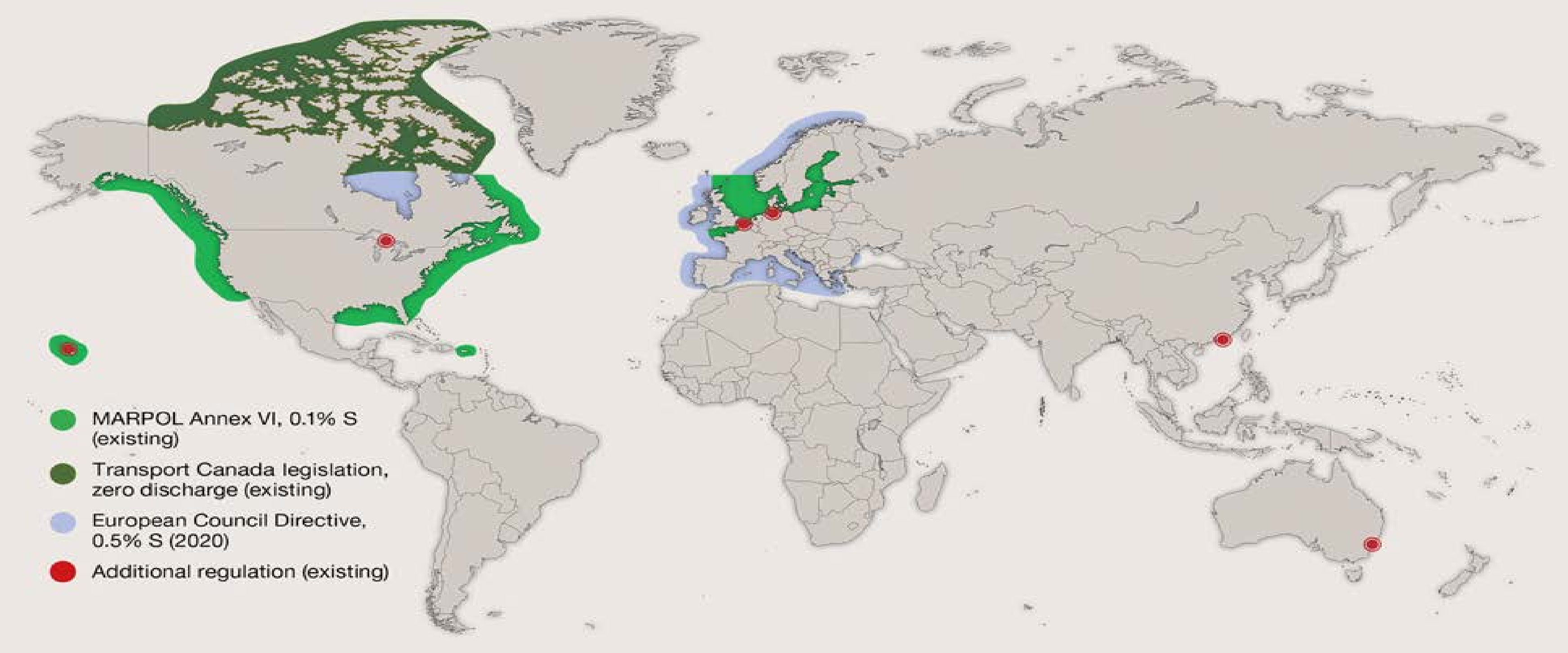


- ❑ Represents 80% of the volume and 70% of the value of international trade[1].
- ❑ Linked with increased mortality in coastal regions, with an estimated 60,000 deaths from cardiopulmonary and lung cancer per year[2].
- ❑ Emission effects the people living near the ports and coastlines, and those living hundreds of miles inland[3].

1. United Nations Conference on Trade and Development (UNCTAD), Review of Maritime Transport 2015
2. Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., & Lauer, A. (2007). Mortality from ship emissions: a global assessment. *Environmental science & technology*, *41*(24), 8512-8518.
3. United State Environmental Protection Agency (US EPA), MARPOL Annex VI, accessed on October 5 2016, https://www.epa.gov/enforcement/marpol-annex-vi

*Figure is obtained from www.marinetraffic.com.

IMO Sulfur Rule and Emissions Control Areas (ECAs)



Global Fuel Sulfur Limits		ECA Fuel Sulfur Limits	
Before 1 July 2012	4.5% m/m	Before 1 July 2010	1.5% m/m
1 July 2012 – 1 January 2020	3.5% m/m	1 July 2010 – 1 January 2015	1.0% m/m
After 1 January 2020	0.5% m/m	After 1 January 2015	0.1% m/m

*Figure is obtained from www.alfalaval.com.

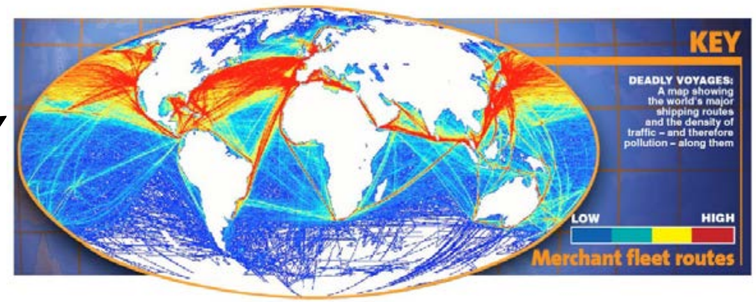
- ❑ IMO is targeting 0.5% of sulfur in the fuel by 2020 internationally.
- ❑ Stricter sulfur limits are in place in ECAs, and potential of increase ECAs.
- ❑ Aftertreatment (e.g. Scrubber) is allowed to use **if achieves the sulfur emissions equivalence** to low sulfur fuel.

Strategies to Control Sulfur Emissions

MARPOL Annex VI

Decision

Avoid ECAs



Switch to Low Sulfur Fuels

Bunker Prices ($/metric tons)	HFO	MGO
Global Average	317.50	527.50
Americas Average	341.00	594.00
APAC Average	348.50	616.50
EMEA Average	347.00	537.00

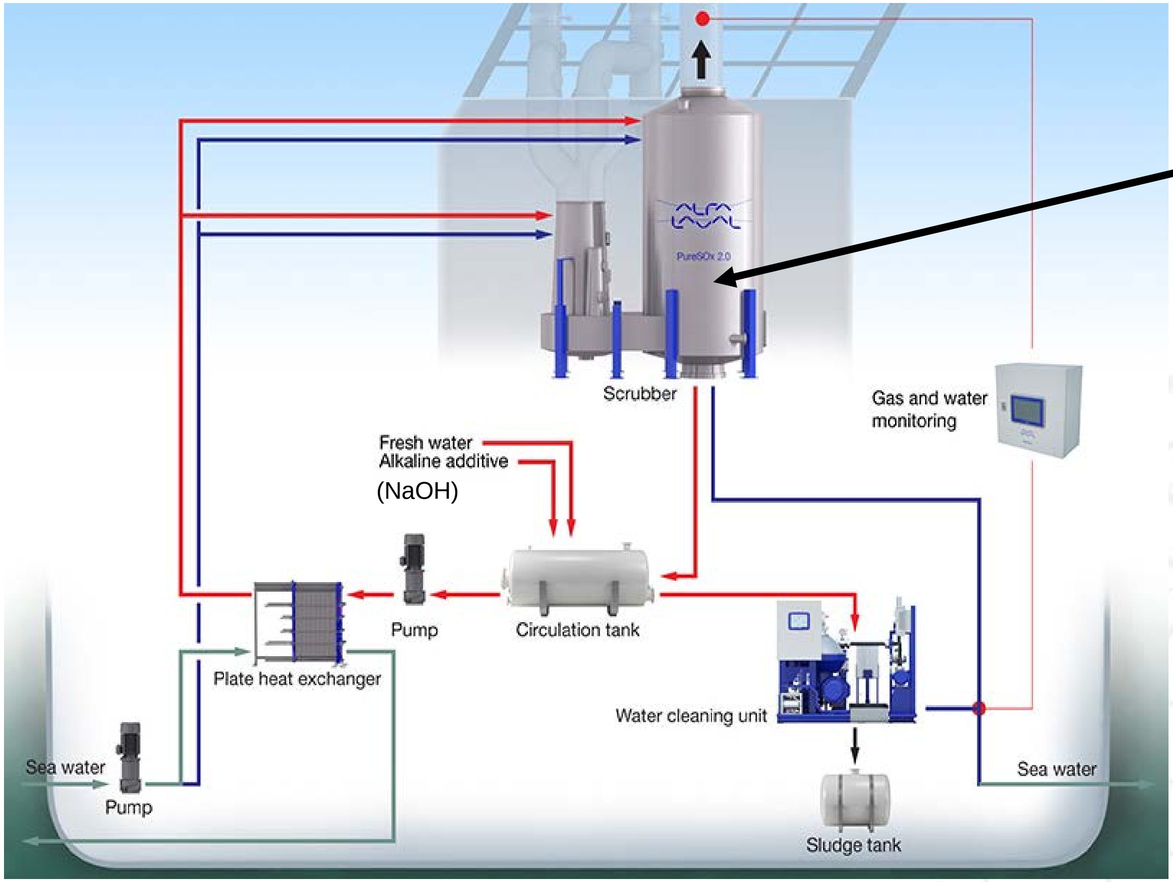
*Information adopted from Ship&Bunker on August 16th, 2017
**Demand driving fuel price

