Marine Scrubber Efficiency and NOx Emission from Large Ocean Going Vessels

Presented By:
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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\(^3\).


\(^*\)Figure is obtained from [www.marinetraffic.com](http://www.marinetraffic.com).
IMO Sulfur Rule and Emissions Control Areas (ECAs)

- 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.

**Global Fuel Sulfur Limits**

<table>
<thead>
<tr>
<th>Before 1 July 2012</th>
<th>4.5% m/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 July 2012 – 1 January 2020</td>
<td>3.5% m/m</td>
</tr>
<tr>
<td>After 1 January 2020</td>
<td>0.5% m/m</td>
</tr>
</tbody>
</table>

**ECA Fuel Sulfur Limits**

<table>
<thead>
<tr>
<th>Before 1 July 2010</th>
<th>1.5% m/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 July 2010 – 1 January 2015</td>
<td>1.0% m/m</td>
</tr>
<tr>
<td>After 1 January 2015</td>
<td>0.1% m/m</td>
</tr>
</tbody>
</table>

*Figure is obtained from www.alfalaval.com.*
Strategies to Control Sulfur Emissions

- Decision
  - Switch to Low Sulfur Fuels
  - Avoid ECAs
  - Switch to LNG/Dual Engine
  - Install a Scrubber

Bunker Prices ($/metric tons)

<table>
<thead>
<tr>
<th></th>
<th>HFO</th>
<th>MGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Average</td>
<td>317.50</td>
<td>527.50</td>
</tr>
<tr>
<td>Americas Average</td>
<td>341.00</td>
<td>594.00</td>
</tr>
<tr>
<td>APAC Average</td>
<td>348.50</td>
<td>616.50</td>
</tr>
<tr>
<td>EMEA Average</td>
<td>347.00</td>
<td>537.00</td>
</tr>
</tbody>
</table>

*Information adopted from Ship&Bunker on August 16th, 2017

**Demand driving fuel price

*Figure is obtained from www.alfalaval.com.
Marine Scrubber System

- 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.

- Both open and close loop System
- Typical venturi and a cyclone separator
- Requires continuous monitoring SO₂, CO₂, PH, PAH, and turbidity

*Figure is obtained from www.alfalaval.com.*
# Vessels, Engines, Fuels

<table>
<thead>
<tr>
<th></th>
<th>Vessel 1</th>
<th>Vessel 2</th>
<th>Vessel 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year Build</strong></td>
<td>1987</td>
<td>2006</td>
<td>2015</td>
</tr>
<tr>
<td><strong>Vessel Type</strong></td>
<td>Container</td>
<td>Cruise</td>
<td>Ro-Ro</td>
</tr>
<tr>
<td><strong>IMO Category</strong></td>
<td>Tier 0</td>
<td>Tier 1</td>
<td>Tier 2</td>
</tr>
<tr>
<td><strong>ME Engine</strong></td>
<td>Mitsui Man B&amp;W</td>
<td>Wartsila</td>
<td>Hyundai Man B&amp;W</td>
</tr>
<tr>
<td><strong>ME Year Build</strong></td>
<td>1986</td>
<td>2005</td>
<td>2014</td>
</tr>
<tr>
<td><strong>ME Model</strong></td>
<td>7L70</td>
<td>4*12V46CR</td>
<td>8S60ME-C8.2</td>
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<tr>
<td><strong>ME Power Capacity (MW)</strong></td>
<td>16.6</td>
<td>4*12.6</td>
<td>15.6</td>
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<tr>
<td><strong>AE Engine</strong></td>
<td>Wartsila</td>
<td>Wartsila</td>
<td>Hyundai HiMSEN</td>
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<td><strong>AE Model</strong></td>
<td>2*6R32D</td>
<td>2*8L46CR</td>
<td>2<em>7H25/33 + 1</em>6H25/33</td>
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<tr>
<td><strong>AE Power Capacity (MW)</strong></td>
<td>2*2.1</td>
<td>2*8.4</td>
<td>2*1.9 + 1.7</td>
</tr>
<tr>
<td><strong>Go Through Scrubber</strong></td>
<td>ME+1*AE</td>
<td>2*ME</td>
<td>ME+3*AE</td>
</tr>
<tr>
<td><strong>Test Fuel</strong></td>
<td>HFO (1.9% S)</td>
<td>RMG 380 (2.8% S)</td>
<td>HFO (2.5% S)</td>
</tr>
<tr>
<td><strong>Scrubber</strong></td>
<td>Alfa-Laval</td>
<td>n/a</td>
<td>Wartsila</td>
</tr>
</tbody>
</table>
SO₂ Reduction

