# Evaluation of a Modern Tier 2 Ocean-going Vessel Equipped with a Scrubber

**Final Report**

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CARB

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## Disclaimer



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# Acronyms and Abbreviations

σ…………………… ....................standard deviation
BC ....................................................black carbon
CARB................................................California Air Resources Board
CE-CERT ..........................................College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR ..................................................Code of Federal Regulations
CEMS................................................continuous emissions measurement system
cm/s ..................................................centimeters per second
CO ....................................................carbon monoxide
COV .................................................coefficient of variation
$CO_2$...................................................carbon dioxide
CPC ..................................................condensation particle counter
DMA .................................................differential mobility analyzer
DF ....................................................dilution factor
DG....................................................diesel generator
eBC ..................................................equivalent black carbon
EC ....................................................elemental carbon as defined by NIOSH methods
ECA..................................................emissions control area
EGCS ................................................exhaust gas control system
EFM ..................................................exhaust flow meter
EPA ...................................................United States Environmental Protection Agency
ETV...................................................Environmental Testing Verification
IMO...................................................international maritime organization
IPSD..................................................integrated particle size distribution
HCLD................................................heated chemiluminescent detector
HFO...................................................heavy fuel oil
IMPROVE.........................................Interagency Monitoring of Protected Visual Environment
ISO ....................................................International Organization for Standardization
kPa.....................................................kilo Pascal
LNG ..................................................liquid natural gas
lpm ....................................................liters per minute
MCR..................................................maximum continuous rating
MDL..................................................minimum detection limit
ME.....................................................main engine
MFC ..................................................mass flow controller
MGO .................................................marine gas oil
ms ......................................................milliseconds
MSS...................................................Micro Soot Sensor
NCR ..................................................nominal continuous rating
NIOSH ..............................................National Institutes of Safety and Health method
NIST..................................................National Institute for Standards and Technology
NDIR.................................................nondispersive infrared analyzer
$NO_x$ ..................................................nitrogen oxides

OC ....................................................organic carbon
o.d.....................................................outer diameter
OEM.................................................original equipment manufacturer
sampling
OGV..................................................ocean going vessel
PM.....................................................particulate matter
$PM_{2.5}$ ................................................fine particles less than 2.5 µm (50% cut diameter)
PN .....................................................particle number
PSD ...................................................particle size distribution
PTFE .................................................polytetrafluoroethylene
QC.....................................................quality control
RPM..................................................revolutions per minute
S ........................................................sulfur
scfm..................................................standard cubic feet per minute
SMPS ................................................scanning mobility particle sizer
$SO_2$ ...................................................sulfur dioxide
$SO_x$ ...................................................sulfur oxide
SSD ...................................................slow speed diesel
UCR ..................................................University of California at Riverside
ULSFO..............................................ultra-low sulfur fuel oil
USACE .............................................U.S. Army Corp of Engineers

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# Executive Summary

***Introduction***: Emissions from marine engines (container vessels, crude tankers, bulk cargo, auto carrier, cruise ships, and other ocean-going vessels) represent a significant contribution of particulate matter (PM), sulfur oxide ($SO_x$) and nitrogen oxide ($NO_x$) emissions where marine engines represents 15% of global anthropogenic $NO_x$ and 5-8% of the global $SO_x$ emissions (Viana M. et al 2014, Eyring V. et al 2005). To control $SO_x$ emissions from marine engines, Annex VI regulations include caps on the sulfur content of fuel oil which indirectly also reduces PM emissions. However, the International Maritime Organization (IMO) does not have any explicit PM emission limits. Providing the vessel meets the applicable sulfur limit (0.1% within the emissions control area (ECA) and 0.05% outside the ECA), HFO is allowed if alternative technology is used to limit $SO_x$ emissions to a fuel equivalent 0.1% sulfur (S). Scrubbers, or other exhaust gas cleaning systems, are alternatives to using 0.1% S fuel. Scrubber technology is designed to reduce $SO_x$ emissions and has the potential to reduce $PM_{2.5}$ emissions. It is of interest to the California Air Resources Board (CARB) to quantify the in-use emissions control effectiveness on emissions from scrubber technology.

**Scrubber:** The scrubber evaluated was a Wärtsilä hybrid wet scrubber system designed to operate in both open loop mode (using seawater to remove $SO_x$ from the exhaust gas), and in closed loop mode (reagent is used in combination with sea water to remove $SO_x$ from the exhaust gas). The scrubber was operated in open loop mode for this testing where in previous scrubber evaluations it has been demonstrated closed loop and open loop emission reductions are similar (Johnson et al 2016).

***Methods***: The test loads utilized were based on ISO-8178 E3 and D2 protocols for the main engine (ME) and diesel generators (DG), respectively. Emissions were measured for gaseous, $PM_{2.5}$ (total mass, elemental, organic carbon, and sulfated species, but not metals), and particle size distribution (PSD), following ISO and Code of Federal Regulations (CFR). In addition, upgrades were performed to meet 40 CFR Part 1065 dilution ratios and filter temperatures on an exhaust that was cooled with sea water.

**Objectives:** The primary aim of this work is to study the in-use emissions from a modern Tier 2 OGV equipped with a scrubber while operating on 2.5% sulfur Heavy Fuel Oil (HFO).

***Results***: Emissions measurements were made before and after the scrubber at load points of 33%, 50%, and 75% for the ME and 50% for the DG. The analysis presented is based on the combined exhaust of the ME and DG through the scrubber system. The measured combined weighted emission reductions across the scrubber were 97% for sulfur dioxide ($SO_2$) and 6% for the organic carbon (OC) PM species where the rest of the PM increased across the scrubber ($PM_{2.5}$ 4%, EC 12% and 5% for Sulfate, see Table ES-1). $PM_{2.5}$ emissions pre- and post-scrubber ranged from about 1.0 to 1.3 g/kWhr where there was not an observed PM reduction resulting from the scrubber. Other studies show switching from HFO to a low sulfur marine gas oil (MGO) can have a 75% reduction in $PM_{2.5}$ emissions (Kahn et al 2012). This suggests scrubbers may not be effective in reduceing total PM even though they meet the requirements of IMO.

**Table ES-1 Percent change from baseline (positive implies increased)**

| Pollutants [1] | $PM_{2.5}$ | PM TC | PM EC | PM eBC | PM OC | PM Sulfate | $SO_2$ | $NO_x$ | $CO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Reduction | 4.2% | 8.6% | 12% | 5.0% | -6.1% | 5.0% | -97% | 4.6% | 1.6% |

*[1] PM2.5 is the PM gravimetric mass measurement (<2.5 µm), PM TC is the total speciated PM mass (EC+OC + S PM fractions, it does not include metals). EC and OC are the thermal optical IMPROVE measurement, eBC is the photoacoustic BC measurement. Sulfur PM is from the ion-chromatography method.*

The gas-phase $SO_x$ emissions were equivalent to a fuel sulfur percent estimated at 0.08% at high load and 0.1% at low load, all of which are at or below the 0.1% ECA $SO_x$ requirement, see Figure ES-1. When particle bound sulfur is added to the sulfur balance (gas + particles), the fuel sulfur percent is estimated at 0.15% to 0.18% from high to low load, which are above 0.1% $SO_x$, see Figure ES-1. The scrubber system meets the requirements of the ECA fuel sulfur rule, but scrubbers operating on HFO may have higher sulfur (gas + particles) emissions than vessels operating with 0.1% sulfur fuel. Research at UCR has shown that low sulfur HFO fuels (<0.1% sulfur) can show a reduction in total PM, mostly from sulfur, but with a slight increase in EC and OC PM emissions compared to high sulfur HFO fuels (Johnson et al, 2016).

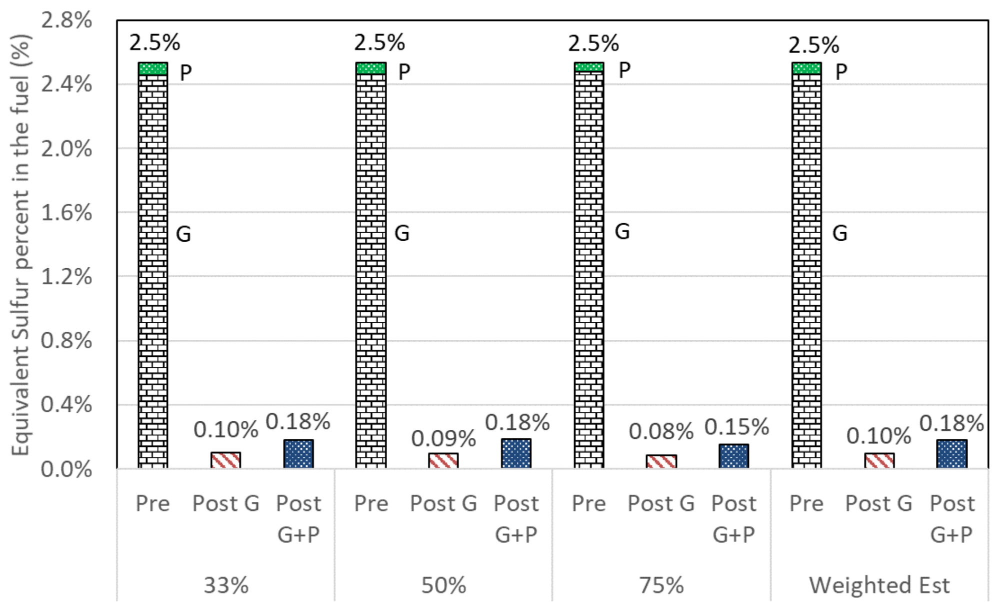


**Figure ES-1 Estimated fuel sulfur balance [1]**

[1] P denotes particle bound sulfur, G denotes gaseous sulfur, and Pre denotes pre-scrubber and Post denotes post-scrubber. G+P denotes gaseous plus particle bound sulfur.

***Summary***: The scrubber system was performing as designed and was meeting the fuel sulfur rule of 0.1% with the North American ECA. The particle plus gas fuel sulfur species, however, are higher than 0.1% fuel sulfur. Components of the total PM mass increased (Sulfate, eBC, and EC) after the scrubber where the increase in Sulfate species may be a result of a gas-to-particle conversion in the exhaust. Although the HFO + scrubber system is meeting the IMO fuel sulfur rule, they are showing higher $PM_{2.5}$ emissions compared to low sulfur MGO fuels (Kahn et al 2012). Additional low sulfur fuels and HFO scrubber data is needed to confirm these results and observations.