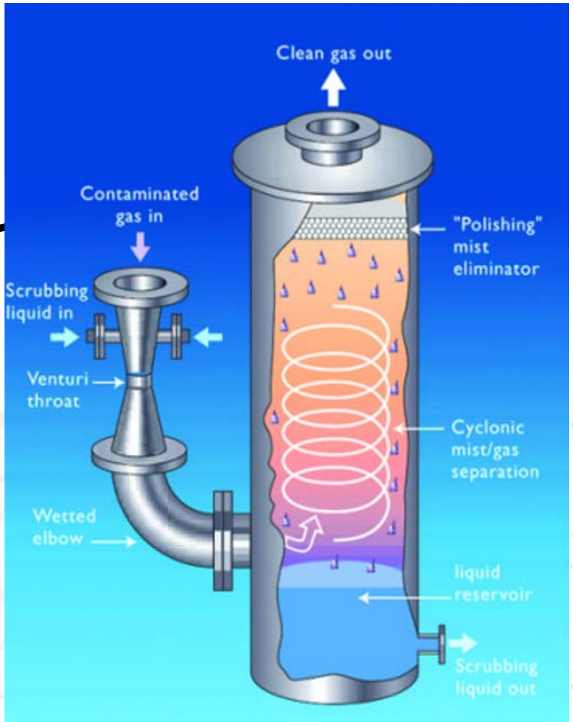
Switch to LNG/Dual Engine

Install a Scrubber

*Figure is obtained from www.alfalaval.com.

Marine Scrubber System





- ❑ Both open and close loop System
- ❑ Typical venturi and a cyclone separator
- ❑ Requires continuous monitoring SO_2, CO_2, PH, PAH, and turbidity

*Figure is obtained from www.alfalaval.com.

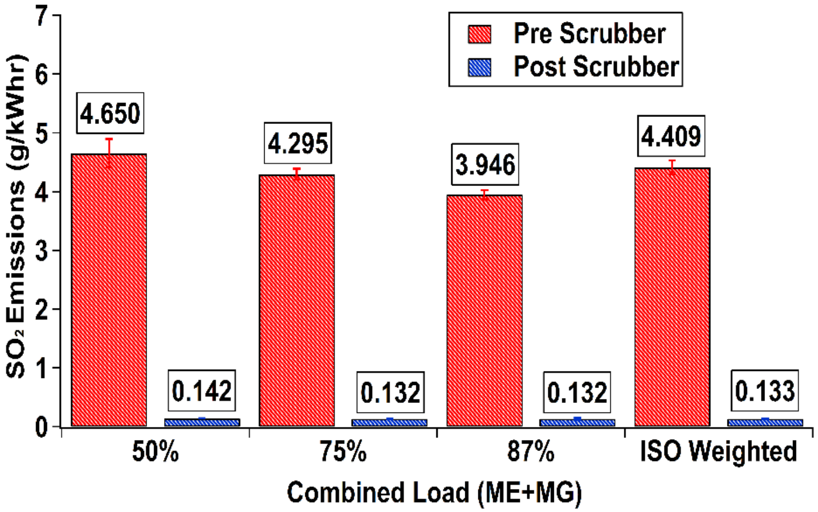
- ❑ The excess heat of the hot exhaust gas will be consumed by evaporating scrubbing water until the gas reaches wet bulb temperature.
- ❑ The mist eliminator is designed to remove entrained droplets from the gas stream.

Vessels, Engines, Fuels

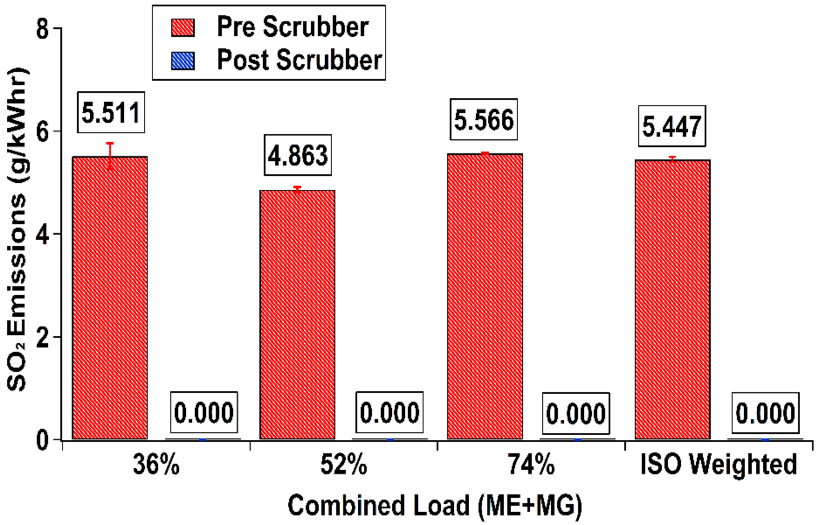
	Vessel 1	Vessel 2	Vessel 3
Year Build	1987	2006	2015
Vessel Type	Container	Cruise	Ro-Ro
IMO Category	Tier 0	Tier 1	Tier 2
ME Engine	Mitsui Man B&W	Wartsila	Hyundai Man B&W
ME Year Build	1986	2005	2014
ME Model	7L70	4*12V46CR	8S60ME-C8.2
ME Power Capacity (MW)	16.6	4*12.6	15.6
AE Engine	Wartsila	Wartsila	Hyundai HiMSEN
AE Model	2*6R32D	2*8L46CR	2*7H25/33 + 1*6H25/33
AE Power Capacity (MW)	2*2.1	2*8.4	2*1.9 + 1.7
Go Through Scrubber	ME+1*AE	2*ME	ME+3*AE
Test Fuel	HFO (1.9% S)	RMG 380 (2.8% S)	HFO (2.5% S)
Scrubber	Alfa-Laval	n/a	Wartsila

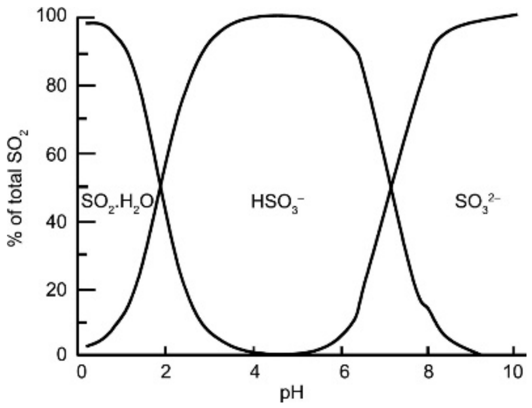
SO_2 Reduction

Vessel 1



Vessel 3

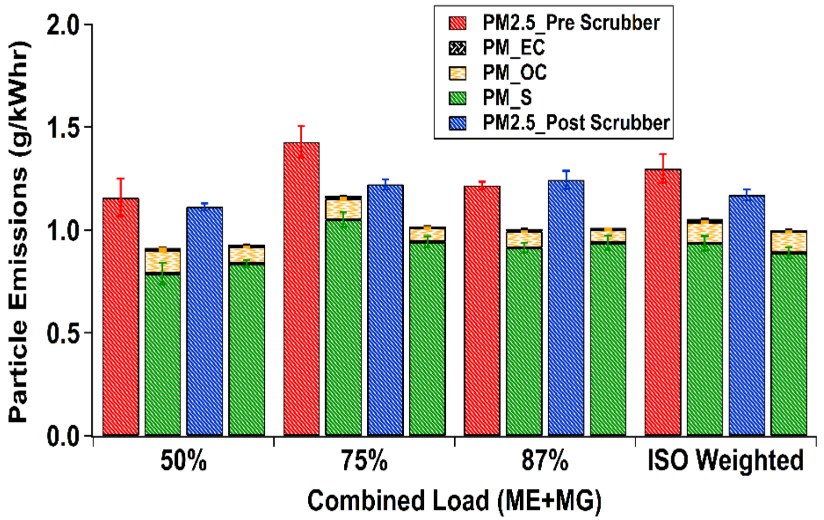




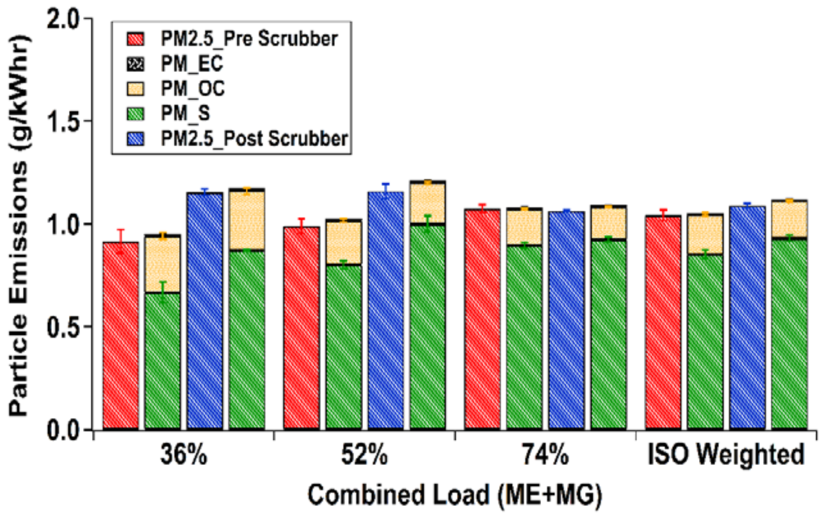
- ❑ Scrubber shows a 96-100% of the SO_2 reduction
- ❑ SO_2(ppm)/CO_2(%) ratio < 4.3
- ❑ SO_2 emission reduction makes the fuel equivalent to 0.1% sulfur
- ❑ Fuel sulfur rule is being met with scrubber system (on a SO_2 basis)

Sulfate PM ($H_2SO_4*6.65H_20$) Reduction

Vessel 1



Vessel 3



- ❑ Major Component of PM mass are Sulfate PM.
- ❑ There is no PM reduction with scrubber, and potentially more sulfate PM formation due to the scrubber.
- ❑ Sulfate PM reduction were not equivalent to the use of low sulfur fuel.