Vessel 1

- Scrubber shows a 96-100% of the SO₂ reduction
- SO₂(ppm)/CO₂(%) ratio < 4.3
- SO₂ emission reduction makes the fuel equivalent to 0.1% sulfur
- Fuel sulfur rule is being met with scrubber system (on a SO₂ basis)
Sulfate PM ($\text{H}_2\text{SO}_4 \cdot 6.65\text{H}_2\text{O}$) Reduction

- 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?

- 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?
US and Europe Sampling Comparison-Scrubber

- **US CFR and ISO**
  - Dilution Ratio 6-20
  - Filter temperature 47°C ± 5°C

- **Europe ISO**
  - Dilution Ratio above 20 (~50)
  - Above 250°C tunnel isokinetic sampling

![Diagram of particles and reactions](image)

**Reactions:****

\[
\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4
\]

Hydrated Sulfate

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

Hydrated Sulfate (\(\text{H}_2\text{SO}_4*6.65\text{H}_2\text{O}\)), Size:30 nm

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  - Isokinetic sampling


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Gas and Particulate Partitioning

\[ \text{SO}_3 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{SO}_4 \]

Size: 30 nm

Hydrated Sulfate
\( \text{(H}_2\text{SO}_4*6.65\text{H}_2\text{O}) \)

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


Fuel sulfur rule is being met with scrubber system (on a regulated SO₂ 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.


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

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.

<table>
<thead>
<tr>
<th>Tier</th>
<th>Date</th>
<th>NOx Limit, g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n &lt; 130</td>
</tr>
<tr>
<td>Tier I</td>
<td>2000</td>
<td>17</td>
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<td>Tier II</td>
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<td>14.4</td>
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<td>Tier III</td>
<td>2016†</td>
<td>3.4</td>
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</table>

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

Table 1. MARPOL Annex VI NOx Emission Limits
## Vessel and Engine Details

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<tr>
<th>Vessel Type</th>
<th>IMO Category</th>
<th>ME Engine</th>
<th>Year Build</th>
<th>Model</th>
<th>Power Capacity (MW)</th>
<th>Test Fuel</th>
<th>Special Technology on ME</th>
<th>NOx (g/kwhr)</th>
<th>Sources</th>
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<tbody>
<tr>
<td>Container</td>
<td>Tier 0</td>
<td>Man B&amp;W</td>
<td>1995</td>
<td>11K90MC-C</td>
<td>5.03</td>
<td>HFO (2.05% S)</td>
<td>None</td>
<td>18.21</td>
<td>CECERT: Harshit_2008_AE</td>
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<tr>
<td>Container_ RoRo</td>
<td>Tier 0</td>
<td>Kincaid B&amp;W</td>
<td>1985</td>
<td>6L90 GBE</td>
<td>20.20</td>
<td>HFO (1.97% S)</td>
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<td>14.22</td>
<td>Moldanova_2009_AE</td>
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<tr>
<td>Crude Oil Tanker</td>
<td>Tier 0</td>
<td>Sulzer</td>
<td>NA</td>
<td>6RTA72</td>
<td>15.75</td>
<td>HFO (2.85% S)</td>
<td>None</td>
<td>19.87</td>
<td>CECERT: Harshit_2008_EST</td>
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<td>Container</td>
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<td>Hitachi Man B&amp;W</td>
<td>1998</td>
<td>12K90MC</td>
<td>5.48</td>
<td>HFO (3.01% S)</td>
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<td>19.77</td>
<td>CECERT: Harshit_2010_JGR</td>
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<tr>
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<td>Tier 0</td>
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<td>9RTA84C</td>
<td>36.74</td>
<td>HFO (2.15-3.14% S)</td>
<td>None</td>
<td>19.45</td>
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<tr>
<td>Container</td>
<td>Tier 0</td>
<td>Samsung Man B&amp;W</td>
<td>2000</td>
<td>12K90MC</td>
<td>55.66</td>
<td>HFO (0.95% S) and MGO (0.3% S)</td>
<td>None</td>
<td>20.25</td>
<td>CECERT: Yang</td>
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<td>Mitsui B&amp;W</td>
<td>1987</td>
<td>7L70</td>
<td>16.58</td>
<td>HFO (1.88% S)</td>
<td>Scubber</td>
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<td>NA</td>
<td>1985</td>
<td>NA</td>
<td>17.50</td>
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<td>2009</td>
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<td>68.53</td>
<td>HFO (2.51% S) and MGO (0.17% S)</td>
<td>None</td>
<td>16.1</td>
<td>CECERT: Khan_2012_EST</td>
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<td>Crude Oil Tanker</td>
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<td>Man B&amp;W</td>
<td>2006</td>
<td>6L48/60</td>
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<td>LSHFO and MGO (&lt;0.1% S)</td>
<td>Variable Injection Timing (VVT)</td>
<td>10.45</td>
<td>CECERT: Gysel_2017_EST</td>
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<td>RoRo</td>
<td>Tier 1</td>
<td>NA</td>
<td>2004</td>
<td>NA</td>
<td>20.07</td>
<td>HFO (2.2% S)</td>
<td>None</td>
<td>14.71</td>
<td>Fridell_2008_AE</td>
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<td>21.06</td>
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<td>Scrubber</td>
<td>15.7-13.8</td>
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<td>2014</td>
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<td>HFO (2.5% S)</td>
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<td>12K98ME6.1</td>
<td>69.68</td>
<td>MGO &lt;(0.1% S)</td>
<td>Electronic Controlled Fuel and Oil Injection; Turbocharger cut off fuel economy operation</td>
<td>15.5 or 17.8</td>
<td>CECERT: Yang</td>
</tr>
</tbody>
</table>
Large Ocean Going Vessels (rpm<130)
NOx Emissions Rate