# 1 Background

## 1.1 Marine emissions

Global shipping represents over 80% of the volume and 70% of the value of goods (UNCTAD, 2015 and 2017). Marine engines major exhaust emissions are carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), particulate matter with an aerodynamic diameter less than 2.5 µm ($PM_{2.5}$), and sulfur oxides ($SO_x$) (Smith et al 2014, Dalsøren et al 2009, Endresen et al 2007, and Endresen et al 2005). International ship $CO_2$ emissions represent 2.2% of the global anthropogenic $CO_2$ emissions and are 2.4% of the total global house gas (GHG) emissions (Smith et al 2014). $NO_x$ emissions cause photochemical smog and marine engines represents 15% of global anthropogenic $NO_x$ emissions. Ships typically burn residual high sulfur heavy fuel oil (HFO) containing polycyclic aromatic hydrocarbons and transition metals, and thus emissions of PM are of particular concern. International shipping PM has been linked with increased mortality in coastal regions, with an estimated 60,000 deaths from cardiopulmonary and lung cancer per annum (Corbett et al., 2007) and more recently these estimates have increased up to 250,000 deaths (Sofiev et al 2018). $PM_{2.5}$ is composed of sulfate particles, organic carbon (OC), elemental carbon (EC), and trace metals. The PM composition varies widely with the fuel sulfur, fuel quality, engine type (two vs four stroke), engine load, engine age, and engine size. Large slow speed diesel (SSD) engines operating on high sulfur fuels emit mostly hydrated sulfate particles and for low sulfur fuels SSD engines emit mostly EC and OC PM fractions where the split depends on the fuel quality (Johnson et al 2015).

To control sulfur oxide ($SO_x$) emissions from marine engines, the International Maritime Organization (IMO) Annex VI regulations include caps on the sulfur content of fuel oil in emission control areas (ECA) and globally, see Figure 1-1 and Figure 1-2. The regulation requires vessels entering into designated ECAs to be operating on fuels with an equivalent sulfur content of 0.1% starting in 2016 and outside the ECA with an equivalent sulfur of 0.5% in 2020 (MARPOL 2017). The North American (NA) ECA represents a boarder of approximately 200 nautical miles from the coast line of NA. The ECA sulfur regulation indirectly reduces PM emissions where IMO does not have any explicit PM emission limits. Providing the vessel meets the applicable sulfur limit, HFO is allowed even with the fuel sulfur rule if alternative technology is used to limit $SO_x$ emissions to a fuel equivalent 0.1% sulfur. Scrubbers, or other exhaust gas cleaning systems, are alternatives to using 0.1% sulfur (S) fuel. Recently, ultra-low sulfur fuel oils (ULSFO) have become available that meet the 0.1% sulfur limit, but their total PM and composition are not well understood.

Sulfur emissions have a relatively short atmospheric lifetime, 1.0-2.5 days for gaseous $SO_2$ and 4-6 days for particle sulfate (Berglen et al., 2004 and Endresen et al. 2007). This implies that the highest and strongest deposition of sulfur is found close to the sources. Emissions of $SO_x$ are a major contributor to acid deposition, which have harmful effects to the natural environment as well as building structures. Unlike land based mobile sources, marine shipping can burn low cost high sulfur fuels which has been reported to cause high $SO_x$ and $PM_{2.5}$ emissions (Fridell and Salo, 2014; Winnes and Fridell, 2009). For comparison, a switch from high sulfur HFO to a low sulfur marine gas oil (MGO) resulted in a 75% $PM_{2.5}$ and 98% $SO_x$ mass reduction where most of the $PM_{2.5}$ reduction was sulfur bound species (Winners et al 2009 and Kahn et al 2012). Thus, reducing the sulfur in the fuel can greatly reduce the $SO_x$ and $PM_{2.5}$ emissions, but at a higher cost for the fuel. As such, many shipping companies are considering PM scrubbers and low sulfur residual fuels to meet the ECA requirements, but it is not clear what impact this has on the $PM_{2.5}$ emissions. Scrubber technology is designed to reduce $SO_x$ emissions and has the potential to reduce $PM_{2.5}$ emissions where it is of interest to the California Air Resources Board (CARB) to quantify the in-use emissions from scrubber technology on modern ocean-going vessels (OGVs).

Recently black carbon (BC) emissions from ships have drawn attention due to its strong global warming effect (Corbett et al., 2007; Cappa et al., 2012, Comer et al 2017). BC is the second largest contributor to anthropogenic climate change and is a major concern for the rapid decline in the Arctic sea ice (Cappa et al., 2012). Marine SSD engines account for a significant and growing share of the BC emissions for transportation (Comer et al 2017). BC is similar to elemental carbon, where BC is defined based on its aerosol absorption qualities and elemental carbon is defined based on its thermal optical properties (Bond et al 2013). In general, BC is a defined measurement method to help understand its impact on climate change (Bond et al 2013). Some suggest BC emissions increase with higher sulfur fuels (Comer et al 2017) and other have shown that BC is not directly tied to the sulfur fuel but is more directly tied to fuel combustion (Johnson et al 2016). As such, it is important to understand the PM and BC emissions from modern SSD engines operating on different fuels and fuel sulfur levels.

A vehicle carrier (Ro-Ro) was selected for this study since they represent a larger consumer of fuel, frequently visit US ports, and represent a large fraction of the fleet. Figure 1-3 shows a distribution of vessels tracked by the U.S. Army Corp of Engineers (USACE) operating in the global network (ERG 2015). This data in the figure represents USACE entrances and clearances for (mainly) foreign flagged ships that call on U.S. ports. The distribution should also be representative of the global fleet make-up. The figure suggests bulk carriers, tankers, container ships and crude vessels are most representative vessels where they also represent the largest fuel consumers of the total fleet inventory. The top five categories of marine vessels utilize large two stroke SSD engines which show the value and importance of SSD's for their impact on Marine emissions.


**Figure 1-1 Existing and proposed future emission control areas** (source IFPEN)
[1] IFP Energies Nouvelles (IFPEN)

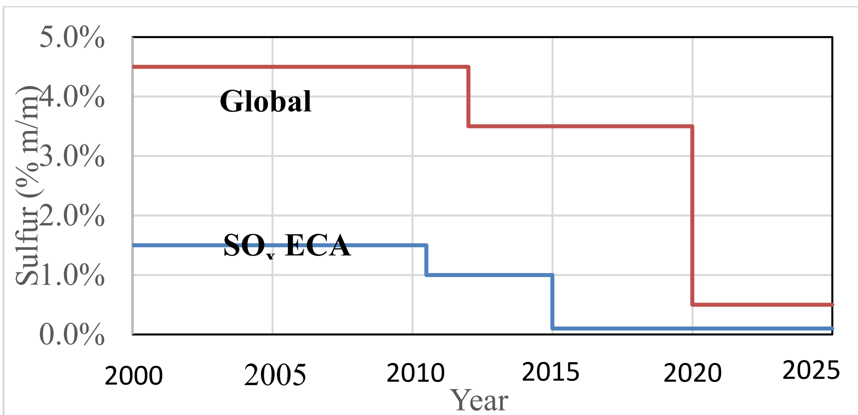


**Figure 1-2 Global and ECA fuel sulfur limits**

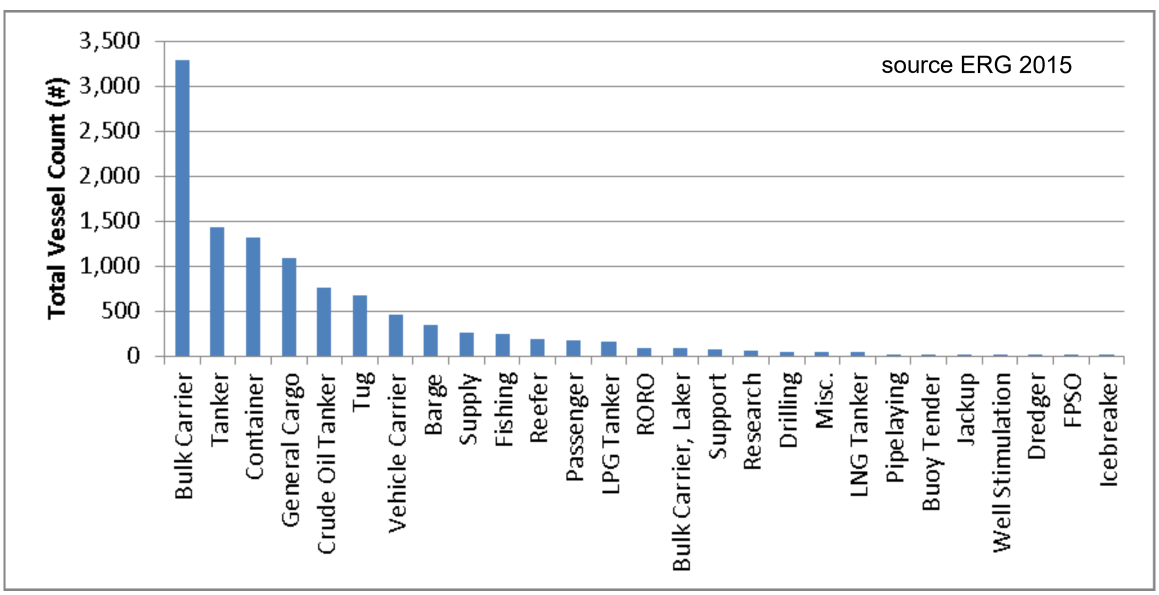


**Figure 1-3 Ship inventory count by vessel category**

## 1.2 Objective

The objective of this research is to test the emissions of existing technologies that offer the potential for further reductions in emissions associated with ocean-going vessels (OGV). Testing of interest includes direct measurements of in-use emissions of criteria pollutants (CO, $NO_x$, $PM_{2.5}$), long-lived climate pollutants ($CO_2$), short-lived climate pollutants (black carbon, methane) and air toxics, as needed. The sources of primary interest include OGV with scrubbers, Tier 2 engines operating on ULSFO and MGO, boilers, and LNG vessels.

While there are many available technologies to focus on that have been successful in reducing criteria pollutants such as PM, SOx and NOx, further reductions are needed to help achieve California's air quality, climate, and public health mandates. In particular, additional efforts need to be directed towards the reduction of greenhouse gases (GHG), including short-lived climate pollutants (SLCPs), from the freight movement system.