Why no PM reduction?

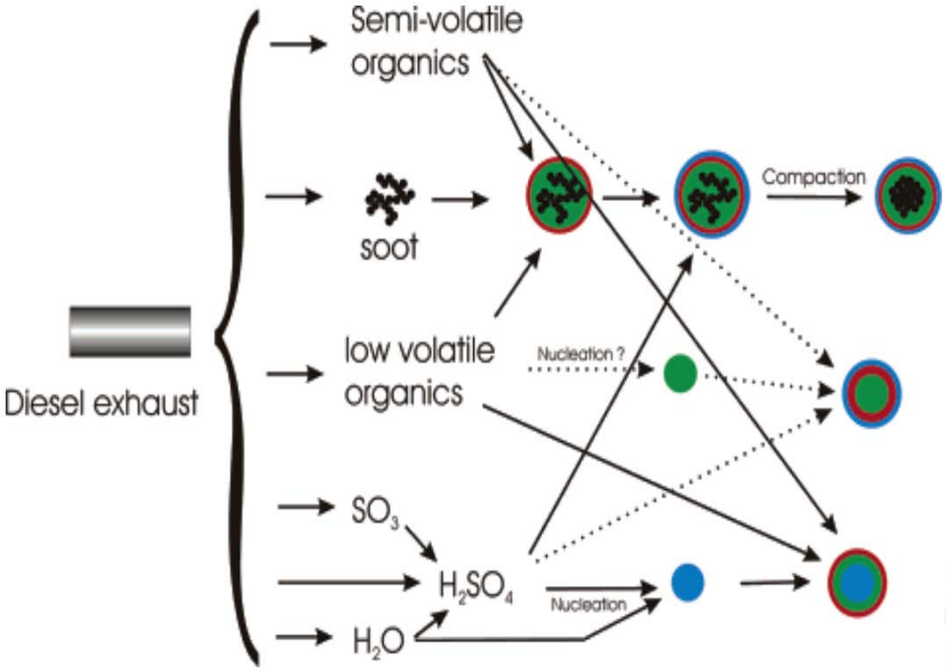


FIGURE 1. Schematic of the emissions and particle formation mechanisms in diesel exhaust. Solid lines indicate well-established processes, dotted lines indicate processes under discussion.

- Why our results are different from European?
- What does the cold sea water scrubber impact on the particle formation?
- What does the challenge of particle formation to particulate sampling methodology?

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.
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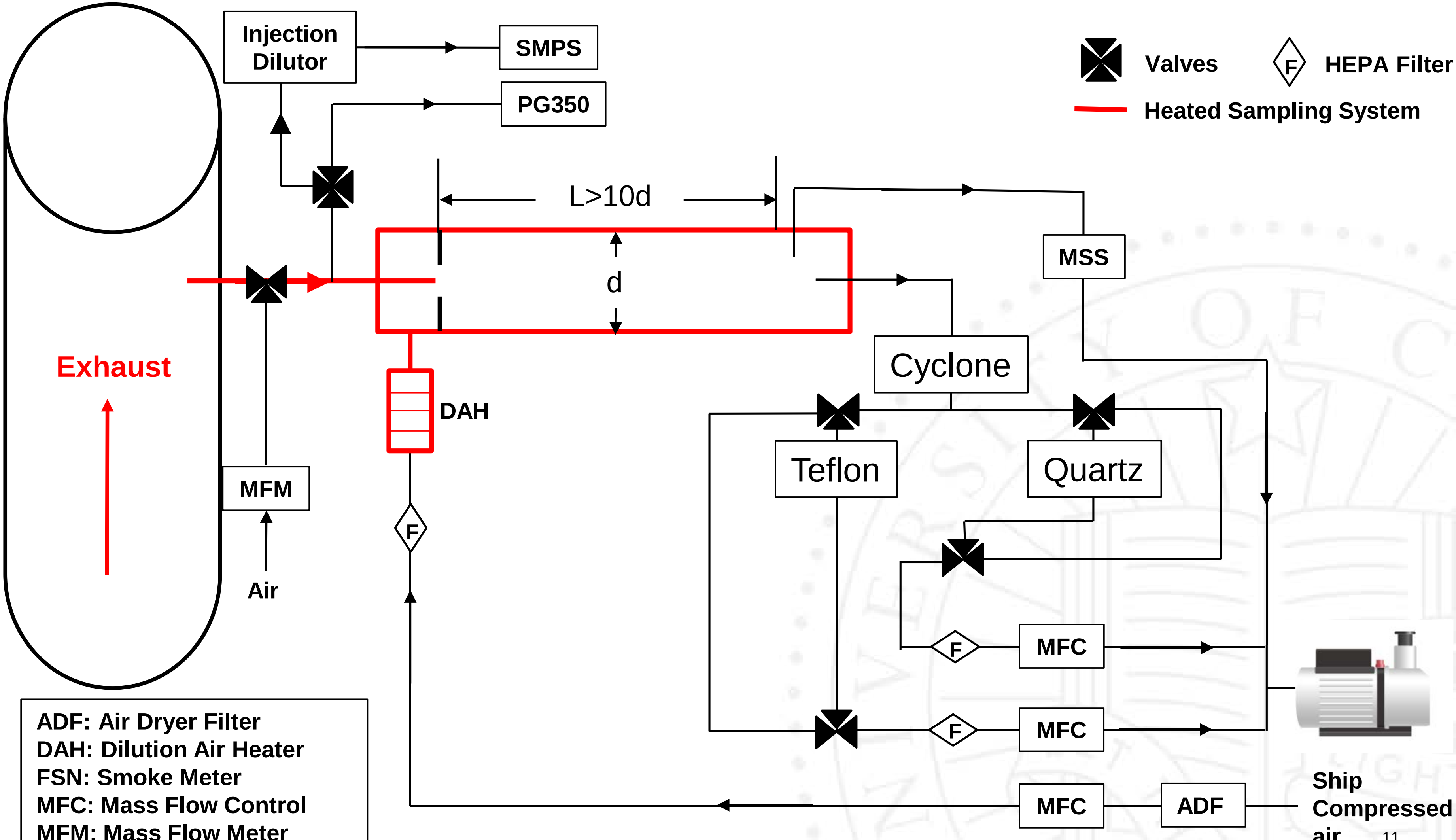
Particulate Emission Sampling System

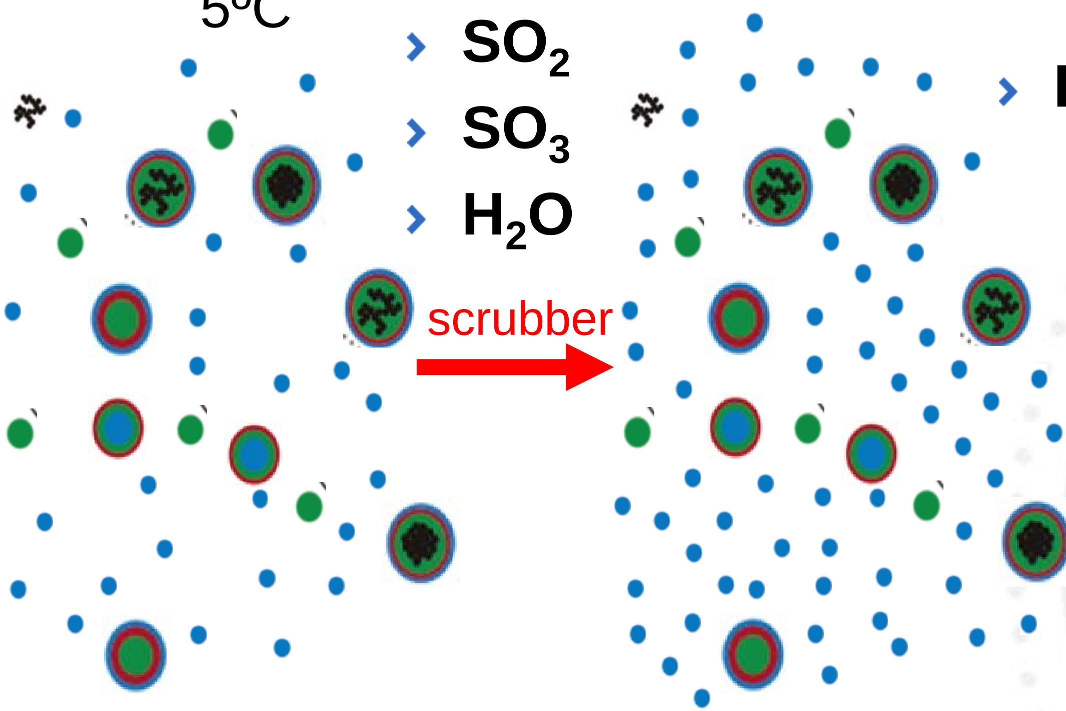


ADF: Air Dryer Filter
DAH: Dilution Air Heater
FSN: Smoke Meter
MFC: Mass Flow Control
MFM: Mass Flow Meter
MSS: Micro Soot Sensor
PG350: Horiba Gas Analyzer