- Engine NOx Emissions
- Tier I Regulation
- Tier II Regulation

Vessel Number:
1  2  3  4  5  6  7  8  9  10  11  12_1  12_2  12*  13  14  14_1

NOx Emissions (g/kwhr):
10  11  12  13  14  15  16  17  18  19  20

- Vessel 6: 21
- Vessel 12*: 14.4
- Vessel 14_1: ?
## Vessel and Engine Details

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<tr>
<th>Vessel Type</th>
<th>IMO Category</th>
<th>ME Engine</th>
<th>Year Build</th>
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<td>CECERT_Yang</td>
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*Note: The data includes various vessel types and engine models with specific details such as year build, model, power capacity, test fuel, and special technologies. The NOx emissions vary, with values ranging from 14.22 g/kwhr to 20.25 g/kwhr. The sources for this data include various research papers and reports referenced within the table.*
**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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Participate Shipping Lines!!
Emissions Studies are also Important to Port Policies

**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](http://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 auxiliary engines while at berth. Additional information on the Port's Low-Sulfur Fuel Incentive Program can be found at [www.polb.com/greenship](http://www.polb.com/greenship).
Large Ocean Going Vessels (rpm<130) NOx Emissions Rate

- Engine NOx Emissions
- Tier I Regulation
- Tier II Regulation

NOx Emissions (g/kwhr) vs Vessel Number

Vessel Numbers 1, 2, 3, 4, 5, 6, 8, 10, 11, 12_1, 12_2, 12*, 13, 14, 14_1

- Vessel 1: 18 g/kwhr
- Vessel 3: 20 g/kwhr
- Vessel 4: 19 g/kwhr
- Vessel 5: 18 g/kwhr
- Vessel 6: 20 g/kwhr
- Vessel 7: 16 g/kwhr
- Vessel 8: 15 g/kwhr
- Vessel 9: 14 g/kwhr
- Vessel 10: 13 g/kwhr
- Vessel 11: 14 g/kwhr
- Vessel 12_1: 17.0 g/kwhr
- Vessel 12_2: 14.4 g/kwhr
- Vessel 12*: 14.4 g/kwhr
- Vessel 14: 14.4 g/kwhr
- Vessel 14_: 14.4 g/kwhr

Note: Vessel 12* has an unknown NOx emissions rate.
Strategies to Reduce Oxides of Nitrogen Emissions: Tier 3

- Install Selective Catalytic Reduction (SCR)
- Switch to LNG/Dual Engine
- Avoid ECAs
- MARPOL Annex VI
- Advanced Exhaust Gas Recirculation (EGR)

- 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.