The purpose of this testing is to understand the in-use emissions from a modern ocean-going vessel equipped with a scrubber. The testing includes the direct measurement of criterial pollutants ($PM_{2.5}$, CO, $CO_2$, $NO_x$, and $SO_2$) in addition to some other pollutants of interest which include PM speciation (elemental, organic, and sulfate PM species), black carbon (eBC), and particle size distribution (PSD).

# 2 Project approach

This section outlines the in-use emissions testing approach for the scrubber system. This section describes the test article (vessel, engine, fuels, and load points), emissions systems (sample location, gaseous and PM measurement methods, and exhaust flow determination), and the calculations. The test article sections cover details on the specifics of the vessel and any details of importance to the stability of the emission and the validity of the testing. The sampling approach describes the vessel operation, where the samples were collected from the exhaust, the test matrix, and the test protocol. The measurements section describes the measurement methods for the gaseous, PM (including its components), exhaust flow, and engine load. The calculations section provides details on the exhaust flow, emission factors, and in-use estimated calculations.

## 2.1 Test article

The test engine, vessel, and fuel are described in this section.

### *2.1.1 Vessel details*

The vessel tested was an automobile cargo vessel with a gross tonnage of 75,283 tons, a deadweight of 23,786 tons, an overall length of 199.97 m, and a breadth of 36.54 m. The vessel's keel was laid in June 2014 and was delivered in 2015 for service, see Appendix D. The vessels service speed is up to 19.6 knots. The vessel is equipped with one main engine (ME), three diesel generator engines (DGs), and one boiler. Additionally, the vessel incorporated a scrubber system to allow the use of high distillate HFO fuels while operating in ECA compliant areas under MARPOL Annex VI regulations. For the testing performed, the ME and one DG were routed through the scrubber and the other two DGs were in bypass mode (see details in Table 2-1 and photo in Figure 2-1). The boiler and non-scrubbed DG's were run on ECA compliant fuels while in the ECA and were not tested as part of this study.

**Table 2-1 Scrubber vessel specifications**

| *MY* | *Class* | *Cars* | *Draught (m)* | *Length (m)* | *Breadth (m)* | *Speed (knots)* |
|---|---|---|---|---|---|---|
| 2015 | DNV-GL | 8000 | 9 | 200 | 36.4 | 19.6 |
| ***HFO $m^3$*** | ***DGO Capc. $m^3$*** | ***Ballast $m^3$*** | ***Fresh Water $m^3$*** | ***ME*** | ***DG*** | ***Boiler*** |
| 3761 | 554.1 | 11257 | 361 | 1 | 3 | 1 |

[1] MY is the delivery model year of the vessel, ME is the main engine, and DG is the diesel generator there are three DG on the vessel. HFO is the heavy fuel oil.

**Figure 2-1 Ocean going vessel main engine (ME) tested**

#### *2.1.2 Engines*

The ME is an 8-cylinder Hyundai MAN-B&W AA5516 16.56 MW low speed 2-stroke diesel engine. The DGs are HiMSEN 7.6H25 1.9 MW medium speed 4-stroke diesel engines. Of the three DGs, one is used as the primary extra power source, while the other two are used more for backup operations or when the vessel is entering or exiting the port. The engine loads while operating "at sea" are about 70% for the ME and 50% for the DG (based on maximum continuous ratings, MCR). The DG represents around 10% of the total exhaust flow compared to the ME under these conditions, so the ME represents the most significant impact on the emissions from the vessel. The vessel ME sea-trial was performed on 4/2014 from 25% to 110% engine load and showed a brake specific fuel consumption (BSFC) of 167 g/kWhr at 75% load (assuming a fuel net heating value of 10,130 kcal/kg), see Appendix E Figure E-1.

**Table 2-2 Specifications of emissions sources on the test vessel [1]**

| *Source* | *Engine Mfg.* | *Model* | *Engine Power kW* | *Run Hours* | *Scrubber* | *Exhaust Fraction [2]* |
|---|---|---|---|---|---|---|
| ME | MAN-B&W | AA5516 | 15,560 | 14,387 | Yes | 90% |
| DG | HiMSEN | 7.6H25 | 1,900 | 2,559 | yes | 10% |
| DG | HiMSEN | 7.6H25 | 1,900 | - | bypass | n/a |
| DG | HiMSEN | 7.6H25 | 1,900 | - | bypass | n/a |
| Boiler | n/a | n/a | n/a | | no | n/a |

[1] The main engine (ME) is a 2015 Hyundai two stroke slow speed (94 RPM) direct drive engine, the main generators (DG) are 2014 Hyundai medium speed (900 RPM) 4-stroke diesel engines.
[2] Normal at-sea exhaust flow fractions is the ME at 70% MCR load and one DG at 50% MCR.

PM emissions are known to vary with the condition and age of diesel engines. OGVs accumulate some of the highest engine hours of diesel-powered equipment, therefore PM emissions may be significantly impacted by the status of the engine age and maintenance. After an engine overhaul, 2-stroke engines utilize increased lubrication during the running-in period where it is expected PM emissions will be elevated. At the time of testing, the ME accumulated hours were 14,387 (Table 2-2) and 2,559 for the DG. Typical ME recommended cylinder overhaul interval is 20,000 hrs where an overhaul was not recently performed and not needed.

The DGs showed similar records, and the tested engine was not in need of an overhaul and was in good working order. If an engine overhaul is performed for the DG, it is recommended to wait 200 hours for a 4-stroke engine before its emissions are representative. The hours observed did not conflict with any of the testing desires for emissions measurements and thus represent valid results.

In general, the ME and DG maintenance records at the time of testing suggest the PM emissions from the vessel should be representative of a properly operating OGV.

### *2.1.3 Scrubber*

The scrubber evaluated is a Wärtsilä hybrid wet scrubber system designed to operate in both open loop mode (using seawater to remove SOx from the exhaust gas), and in closed loop mode (where additional reagent is used in combination with sea water). The scrubber includes an inlet and bypass valve sections, a jet section, and an absorber section (Figure 2-2 and Figure 2-3). The inlet and bypass valves are used to allow engine exhaust to either bypass the scrubber or go through the scrubber. The jet section is utilized to accelerate the particles to create more impaction contact areas for $SO_2$ removal. The absorber section is utilized to slow down the exhaust and collect the mist and remove the remaining particles by gas phase absorption. The absorber section is critical for proper mist removal, where if the mist is not removed then the sulfur containing species can exit the stack as hydrated particles and may be collected as PM mass with the 40 CFR Part 1065 sampling methods.

The scrubber is designed to operate with one ME and the vessels three DGs. The other emission source, the boiler, was not designed to be operated with the scrubber. The ME and DGs can be placed in either bypass (not going through the scrubber) or in scrubber mode (going through the scrubber system). Additionally, the ME and DGs can be operated on either high or low sulfur fuels. For the testing proposed in this project, the ME and one DG were operated on high sulfur fuels with the exhaust gas scrubber while the other two DGs were in bypass mode and utilized as needed. The exhaust from the DGs in bypass did not go through the scrubber.

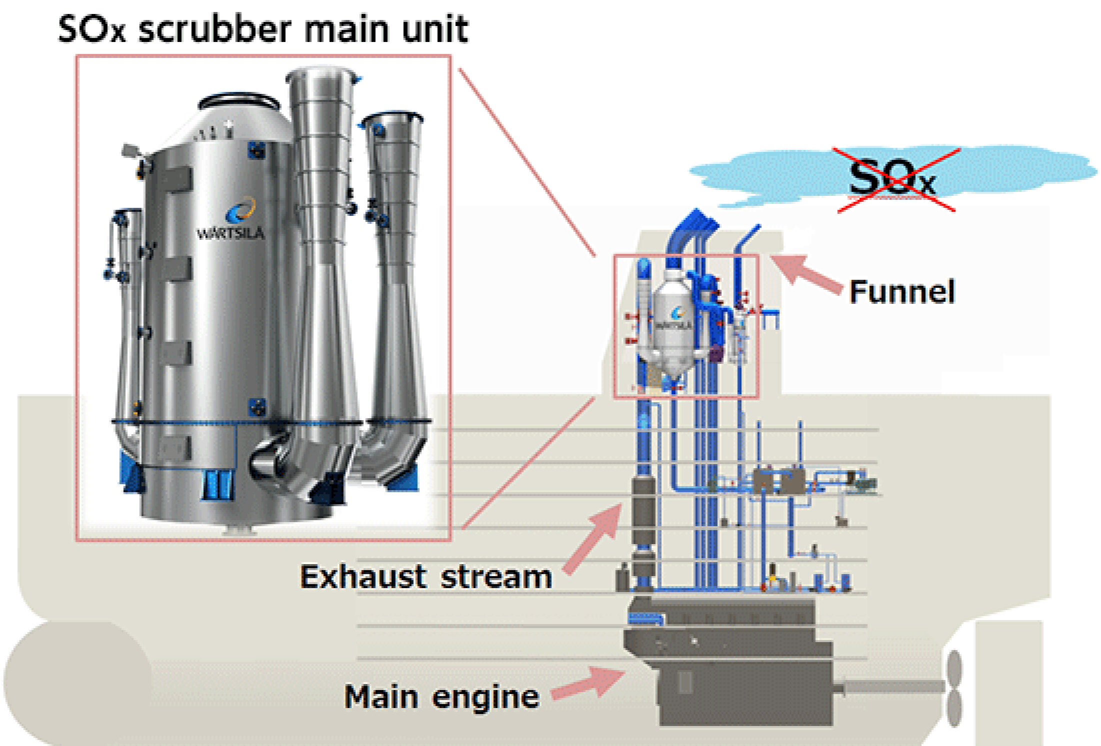


**Figure 2-2 Scrubber installed on the ME and DG engine of the OGV (source MOL)[1]**

### *2.1.4 Test fuels*

Standard commercial marine HFO and lubricants were used during testing. For the testing campaign, the vessel was operated in the ECA zone using high sulfur HFO and its scrubber system. The scrubber is designed to work with sulfur levels up to 3%. A fuel sample was collected during testing and sent out for analysis. The results are shown in the table below. The fuel sulfur was 2.5% for the HFO fuel tested, see Table 2-3. The on-vessel fuel sulfur concentration was reported at 2.5%, see Appendix E, Figure E-2. This matches UCR's analysis. The heating value of the fuel was reported at 40.3 MJ/kg and the sea-trial was performed using fuel at 42.26 MJ/kg, see report copy Appendix E, Figure E2.