Designed by: Kent Johnson

US and Europe Sampling Comparison-Scrubber

- US CFR and ISO
  - Dilution Ratio 6-20
  - Filter temperature 47ºC ± 5ºC
    - SO_2
    - SO_3
    - H_2O



- Europe ISO
  - Dilution Ratio above 20 (~50)
  - Above 250ºC tunnel isokinetic sampling
- H_2O

$$SO_3 + H_2O \xrightarrow{\text{cold sea water}} H_2SO_4 \xrightarrow{\text{nucleation}} \text{Hydrated Sulfate}$$

Hydrated Sulfate (H_2SO_4*6.65H_2O), Size:30 nm

Blue: Hydrated Sulfate
Green and Red: Organic Particles
Black: EC/BC

Fridell, E., & Salo, K. (2016). Measurements of abatement of particles and exhaust gases in a marine gas scrubber. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *230*(1), 154-162.
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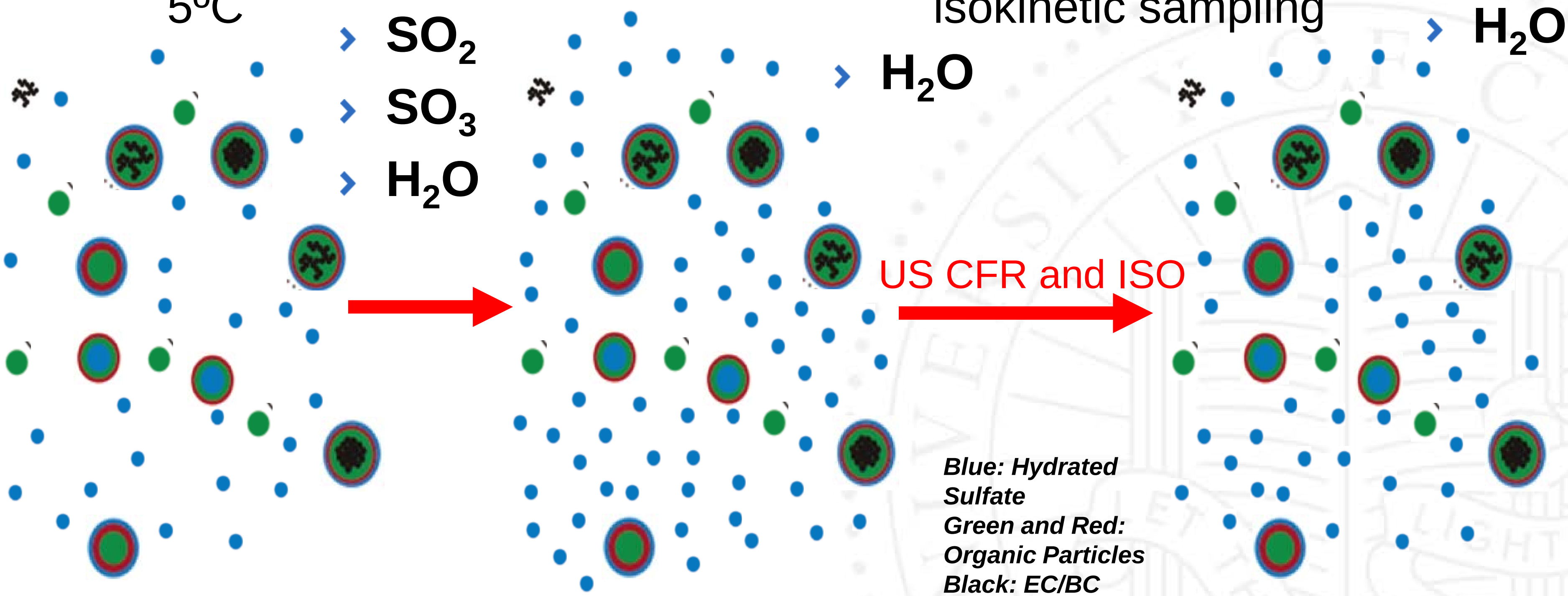

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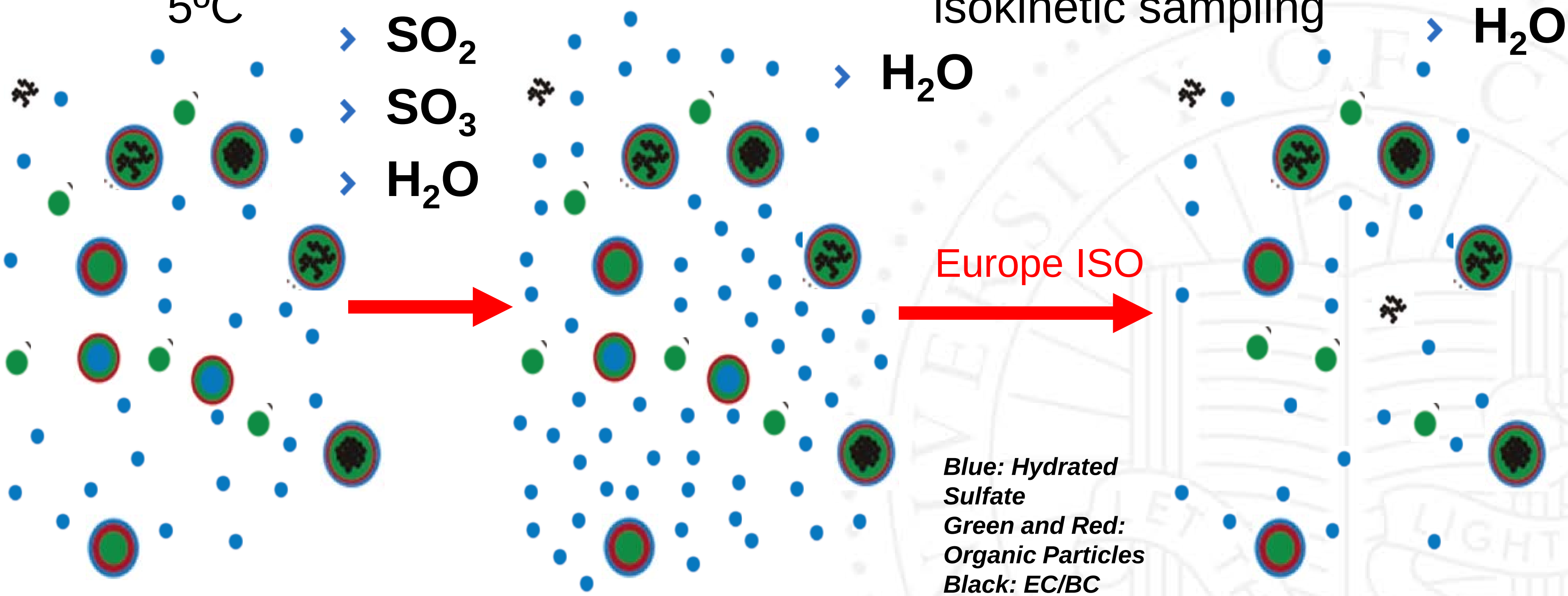

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Gas and Particulate Partitioning

$$SO_3 + H_2O \xleftarrow{\text{Heating and dilution}} H_2SO_4$$

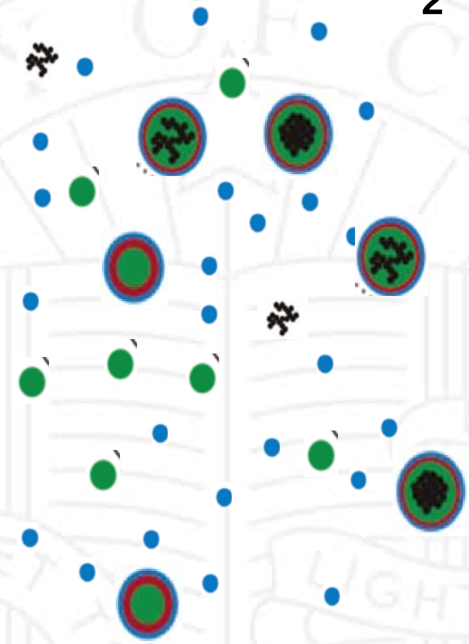
Heating and dilution

Size:30 nm

Hydrated Sulfate (H_2SO_4*6.65H_2O)