**Table 2-3 Test cycle for main engine constant speed (variable prop)**

| Tests | Method | Units | Results |
|---|---|---|---|
| Density@15 | | kg/m3 | 990.1 |
| Viscosity | D445 50c | cSt | 370.3 |
| Cetane Index | D4737B | | |
| Ash | D482 | Mass% | |
| Sulfur | D5453 | ppm | 25334 |
| CCAI | calc. | n/a | 816 |

[1] Source for image credit is MOL at http://www.mol.co.jp/en/

The test vessel used Shell S6 300 for the cylinder oil, Shell Melinea S30 for circulating oil and Shell Melina S30 for turbo oil, see Appendix E, Figure E-4. No oil sample was collected or analyzed as part of this testing.

## 2.2 Sampling approach

This section provides a discussion of the selection of sample locations (PM representativeness and accessibility), the load points (achievable and practical), the test matrix (proposed load points to meet objectives), and the test protocol (methods of sampling).

### *2.2.1 Sample locations*

The sampling approach included both pre and post-scrubber samples. For the pre-scrubber testing there were two separate sample locations one for the ME and one for the DG, see Figure 2-3 for pictorial layout and Figure 2-4 and Figure 2-5 for the instrument setup. For the post-scrubber testing, there was a single sample location with the ME and DG exhaust sources combined. The ME pre-scrubber source samples were collected before the scrubber and economizer and the post-scrubber samples were collected at the same level as the scrubber's continuous emissions monitoring system (CEMS) connection.

Sampling around an economizer was confounded because PM adsorption and desorption processes occur on the heat exchanger surfaces. During waste heat recovery (heating water to make steam for the ship's needs), the heat exchanger surfaces cool the exhaust gas constituents and PM (predominantly EC and BC) adsorbs on the cool surfaces. The adsorption of PM on a cool surface can be described by thermophoretic loss models. When PM is adsorbed onto the surface, stack PM emission factors can be underestimated (by about 10%) over short periods of time (measured in hours). To prevent the economizer from fouling, ships employ a periodic (at best daily) cleaning process of the heat exchanger surfaces. During cleaning, large amounts of PM (>20% of the source) can be expected to be released, and if sampled, would lead to an overestimate of the PM emissions factors of the ship. Thus, for an optimum scrubber performance evaluation, the ideal sampling location would be after the economizer, but before the scrubber.

The selection of sampling locations is often determined by space constraints and desired measurement practices (e.g., the potential to sample from straight sections of exhaust). On this vessel, access to the exhaust after the economizer was not possible due to the many tight bends, short distances, and hard to reach areas. As such, the pre-scrubber ME sampling was done prior to the economizer. As no noticeable real-time PM spikes that could be attributed to cleaning were observed during the testing, as discussed above, the data presented is considered to be representative of in-use emissions from an OGV equipped with a scrubber.

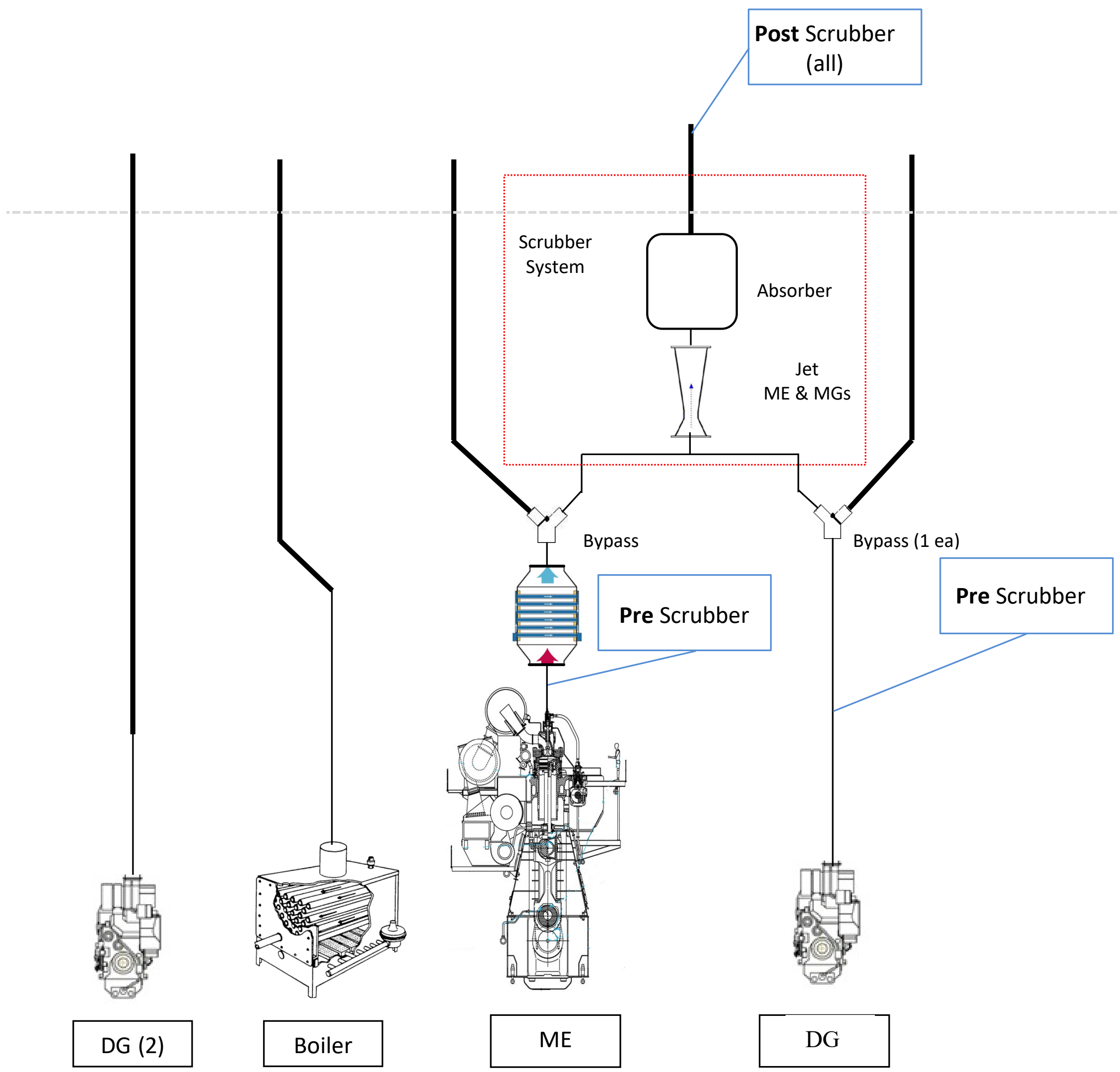


**Figure 2-3 Schematic diagram for the test OGV engine layout**

### *2.2.2 Scrubber sampling*

During previous scrubber evaluations, the post-scrubber sample location has been problematic due to low exhaust temperatures (<20˚C) and high water contents (possibly oversaturated if scrubber mist collection is less than ideal). During these conditions, PM formation mechanisms could be different between pre and post-scrubber sampling.

According to previous discussions with scrubber manufacturers, the best sample location is 1 to 1.5 meters from the exit of the absorber section at or near the location of the scrubber CEMS. UCR sampled the post scrubber location near the CEMS system. UCR selected this location to minimize water sulfur interactions during PM sampling. Additionally, UCR heated the dilution air to maintain a filter temperature that was closer to 47˚C so as to maintain consistency between pre and post-scrubber sampling (as recommended by 40 CFR Part 1065 and ISO). During pre-scrubber testing, the dilution air heating was not necessary because the exhaust was hot and needed to be cooled. During post-scrubber testing, the exhaust was cool and the dilution air needed to be heated. See Section 2.2.4 for more details.

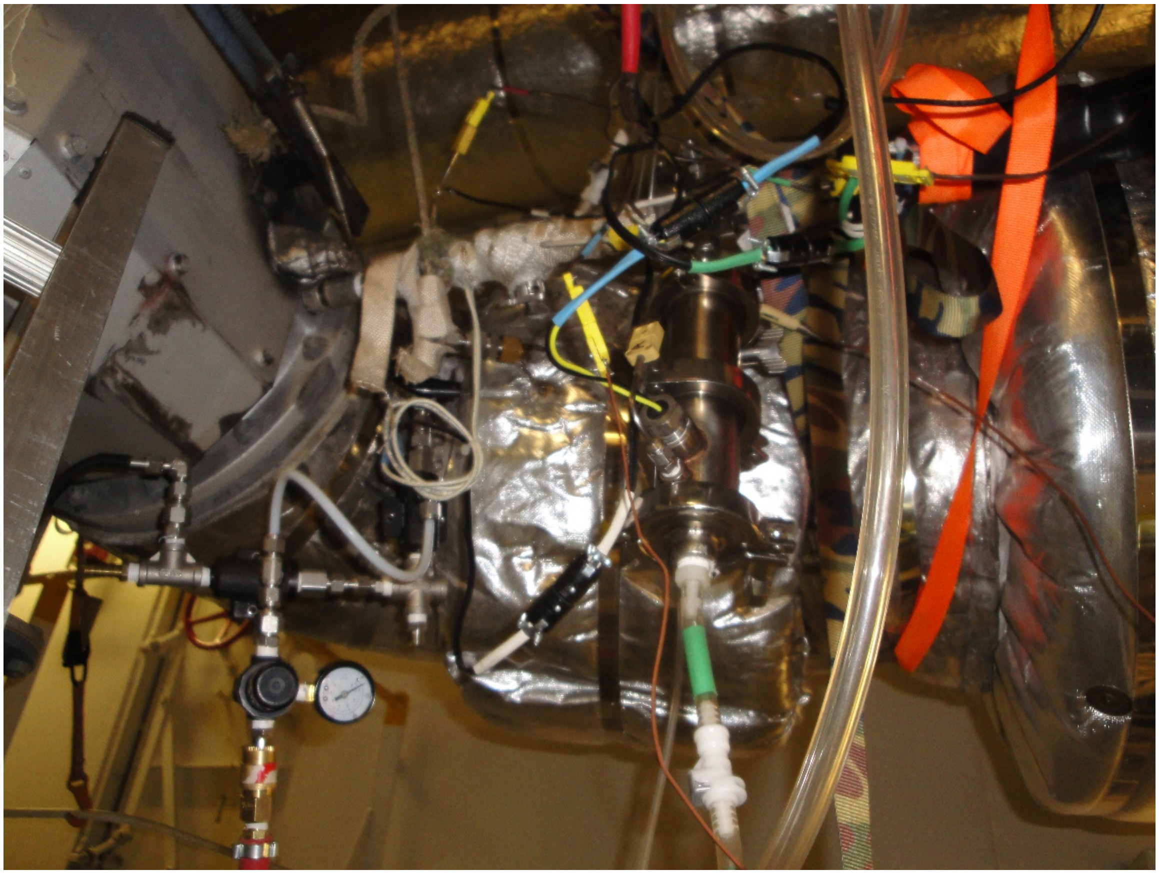

**Figure 2-4 Pre-scrubber sample location setup**

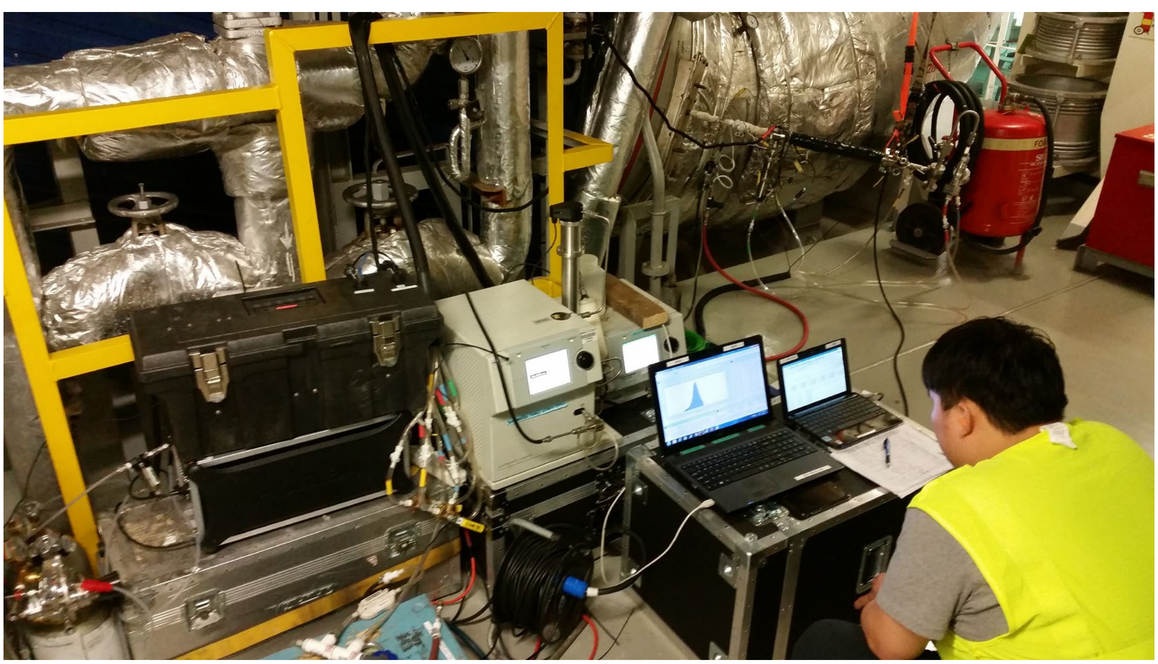

**Figure 2-5 Instrumentation sample setup and operation.**

#### *2.2.3 Test matrix*

The test matrix subsection covers the engine certification cycles, proposed test modes, the impact these modes had on the scrubber, and the sequence of performing these modes.

**Engine certification:** The ME is directly connected to the propeller where vessel speed is controlled by engine speed following the propeller curve. Direct drive engines are certified per the ISO-8178 E3 marine test cycle, see Table 2-4, and constant speed generators follow the ISO-8178 D2 test cycle, see Table 2-5. The maximum achievable load may be less than 100% and can depend on several factors including navigational constraints, engine configurations, currents, wave patterns, wind speed and direction, and loads allowed by the Chief Engineer or ship Master. For this testing the maximum allowable ME load was specified at 72% MCR as per the Chief Engineer. For additional information on engine test cycles see Appendix C.

**Table 2-4 Test cycle for main engine constant speed (direct drive)**

| Main engine testing (ISO 8178 E3) | | | | |
|---|---|---|---|---|
| Mode | 1 | 2 | 3 | 4 |
| Speed (%) | 100 | 91 | 80 | 63 |
| Power (%) | 100 | 75 | 50 | 25 |
| Weight Factor | 20% | 50% | 15% | 15% |

[1]Vessel speed reduction (VSR) is also of interest to EPA and typically represents a 5$^{th}$ mode at around 10% load and 50% speed. The vessel did operate in areas that utilize VSR, thus, the 10% point is not recommended.

**Table 2-5 Test cycle for constant-speed generator engines**

| Generator engine testing (ISO 8178 D2) | | | | | |
|---|---|---|---|---|---|
| Mode | 1 | 2 | 3 | 4 | 5 |
| Speed (%) | Rated RPM | | | | |
| Power (%) | 100 | 75 | 50 | 25 | 10[1] |
| Weight Factor | 5% | 25% | 30% | 30% | 10% |

**Common operation:** Common operational modes for the vessel include normal at-sea conditions (fully loaded and partially loaded), entering and exiting ports, and in port. Table 2-6 shows typical ME and DG operation for the vessel under these different conditions. While at sea, the ME typically operates at 70% load and one DG is operated for ship services, hotel, and maneuvering power (typically at loads from 45% to 65% and depends on the vessel's needs). During berth entry and exit maneuvers, the ME power is reduced to 25% to 50% load while the main DG increases in load and one of the other two DGs is also operated. While in port (loading and unloading goods), one DG is used at around 60% load while the other two are for backup and the ME is at zero load (all DGs are at 0% if there is shore power). Most of the vessel's operation is based on at-sea conditions that are estimated to be 95% of the vessel operation, while approximately 1% (or less) is representative of berth exit and entry and 4% is representative of dock conditions.

**Table 2-6 Expected vessel scrubber operation modes**

| Activity | % Load MCR | | | Est. Time Fraction |
|---|---|---|---|---|
| | ME | DG1 | DG2,3 | |
| At Sea | 70% | 60% | backup | 95% |
| Berth enter/exit | 25-50% | 40% | 40% | 1% |
| At Dock | 0% | 60% | backup | 4% |

The matrix of test points and their sequence is provided in Table 2-7. This matrix includes testing the ME at a 25%, 50%, and 75% load and the DG at 25%, 50% and 75% load. Efforts were made in consulting with the Master and Chief to target loads as close as possible to those in Table 2-5. Although slight deviations from the target loads occurred, due the constraints of the in-use ship operations, overall the actual loads were close to the target loads.

**Scrubber max flow:** The test matrix shown in Table 2-7 covers a large range which includes low and high flow conditions. For the at-sea post-scrubber testing, the 75% ME load and 50% DG load was the high flow condition and the 25% ME and 50% DG was the low flow condition. This range provided an evaluation of the scrubber from 90% to 30% of its exhaust flow range. UCR did not test the generator only mode where the DG is at 50% and the ME is at 0%, simulating an at-berth condition with no shore power. Previous testing was performed under this condition and showed the scrubber had lower conversion efficiencies at this mode (Johnson et al., 2016).

**Scrubber control:** The scrubber is designed for open loop (OL) and closed loop (CL) modes. The OL mode is used while the vessel is at-sea and the ocean water provides the alkalinity for proper scrubber performance. During previous testing of OGV scrubbers, the OL vs CL was evaluated. No significant emissions findings were observed during these different modes as long as the alkalinity is controlled as is expected for a properly operating scrubber system, (Johnson et al., 2016). As such, the operational mode was not evaluated on this scrubber. The pH control was robust and representative of a properly operating scrubber system, see details in Appendix D.

**Sequence of events:** Due to the various pre and post-scrubber sample locations, several setups were needed. Table 2-7 shows the sequence of events used to collect the data in this report. The test setup moved between different sampling locations. Overall, it took four days to do the work (one day for initial setup and then testing on days 1, 2, and 3), with each setup move taking approximately 6 to 8 hours. As a result, moves were minimized by focusing on the three proposed setups, DG pre-scrubber, ME pre-scrubber, and ME + DG post-scrubber. Testing of the DG started in LA prior to leaving the dock. Next, testing moved to the ME pre-scrubber location and then moved to the ME+DG post-scrubber test on the third day. Testing on different days will not inherently impact the emission factors of the vessel as long as the loads can be similarly maintained. During testing the ME loads were similar from test to test so the data is representative of a properly tested OGV equipped with a scrubber.

**Table 2-7 Test plan sequence**

| Day | Location | Special Notes [3] | Source | Scrubber | Mode | ME Load | DG Load |
|---|---|---|---|---|---|---|---|
| 1 | Dock [1] | - | DG | Pre | 2 | - | 50% |
| 1 | Dock [1] | - | DG | Pre | 3 | - | 75% |
| 1 | Dock [1] | - | DG | Pre | 1 | - | 25% |
| 2 | at-sea [2] | - | ME | Pre | 3 | 75% | - |
| 2 | at-sea [2] | - | ME | Pre | 1 | 50% | - |
| 2 | at-sea [2] | - | ME | Pre | 1 | 25% | - |
| 3 | at-sea [2] | - | ME+DG | Post | 1 | 75% | 50% |
| 3 | at-sea [2] | - | ME+DG | Post | 2 | 50% | 50% |
| 3 | at-sea [2] | - | ME+DG | Post | 3 | 25% | 50% |

[1] Testing of the pre-scrubber DG occurred in LA/Long Beach, CA [2] Testing of the main engine pre-scrubber and ME+DG post-scrubber system occurred at-sea between LA/Long Beach and Oakland.

### *2.2.4 Test protocol*

When following the ISO cycles, the engine was operated for more than 30 minutes at the highest power possible to warm the engine and stabilize emissions. Repeats of the same load are performed prior to changing loads (i.e., mode 1, 1, 1 change load, mode 2, 2, 2 load change…). Based on experience testing OGVs, repeating test points with this approach is needed to manage the time it takes between different load points and to prevent issues when navigating in areas with speed restriction. At each steady state test mode, the protocol requires the following:

- Allow the gaseous emissions to stabilize before measurement at each test mode (minimum 10 minutes as per ISO).
- Measure gaseous and PM concentrations for at least 3 minutes and no longer than 30 minutes (such that approximately 500 μg of filter mass is collected at a minimum dilution ratio of 4:1).
- Record engine RPM, boost pressure, and intake manifold temperature in order to calculate the mass flow rate of the exhaust via the air pump methods. Additionally, UCR records engine fuel consumption, or brake specific fuel consumption (bsFC), where available to calculate exhaust flow by an alternate method for the verification of both exhaust flow methods.
- Record engine load, and if available, bsFC. bsFC will be used for validation of the measurement systems.
- Calculate emission factors from the measured pollutant concentration data and calculated mass flow rates.