Europe ISO

- H_2O



Blue: Hydrated Sulfate
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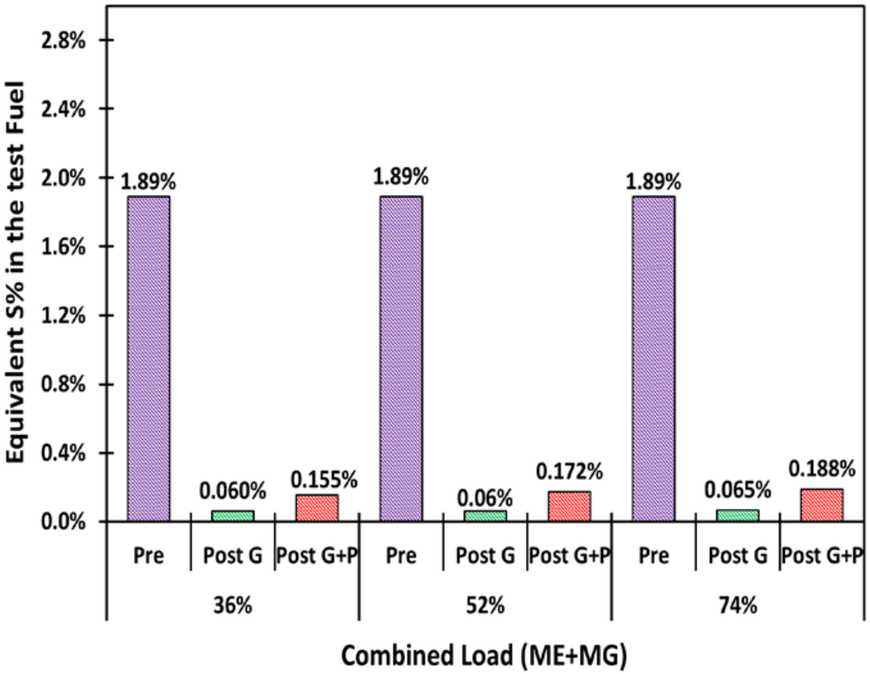
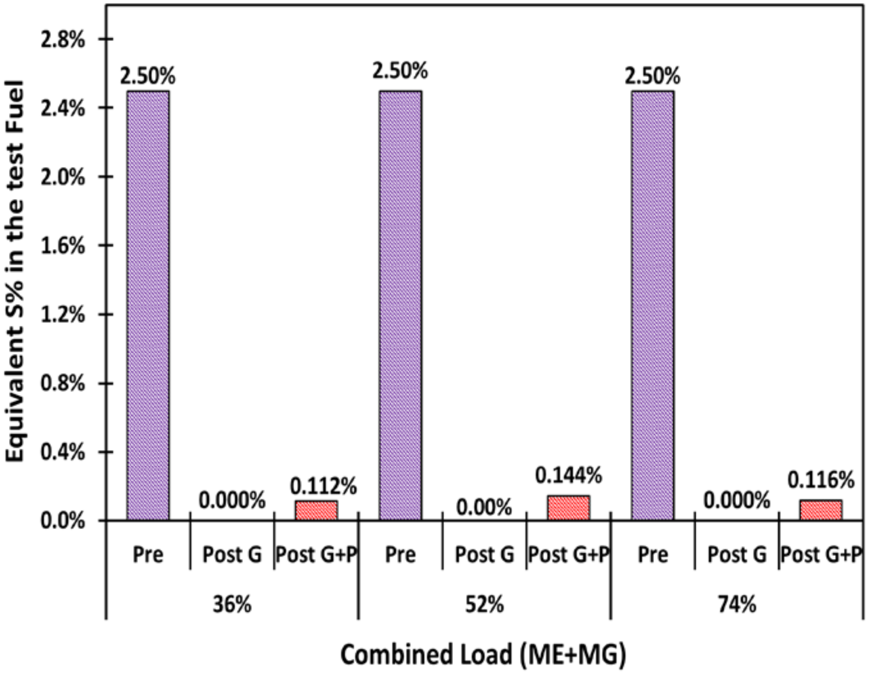
Equivalent Sulfur In the Fuel to 0.1% Sulfur Rule

Vessel 1



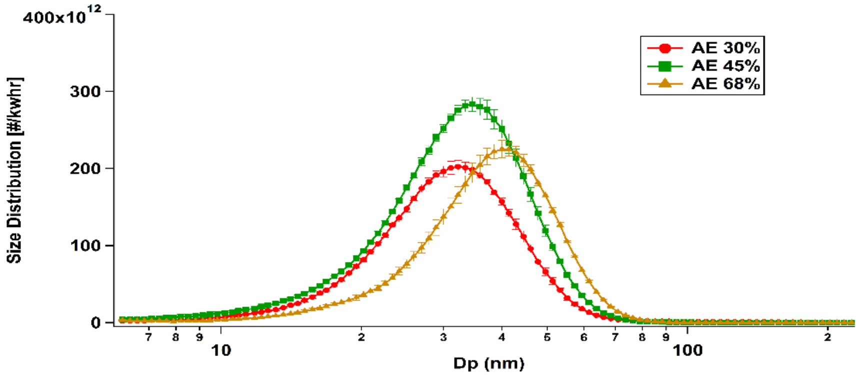
Vessel 3

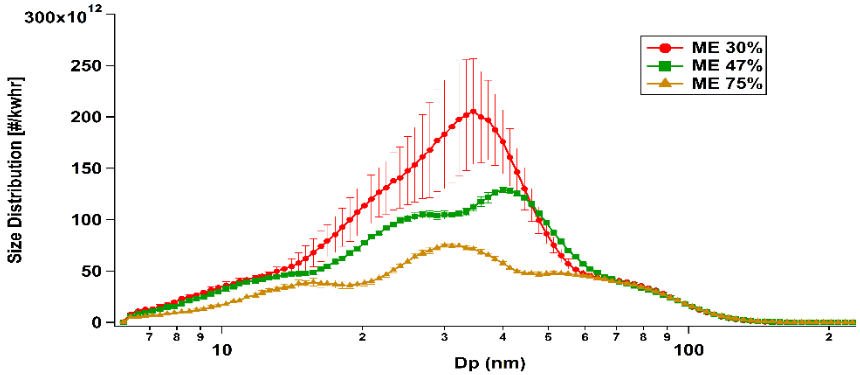


- ❑ Fuel sulfur rule is being met with scrubber system (on a regulated SO_2 basis).
- ❑ Overall sulfur reductions are potentially post challenge to fuel sulfur rule (gas and particulate).
- ❑ Outcome from this study will contribute to regulation development.

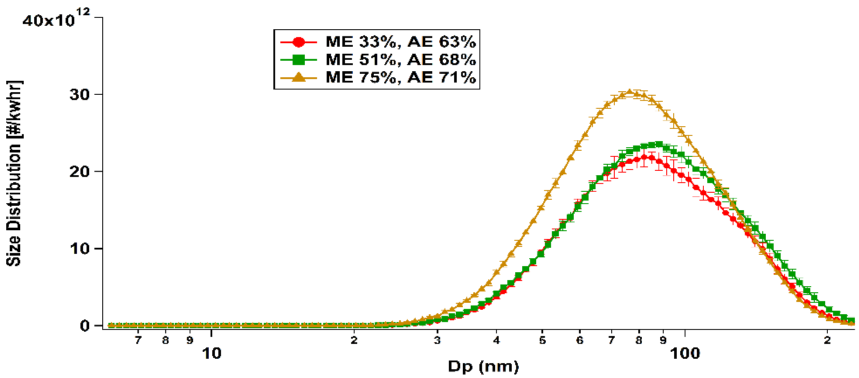
Particle Size Distribution for Vessel 3

Pre Scrubber





Post Scrubber



- ❑ Pre Scrubber particles peak size are around 30-40 nm.
- ❑ Post Scrubber particles peak size are around 80-90 nm.
- ❑ Issue: particle did not grow big enough to remove with cyclone design.
- ❑ Challenge: sulfate particles are so small in nature, very hard to grow big enough.

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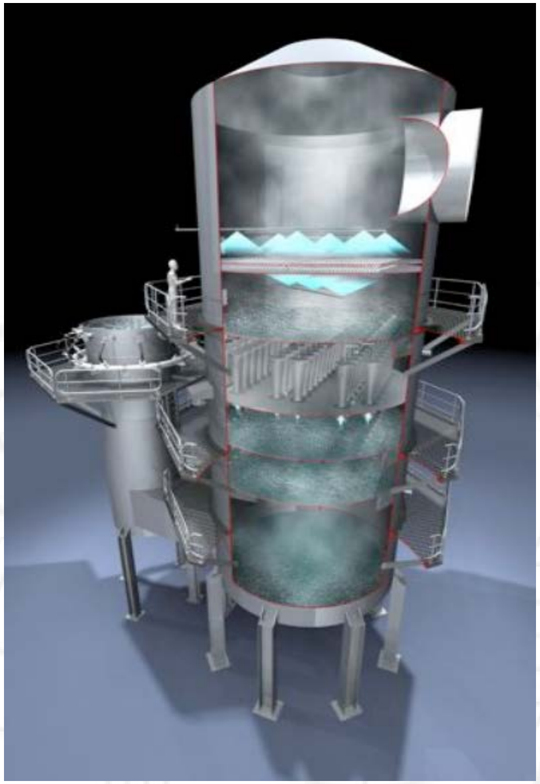
Novel Method on Removing the Sulfuric Acid Particles from ships



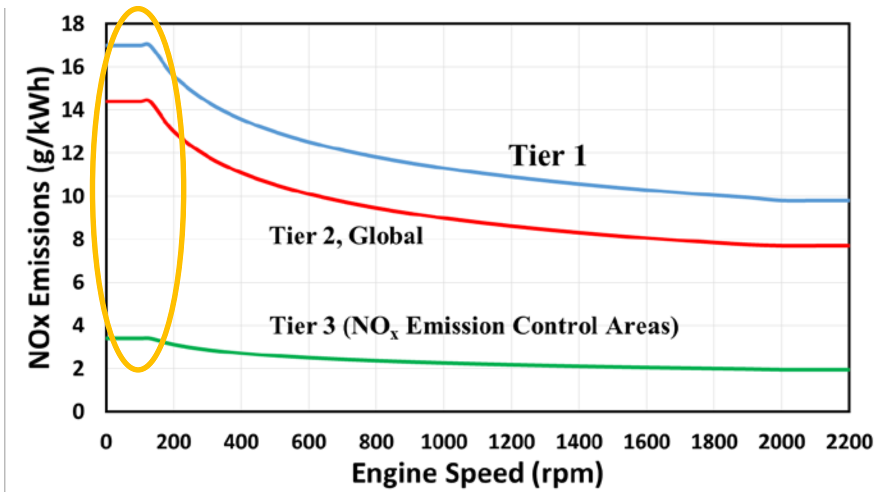
❑ Particle phase sulfur reduction were in the range of 47-68%, made it sufficient to meet IMO sulfur equivalent regulation. Also, 50% more BC reduction.
❑ Further improvement could be achieved by increasing exhaust residence time in scrubber.
❑ Demonstration on a ship by 2018.