## 2.3 Measurements

The sampling approach includes selecting sample locations (PM representativeness and accessibility), load points (achievable and practical), test matrix, and test protocol (methods to use for sampling).

#### *2.3.1 Gaseous and PM emissions*

Best recommended practices for OGV exhaust gas measurements follow 40 CFR Part 1065 for PM measurements with specific details following ISO-8178-1 for dilution and exhaust gas sampling. The measurement approach is summarized here, with more details available in Appendix A.

**Gaseous:** The concentrations of gases in the raw exhaust is measured with a Horiba PG-350. Nitrogen oxides ($NO_x$), carbon monoxide (CO) and sulfur dioxide ($SO_2$), and oxygen ($O_2$) were measured by a heated chemiluminescence detector (HCLD), a non-dispersive infrared absorption (NDIR) with cross flow modulation, and a zirconium oxide sensor, respectively (see Table 2-8). Major features of the PG-350 include a built-in sample conditioning system with sample pumps, data storage on a flash drive, integrated mist and particle filters, and a thermoelectric cooler. The performance of the PG-350 was tested and verified under the U.S. EPA and Environmental Testing Verification (ETV) programs. The signal output of the instrument was interfaced directly with a data acquisition system to view measurement trends and for data recording backup continuously.

**PM2.5:** UCR's PM measurements use a partial dilution system that was developed based on the ISO-8178-1 protocol and detailed information is provided in Appendix A. Total PM mass ($PM_{2.5}$) is measured from the diluted exhaust gas as per 40 CFR Part 1065 recommended practices which utilizes Teflon filters weighed offline and after conditioning. Diluting the exhaust eliminates water condensation in the dilution tunnel and helps to maintain the temperature of the diluted exhaust gas <52°C before the filters. During previous scrubber testing UCR dilution and filter temperature control was found to be inadequate. Scrubbers utilize cold sea water which reduces the exhaust temperature and impacts the PM formation mechanism (as part of the scrubber design). Due to low scrubber exhaust gas exit temperatures (<20˚C vs ~300˚C without a scrubber), sample heating was needed to maintain a filter face temperature near 47˚C, which is above the saturation point of water. Consistent filter face temperatures have been shown to improve PM sampling and are recommended by 40 CFR Part 1065 and are optional (but still better) as per ISO-8178.

UCR implemented a dilution air and sample heating system with active controls for all samples collected for scrubber-equipped and other vessels starting in 2015, see details in Figure 2-6. The heating section was utilized for both pre and post-scrubber in order to maintain similar losses in the PM collection system for both locations. The design of the system has a one second residence time (recommended) and has a heated sample line section followed by a heated dilution air system. Both heated systems were designed to target a 47˚C (±5˚C) filter face temperature for both pre and post-scrubber samples. During pre-scrubber sampling, the active heating section is operated at a lower temperature to prevent over heating the PM filter during sustained high load conditions, as the pre-scrubber exhaust temperatures are high.

**Dilution ratio**: Other scrubber evaluations have sampled at high dilution ratios (~20) as allowed by ISO-8178 methods. EPA 1065 recommendations are to target 6:1 at your maximum load point. Previous testing by UCR evaluated the impacts of dilution factors between 20:1 and 6:1. No statistical findings were observed for an OGV equipped with a scrubber. The testing performed in this project was at the targeted 6:1 ratio following the EPA recommendations as specified in Appendix A.

**PM Composition:** In addition to measuring total PM, the project measured the PM composition which includes elemental carbon (EC), organic carbon (OC) and sulfate PM fractions. The EC/OC were sampled with a quartz filter and analyzed using thermal optical reflectance Interagency Monitoring of PROtected Visual Environments (IMPROVE) method and the sulfate PM was analyzed using a ion-chromatography method during off-site analysis. The PM composition was sampled from UCR dilution tunnel.

**Equivalent black carbon (eBC).** eBC was measured with UCR's AVL MSS-483 photoacoustic real-time analyzer. The eBC photoacoustic measurement was sampled from the dilution tunnel.

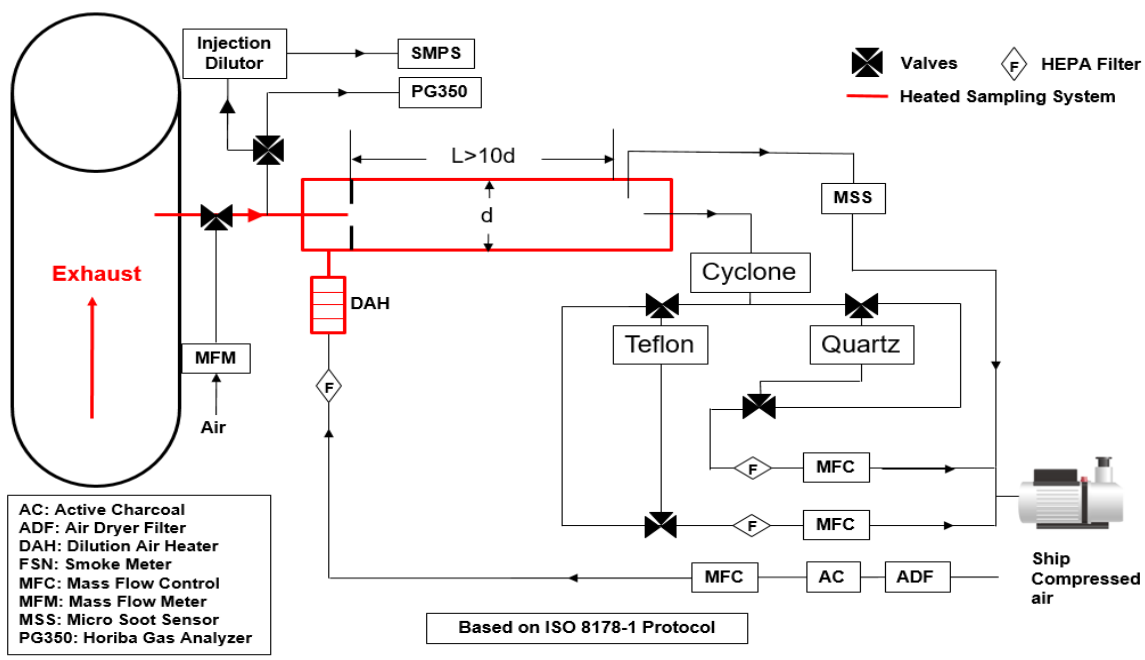


**Figure 2-6 Schematic of the dilution sampling system**

**Table 2-8 Summary of emissions measured by UCR**

| Species Sampled | | | |
|---|---|---|---|
| NDIR CO | NDIR $CO_2$ | CLD $NO_x$ | Photoacoustic eBC |
| NDIR $SO_2$ | Total **$PM_{2.5}$** Gravimetric method | PM EC/OC NIOSH method | PM **Sulfate** Reported as $H_2SO_4*6.65H_2O$ |

### *2.3.2 Particle Size Distribution (PSD)*

Particle size distributions (PSDs) were measured with a TSI Scanning Mobility Particle Sizer (SMPS) 3080 in group with a TSI Condensation Particle Counter (CPC) 3776. The SMPS was set to provide a range of diameters from 5.94 to 224.7 nm in 102 steps to better capture the small sulfuric acid particles and SMPS has a reported size accuracy around 3% for spherical particles (Kinney and Pui 1991). The SMPS requires at least 120 seconds to scan the entire particle size range and it is very suitable for measuring steady-state marine engine exhaust with additional dilution

The dilution stage (see Figure 2-7) before SMPS sampling were provided with dual stage injection dilutor, where the first stage provided a dilution ratio of 8 and the second stage provided a dilution ratio of 37.5. This entire system provide an instant dilution ratio of 300. The dilution ratio was verified in lab with propane injection and the orifices were cleaned after each load testing to prevent dilution ratio change by contamination.

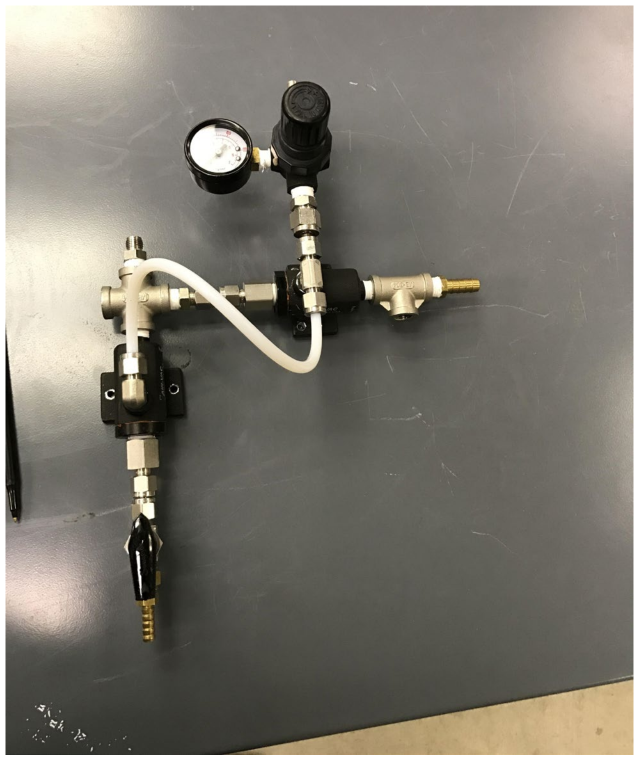

**Figure 2-7 Schematic of the dilution sampling system**

### *2.3.3 Exhaust flow*

The calculated emission factor requires the measurement of the engines exhaust flow rate. The exhaust gas flow can be determined by the following methods:

1. Direct Measurement Method (not available)
2. Carbon Balance Method (utilized with reported vessel fuel consumption)
3. Air and Fuel Measurement Method (not used)
4. Air Pump method (utilized and compared to carbon balance to determine the fraction of exhaust that can be attributed to scavenging)

Direct measurement is complex and requires long straight sections and experienced operation of a sample system which is not typically available on OGVs. Typically, the carbon balance and air pump method are available from the engine room. For the work presented in this study, the exhaust flow is determined by the Carbon Balance Method and by the Air Pump Method. Since the post-scrubber exhaust was ME and DG combined, the carbon balance method was confounded by the addition of the DG flow stream. Thus, the emission factors reported are based on using the exhaust flow calculated by the Air Pump

Method with corrections applied for the carbon balance method during pre-scrubber sampling. For specific calculation details see Appendix A and Appendix E for details on exhaust flow values and assumptions.

#### *2.3.4 Engine*

Some of the engine performance parameters measured or calculated for each mode during the emissions testing are shown in Table 2-9. The records vary depending on available information for the ME and DG.

**Table 2-9: Engine parameters measured and recorded [1]**

| Parameter | Units |
|---|---|
| Engine load, speed, and fuel cons. | kW, RPM, and kg/kWhr |
| Vessel speed | Knots |
| Generator output | amps, volts, kW, PF (where avail.) |
| Fuel consumption | kg/hr |
| Air intake pressure, temperature | Psi, °C |
| Exhaust stack pressure, temperature | inH20, °C |
| Ambient pressure, temperature | kPa, °C |

[1] Engine and vessel measurements are reported where available and estimated if not available using good engineering judgment.

### 2.4 Calculations

The testing results include details of the engine loads utilized, the measured emissions, the calculated flow rates, and emission factors for the individual loads and the weighted emissions factors. Brake specific and time specific emission factors are also provided.

#### *2.4.1 Exhaust flow rate*

Since the analytical instruments measure the concentration in the exhaust, it is essential to have an accurate measure of the exhaust mass flow in order to calculate emission rates and emission factors. UCR has calculated the exhaust flow rate from the reported displacement volume of the diesel engine cylinder and from the following measured values: engine rpm, intake temperature, and intake manifold air pressure. This ISO-8178 approved "air pump" method has been used in combination with fuel consumption carbon balance comparisons, and on-vessel bsFC comparisons.

#### *2.4.2 Emission factors*

The emissions were collected at each mode in triplicate to allow for the determination of confidence intervals for the reported means. The triplicate measurements were performed by collecting three samples (i.e., triple or three repeated measurements) at each load point for all the species of interest (gaseous continuous and integrated PM samples). Because the testing was performed with triple measurements while holding one load, as listed in Table 2-7, the mode averaging was performed prior to applying a weighting function. The weighted result is the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine has been determined by weighting the modal data according to an estimate of the ISO-8178 E3, E2 and the weighting fractions as described below. The equation used for the overall emission factor is as follows:

$$A_{WM} = \frac{\sum_{i=1}^{i=n} (g_i \times WF_i)}{\sum_{i=1}^{i=n} (P_i \times WF_i)}$$

Where:

$A_{WM}$ = Weighted mass emission level (CO, $CO_2$, $PM_{2.5}$, BC, $SO_2$ and $NO_x$) in g/kWhr

$g_i$ = Mass flow in grams per hour (g/hr)

$P_i$ = Power measured during each mode (kW)

$WF_i$ = Effective weighing factor.

### *2.4.3 Weighting fraction*

The ME and DG were combined into a single exhaust stream prior to entering the scrubber system. The scrubber is designed based on the ME and DG combined flows, emissions, and conditions. The results are presented utilizing the combined load conditions for both pre and post-scrubber evaluation. This approach allows the reader to evaluate the overall performance of the scrubber system as installed. The measured ME loads were consistent with that of Table 2-7 where the ME operated from 25% to 75% of MCR, see Table 2-10. The DG loads varied from 25% to 75% for the pre-scrubber condition and a fixed value of 50% for the post-scrubber test point. The combined measured load of the ME and DG divided by their combined MCRs is represented as the % combined load on the scrubber system. The scrubber was operated at 36%, 52%, and 74%, combined load, see Table 2-10. The results are presented on the combined scrubber % load basis for the remainder of this report.

The ISO weighted emission factors are typically based on a single engine over a test stand load condition that reaches full maximum load, see Table 2-4 (for the ME) and Table 2-5 (for the DG). The scrubber system can only handle its designed loads which are normally lower than MCR and are targeted for less than full power of the vessel and all its sources. The evaluation performed here was based on suggested weighting factors, which were 0.72 at 75% load, 0.16 at 50% load and 0.12 at 25% load, see Table 2-10. These proposed weighing factors were used for the overall performance evaluation of the scrubber system and are representative of practical in-use conditions as well. The suggested weighting factors provide similar weighting to the ISO-8178 E2 cycle, but put high weighting on the 75%, since a majority of the operation is at higher loads, and since the 100% load was not used.

**Table 2-10 Combined loads and suggested weighting factors for the scrubber system**

| ISO 8178 E2 | | Measured | | | Suggested |
|---|---|---|---|---|---|
| Load | Factor | ME Load | AE Load | Combined | Factor |
| 100 | 0.20 | | | | |
| 75 | 0.50 | 79.3% | 68.1% | 74.4% | 0.72 |
| 50 | 0.15 | 47.4% | 44.6% | 52.4% | 0.16 |
| 25 | 0.15 | 30.2% | 30.4% | 36.0% | 0.12 |

### *2.4.4 Scrubber efficiency calculations*

The pre-scrubber emission factors are based on separate DG and ME measurements where the post-scrubber results are based on the combination of the ME and one DG engine. In order to compute the scrubber efficiency, the pre-scrubber test results need to be combined to provide a complete estimate of the scrubber performance. The pre-scrubber mass calculations were flow weighted to be representative of both the ME and DG flow streams. The equation below shows how the scrubber efficiency was calculated for each of the species.

$$A_{WMi} = \frac{C_{AE} * Q_{AE} + C_{MEi} * Q_{MEi}}{P_{DG} + P_{MEi}}$$

Where:

$A_{WMi}$ = Mass emission level for Mode "i" where (CO, $CO_2$, $PM_{2.5}$, BC, SO2, and $NO_x$) in g/kWHr

i = mode number where mode 1 (i =1) is the maximum load mode and mode 3 represents i = 3, 50% load.

$C_{DG}$ = Concentration of the species for the DG

$Q_{DG}$ = Exhaust flow for the DG at 50% nominal load

$C_{ME}$ = Concentration of the species for the ME

$C_{MEi}$ = Exhaust flow for the ME at Mode 1, 2, 3 (mode 4 is ME = 0)

$P_{DG}$ = Power measured during each mode for the DG

$P_{MEi}$ = Power measured during the "i" mode for the ME

# 3 Results

The results for the scrubber system are described in this section. Because the scrubber was designed for both the DGs and ME sources, the analysis considers the combined results from the engines. As such, the loads on the x-axis represent scrubber loads or the sum of the two engines (DG + ME). For example, the 33% load represents the ME at 25% and the DG at 50% load and the 75% load represents the ME at 72% load and the DG at 50% load for a combined 75% scrubber load. This approach allows for an evaluation of the emission factors for the vessel as a whole. Some analysis will also be presented from an engine-out perspective to understand the in-use emissions from the ME and DGs individually.

## 3.1 Gaseous

The combined exhaust NOx emissions before and after the scrubber are shown in Figure 3-1 in units of g/kWhr. In general, the Tier 2 engine NOx emissions ranged from about 11.6 to 17.6 g/kWhr over the different load points. The weighted combined NOx emisisons exiting the scrubber was 13.7 g/kWhr.

The pre-scrubber results allow comparison between the in-use testing and the engine standard. The ME pre-scrubber sample showed NOx emissions that varied from 12 to 19.9 g/kWhr and the DG varied from 5.88 to 7.40 g/kWhr, see Appendix F4. The ISO weighted ME-only pre-scrubber NOx emisisons were 14.2 g/kWhr. These results are comparable to the certification values for Tier 2 category 3 marine engines. The ME NOx emissions declined with increasing engine load which is in agreement with previous vessel tests. In general the results show good repeatability at each of the load points, indicating test consistency.

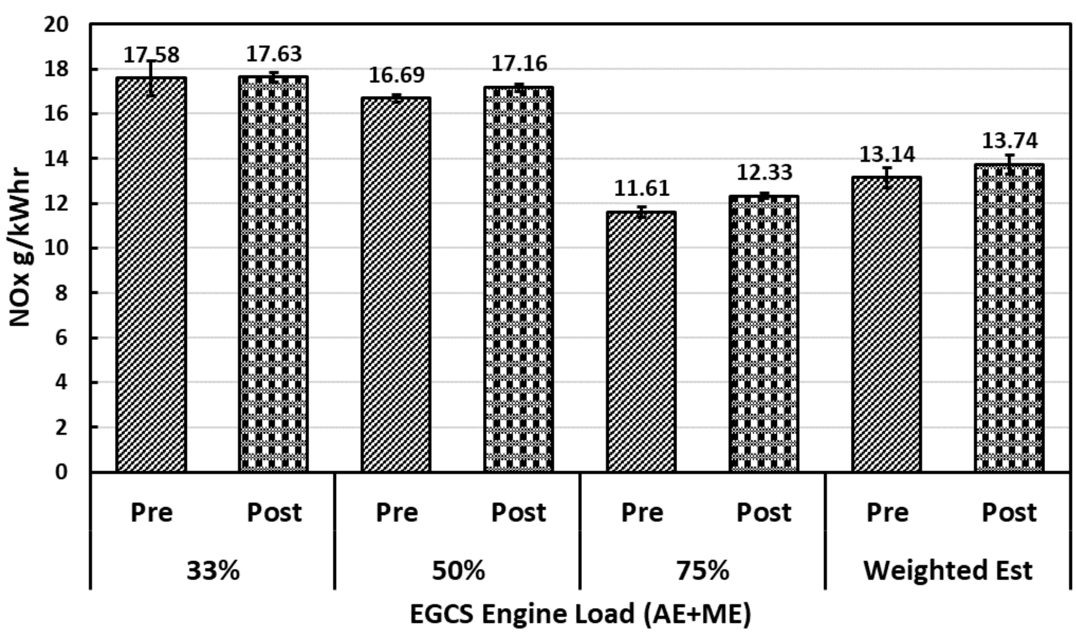


**Figure 3-1 NOx Emissions for the Pre- and Post-scrubber Tests in g/kWhr**

The CO emissions results for the pre- and post-scrubber tests are shown in Figure 3-2 in units of g/kWhr. CO emissions also showed lower emissions for higher loads, with test points in the range of 0.32 to 0.75 g/kWhr. The CO emissions are comparable to those found from other testing campaigns.