IMO NOx Emissions Regulation

Table 1. MARPOL Annex VI NOx Emission Limits

Tier	Date	NOx Limit, g/kWh		
		$n < 130$	$130 \le n < 2000$	$n \ge 2000$
Tier I	2000	17	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

† In NOx Emission Control Areas (Tier II standards apply outside ECAs).



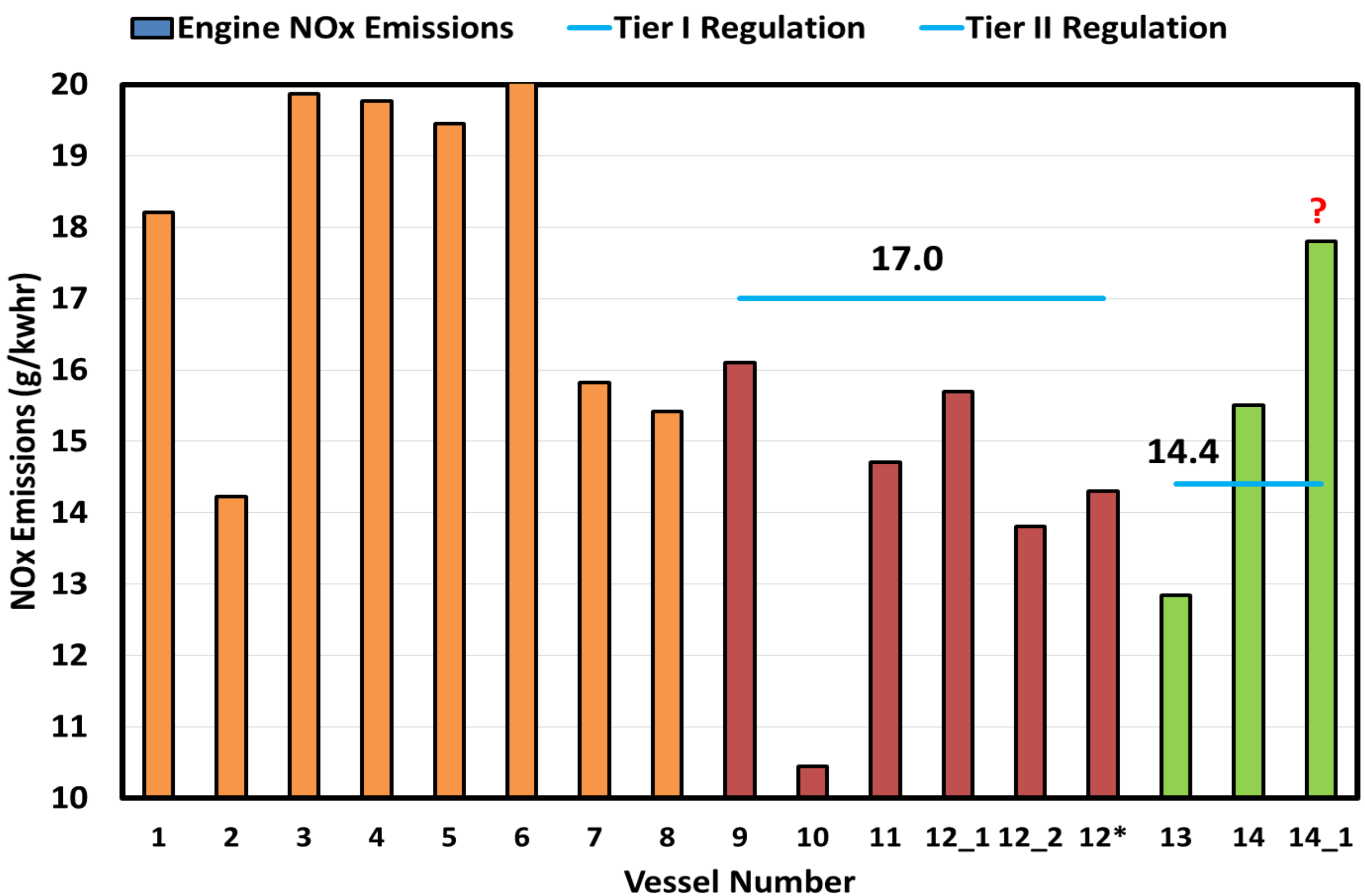
- It is more of a concern since the NOx emissions has been reduced significant by the application of SCR system for on road heavy duty diesel trucks and large off road equipment.

- Under the IMO low sulfur regulation and the upcoming NOx technical code, as well as the ‘saving fuel’ of the marine shipping, advanced engine technologies (electronic controlled fuel and lube oil injection, EGR, turbocharger cutoff operation) and advance aftertreatment technologies (scrubber, SCR, DPF) has been start commercializing. Little studies has been done on these area to understand the NOx performance of these advanced engine and aftertreatment technologies.

Vessel and Engine Details

	Vessel Type	IMO Category	ME Engine	Year Build	Model	Power Capacity (MW)	Test Fuel	Special Technology on ME	NOx (g/kwhr)	Sources
1	Container	Tier 0	Man B&W	1995	11K90MC-C	5.03	HFO (2.05% S)	None	18.21	CECERT: Harshit_2008_AE
2	Container_RoRo	Tier 0	Kincaid B&W	1985	6L90 GBE	20.20	HFO (1.97% S)	None	14.22	Moldanova_2009_AE
3	Crude Oil Tanker	Tier 0	Sulzer	NA	6RTA72	15.75	HFO (2.85% S)	None	19.87	CECERT: Harshit_2008_EST
4	Container	Tier 0	Hitachi Man B&W	1998	12K90MC	5.48	HFO (3.01% S)	None	19.77	CECERT: Harshit_2010_JGR
5	container	Tier 0	Sulzer	1997	9RTA84C	36.74	HFO (2.15-3.14% S)	None	19.45	CECERT: Khan_2013_JAWMA
6	Container	Tier 0	Samsung Man B&W	2000	12K90MC	55.66	HFO (0.95% S) and MGO (0.3% S)	None	20.25	CECERT_Yang
7	Container	Tier 0	Mitsui B&W	1987	7L70	16.58	HFO (1.88% S)	Scubber	15.82	CECERT_Yang
8	Container	Tier 0	NA	1985	NA	17.50	HFO (2.4% S)	NA	15.42	Fridell_2008_AE
9	Container	Tier 1	Hyundai B&W	2009	11K98ME7	68.53	HFO (2.51% S) and MGO (0.17% S)	None	16.1	CECERT: Khan_2012_EST
10	Crude Oil Tanker	Tier 1	Man B&W	2006	6L48/60	6.30	LSHFO and MGO (<0.1% S)	Variable Injection Timing (VVT)	10.45	CECERT: Gysel_2017_EST
11	RoRo	Tier 1	NA	2004	NA	20.07	HFO (2.2% S)	None	14.71	Fridell_2008_AE
12	RoRo	Tier 1	Man B&W	2006	9L60MC-C	21.06	HFO (2.3% S)	Scrubber	15.7-13.8	Fridell_2014_JEME
12*	RoRo	Tier 1	Man B&W	2006	9L60MC-C	21.06	HFO (2.2% S)	Scrubber	14.3	Danish EPA_2012
13	RoRo	Tier 2	Hyundai B&W	2014	8S60ME-C8	15.56	HFO (2.5% S)	Electronic Controlled Fuel and Oil Injection; Scrubber	13.1	CECERT_Yang
14	Container	Tier 2	Man B&W	2011	12K98ME6.1	69.68	MGO <(0.1% S)	Electronic Controlled Fuel and Oil Injection; Turbocharger cut off fuel economy operation	15.5 or 17.8	CECERT_Yang

Large Ocean Going Vessels (rpm<130) NOx Emissions Rate



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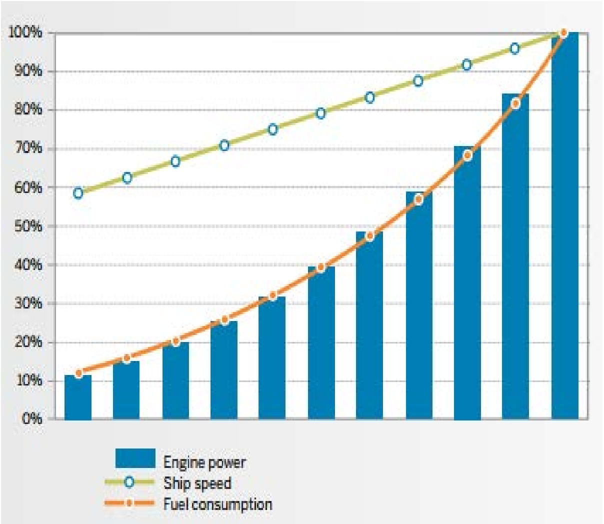
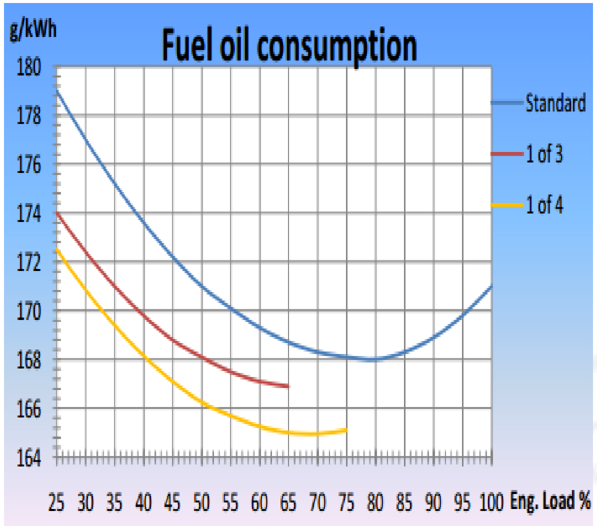
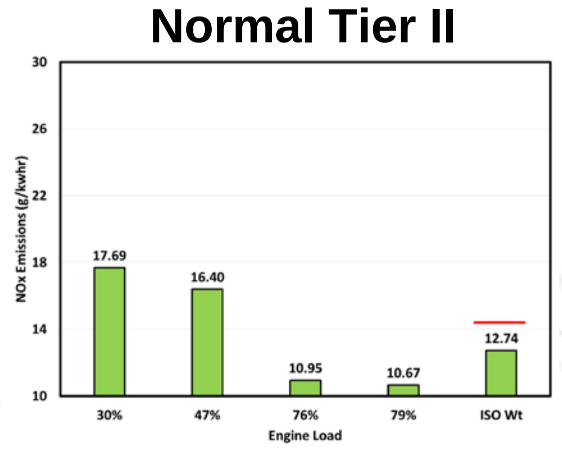
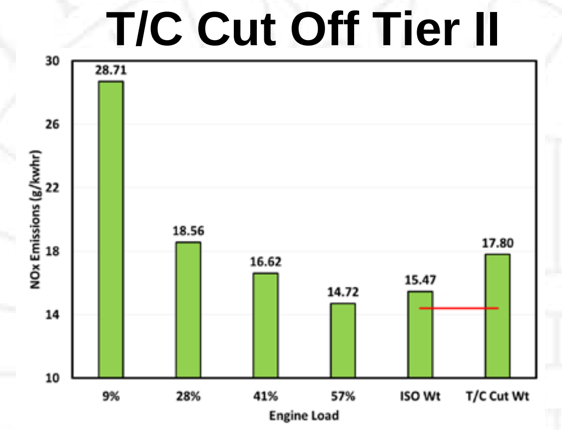
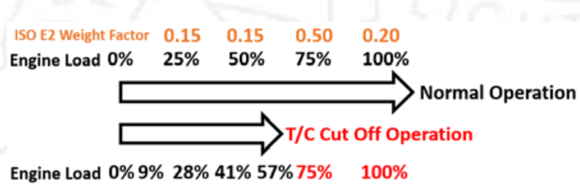
Slow Steaming and Turbocharger Cut Off











- **Slow Steaming:** The easiest way to reduce this cost is to reduce the ship’s speed.
- **Turbocharger (T/C) Cut Off Operation for Slow Steaming:** When the engine is operating at part load, one of the turbochargers is intentionally cut off to increase scavenging air pressure, compression air pressure, and maximum combustion pressure. This pressure increase boosts thermal efficiency.

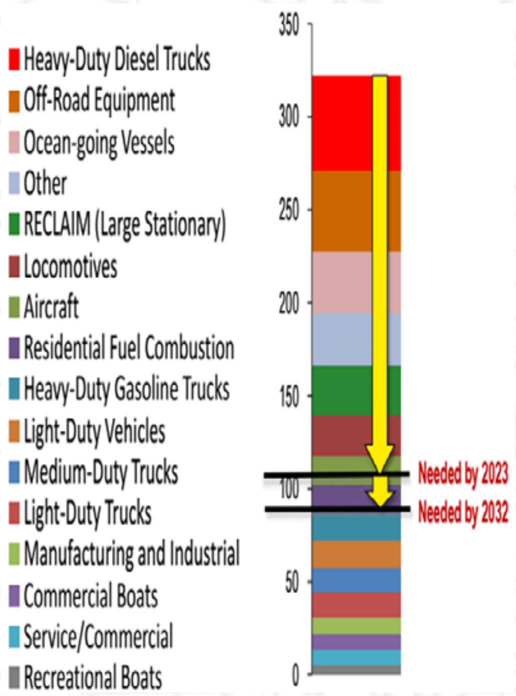
Summary and Conclusion

❑ Nucleation mode sulfuric acid particles were formed through combustion from high sulfur fuel and cooling effect, which is not able to be removed by conventional scrubber system.

❑ Some marine engine technology/operation may lead to higher NOx emissions to save fuel.

❑ Attention needed for new marine engine technologies.

❑ Marine Emission Inventory development needs more data input and a more standardized measurement protocol.



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NRC-Canada: Kevin Thomson, Stephanie Gagne

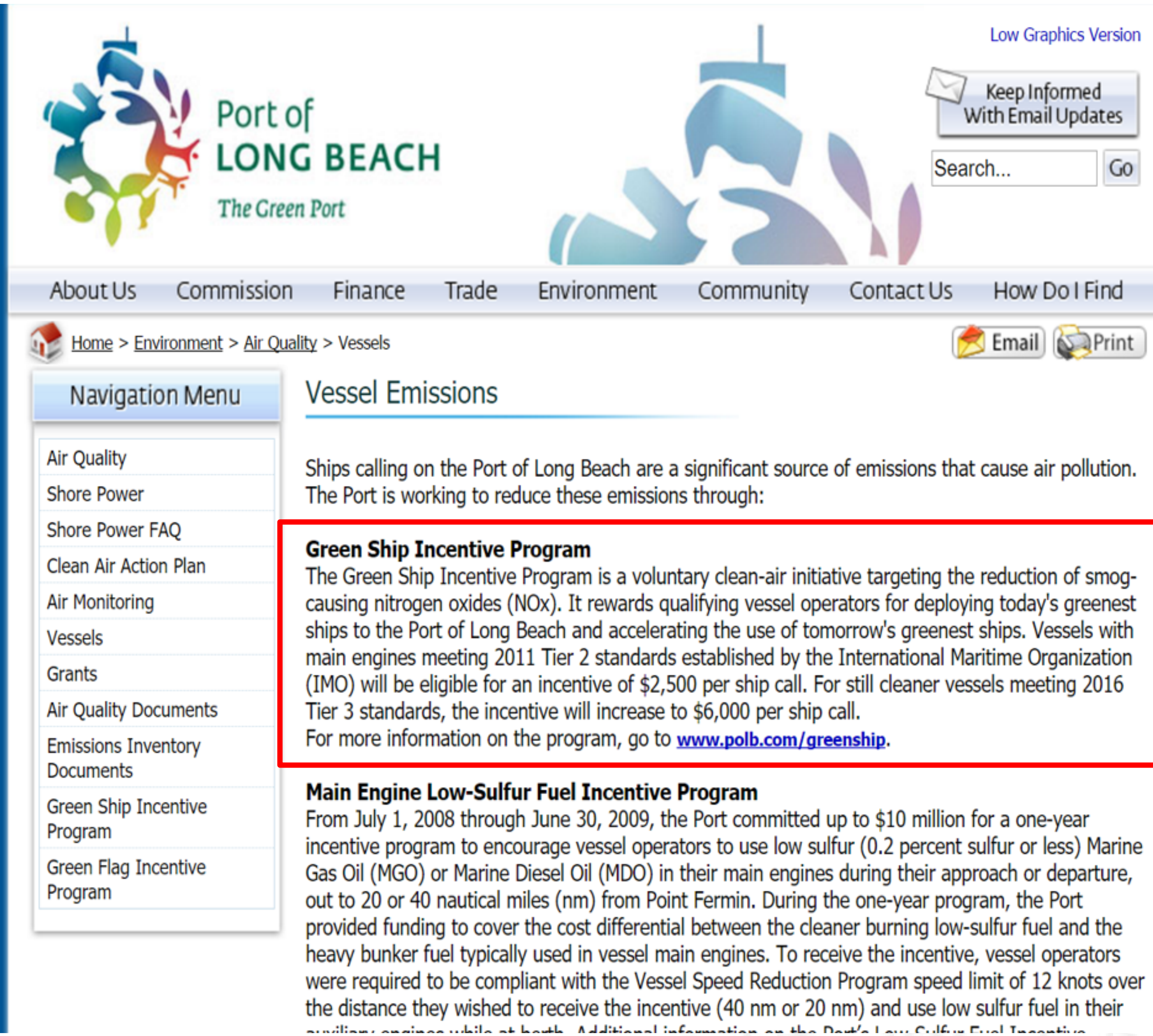
AVL: Monica Tutuianu

MAN B&W Diesel A/S, Copenhagen

Port of Los Angeles, Long Beach, Tacoma, Anchorage

Participate Shipping Lines!!

Emissions Studies are also Important to Port Policies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- Green Ship Incentive Program
- Green Flag Incentive Program

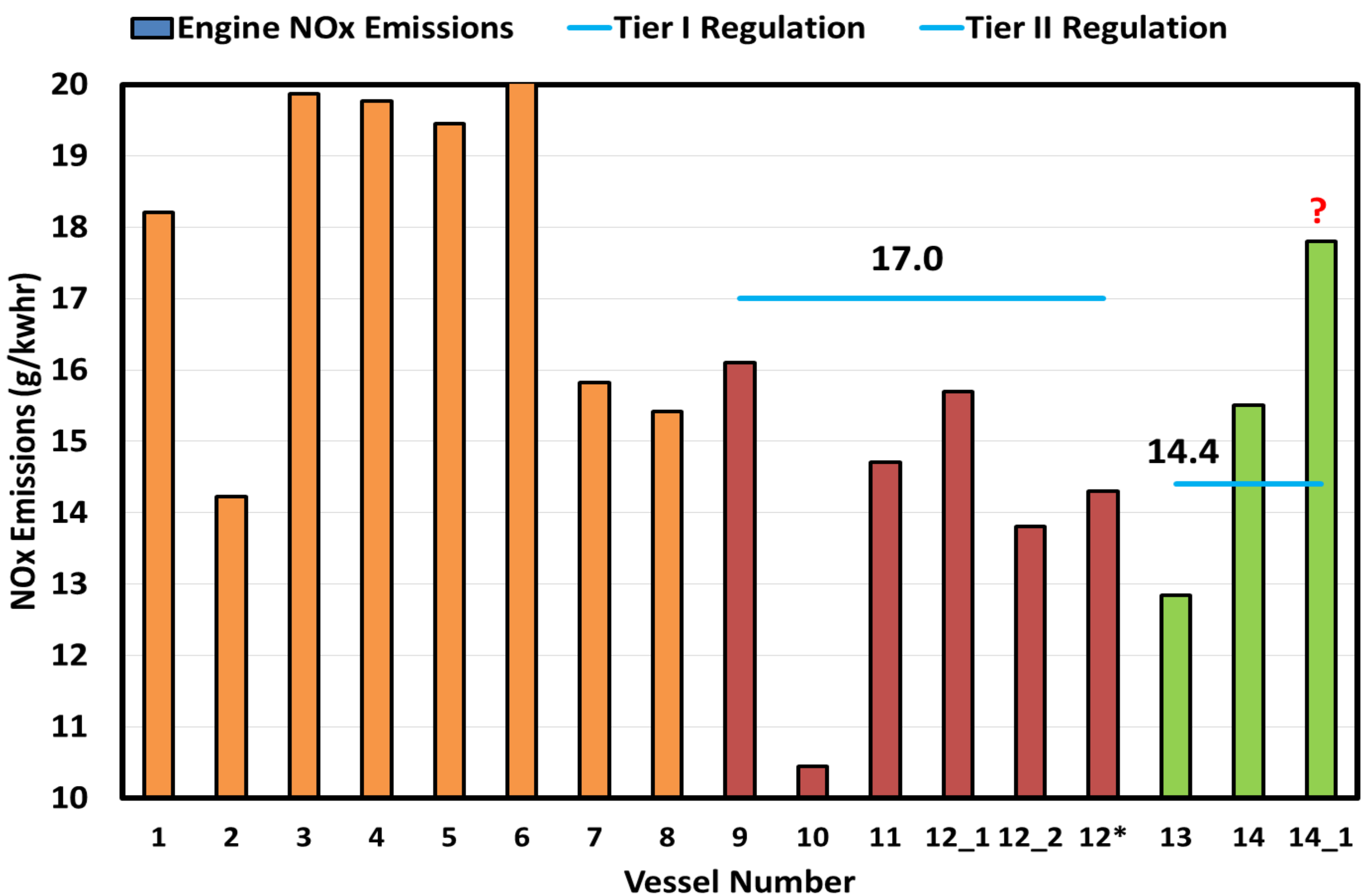
Vessel Emissions

Ships calling on the Port of Long Beach are a significant source of emissions that cause air pollution. The Port is working to reduce these emissions through:

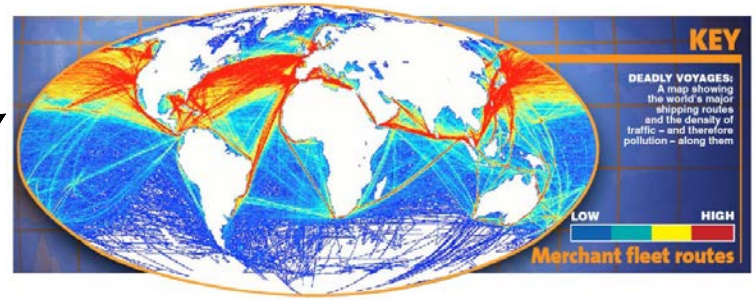
Green Ship Incentive Program
The Green Ship Incentive Program is a voluntary clean-air initiative targeting the reduction of smog-causing nitrogen oxides (NOx). It rewards qualifying vessel operators for deploying today's greenest ships to the Port of Long Beach and accelerating the use of tomorrow's greenest ships. Vessels with main engines meeting 2011 Tier 2 standards established by the International Maritime Organization (IMO) will be eligible for an incentive of $2,500 per ship call. For still cleaner vessels meeting 2016 Tier 3 standards, the incentive will increase to $6,000 per ship call.
For more information on the program, go to www.polb.com/greenship.

Main Engine Low-Sulfur Fuel Incentive Program
From July 1, 2008 through June 30, 2009, the Port committed up to $10 million for a one-year incentive program to encourage vessel operators to use low sulfur (0.2 percent sulfur or less) Marine Gas Oil (MGO) or Marine Diesel Oil (MDO) in their main engines during their approach or departure, out to 20 or 40 nautical miles (nm) from Point Fermin. During the one-year program, the Port provided funding to cover the cost differential between the cleaner burning low-sulfur fuel and the heavy bunker fuel typically used in vessel main engines. To receive the incentive, vessel operators were required to be compliant with the Vessel Speed Reduction Program speed limit of 12 knots over the distance they wished to receive the incentive (40 nm or 20 nm) and use low sulfur fuel in their

Large Ocean Going Vessels (rpm<130) NOx Emissions Rate



Strategies to Reduce Oxides of Nitrogen Emissions: Tier 3



MARPOL Annex VI

Decision

Avoid ECAs

Switch to LNG/Dual Engine

Advanced Exhaust Gas Recirculation (EGR)

Install Selective Catalytic Reduction (SCR)

- ❑ Since Tier 3 is targeting new vessels build after 2016, no Tier 3 vessels are available yet in large ships.

Effect of turbocharger cut out on two-stroke marine diesel engine performance and NOx emissions at part load operation

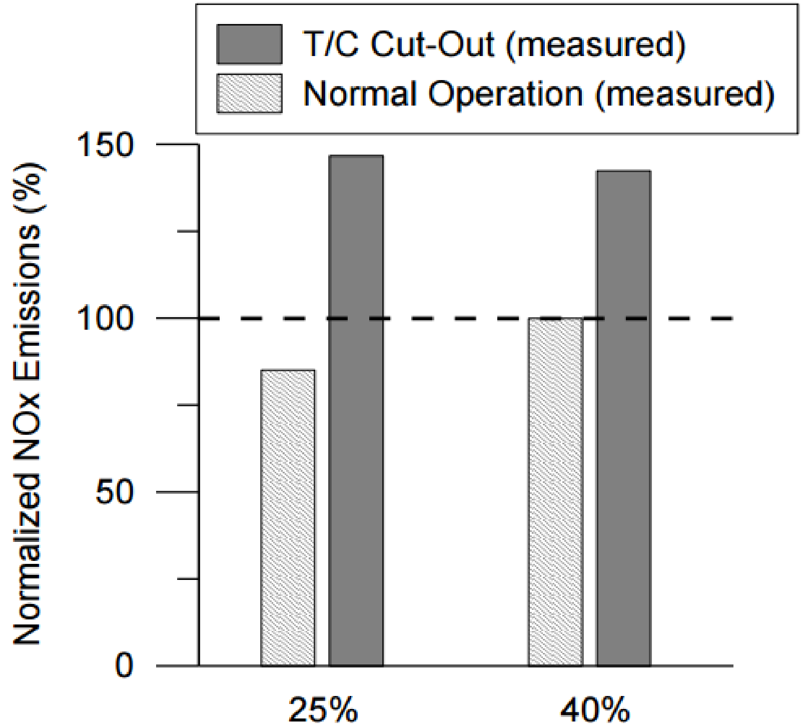


Figure 6: Measured normalized NOx emissions with and without T/C cut-out at low load operation.

Hountalas, D. T., Sakellaridis, N. F., Pariotis, E., Antonopoulos, A. K., Zissimatos, L., & Papadakis, N. (2014, July). Effect of turbocharger cut out on two-stroke marine diesel engine performance and NOx emissions at part load operation. In *ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis* (pp. V002T09A020-V002T09A020). American Society of Mechanical Engineers.