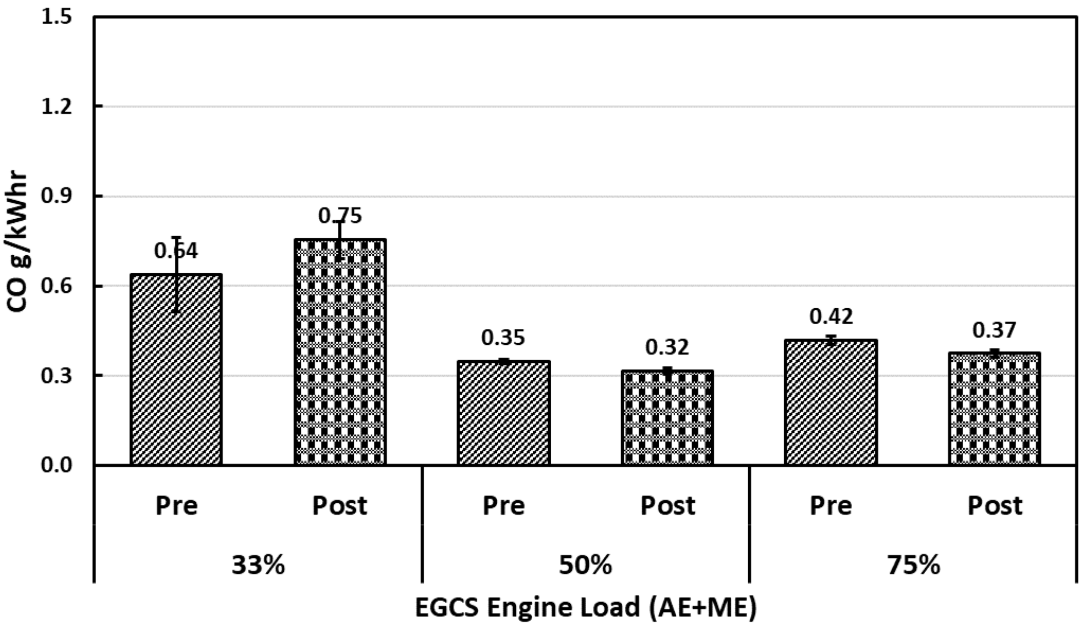


**Figure 3-2 CO Emissions for the Pre- and Post-scrubber Tests in g/kWhr**

The $CO_2$ emissions results for the pre- and post-scrubber tests are shown in Figure 3-3 in units of g/kWhr. $CO_2$ emissions were about 600 g/kWhr for all the different load points and ranged from 624 to 578 g/kWHr. The $CO_2$ emissions are comparable to those for other ME and DG engine tested at-sea where there is a decreasing trend of $CO_2$ emissions as load increases. The DGs had a higher brake specific (bs) $CO_2$ emissions compared to the ME due to lower combustion efficiencies for the smaller displacement engines and differences between 4-stroke and 2-stroke designs. The DGs bs$CO_2$ varied from 770 g/kWhr to 660 g/kWhr were the ME ranged from 569 to 602 g/kWhr for the pre-scrubber tests and various loads. The results show good repeatability at each of the load points, indicating testing consistency. The scrubber is not expected to have a big impact on $CO_2$ emissions, so the differences in $CO_2$ emissions for the pre- and post-scrubber tests are likely a function of the reproducibility of the test between different days and different points in the vessel's operation along the trip.

The $SO_2$ emissions results for the pre- and post-scrubber tests are shown in Figure 3-4 in units of g/kWhr. Pre-scrubber $SO_2$ emissions were relatively constant at approximately 9.2 to 9.7 g/kWhr for the different combined test points. The results show good repeatability, indicating good consistency in the testing. The post-scrubber results show that the scrubber provides significant reductions in $SO_2$ emissions on the order of 97%. The reduction efficiency is sufficient to meet fuel sulfur requirements for scrubber systems. With this reduction efficiency, the $SO_2$ levels are brought down to levels of 0.25 to 0.30 g/kWhr, which is comparable to those found for vessels operating on the lower sulfur fuel. The fuel sulfur concentration was 2.5%, and 3% of the fuel sulfur (at 75% load) formed PM where the remaining portion formed gaseous $SO_2$ emissions. A good sulfur balance was found between the gasoues and PM sulfur species, see Appendix F.

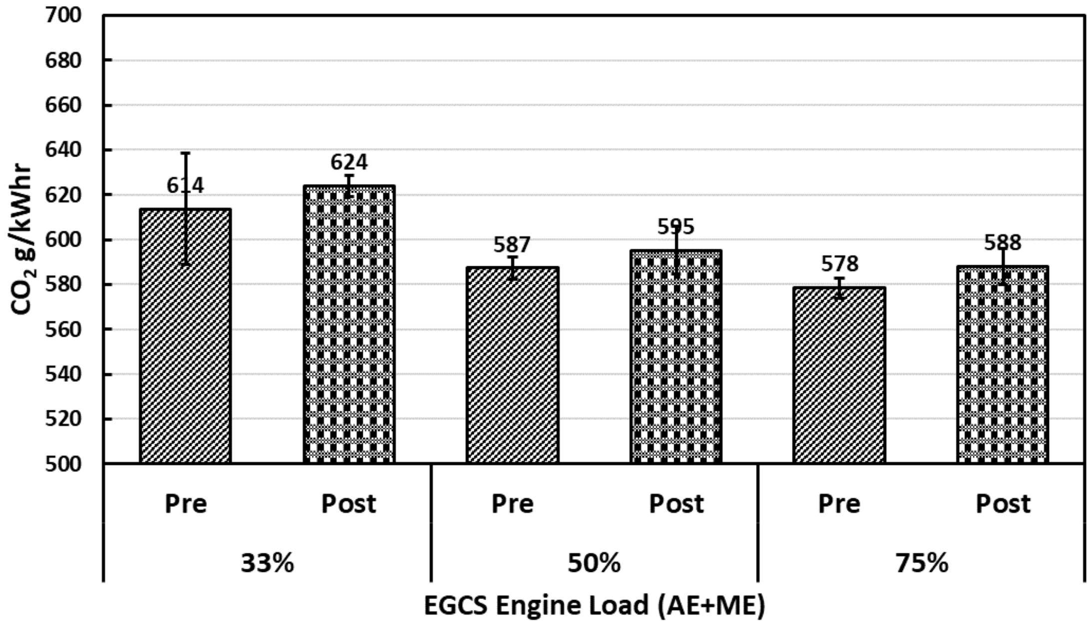


**Figure 3-3 $CO_2$ Emissions for the Pre- and Post-scrubber Tests in g/kWhr**

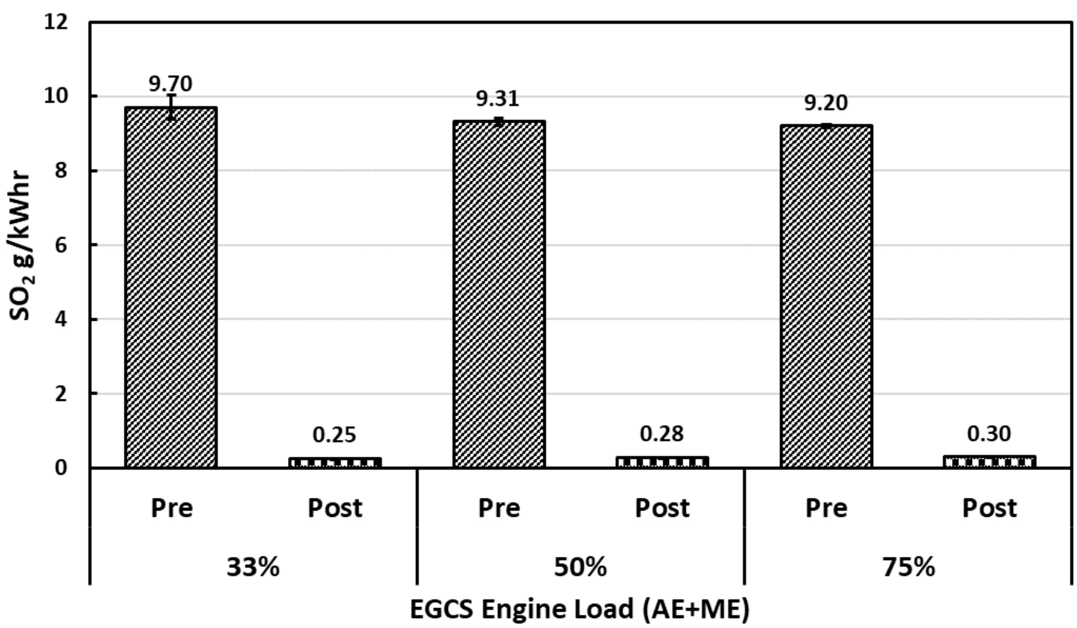


**Figure 3-4 $SO_2$ Emissions for the Pre- and Post-scrubber Tests in g/kWhr**

## 3.2 PM

The $PM_{2.5}$ mass emissions and PM composition results for the pre- and post-scrubber tests are shown in Figure 3-5 in units of g/kWhr. $PM_{2.5}$ emissions pre and post scrubber ranged from about 1.0 to 1.3 g/kWhr where there was no significant PM reduction over the scrubber. In fact, the results show that PM emissions increased post-scrubber compared to pre-scrubber for the 33% and 50% loads with nearly identical results for the 75% load. The $PM_{2.5}$ pre-scrubber or post-scrubber emissions did not show a strong trend with respect to load. The higher PM emissions post-scrubber is different than other published results (Lehtoranta K et al 2019 and Fridell, E et al 2016). CE-CERT suggests there may be a differences resulting from engine, fuel, dilution ratio, transferline, and sampling temperutres between the approachs. Additional investigation on methods is needed to fully understand the differences reported in the literature with the work presented here.

The PM composition results show that the combined exhaust PM is predominantly composed of sulfate PM (75-85%), with a smaller contributions from OC PM (15-25%), and a very small contribution from EC PM (1-2%). The post-scrubber test results are comparable to the results for the pre-scrubber tests, suggesting PM is not significantly reduced between the pre- and post-scrubber samples. This is seen for both the Total PM2.5 mass as well as the PM composition results.

The pre-scrubber ME and DG varied significantly in composition and total PM. The ME composition was < 1% EC, ~ 14% OC, and 85% sulfate. The DG varied from 5% EC to 45% OC and 50% sulfate. The higher sulfate fraction for the ME is a result of the lower overall PM emissions from the ME. The lower PM may be a result of the higher efficiency combustion and lower soot and organic PM formation in the combustion event for a 2-stroke engine. Low soot and organic PM emissions is common from modern 2-stroke engines were most of the mass is a result of the fuel sulfur.

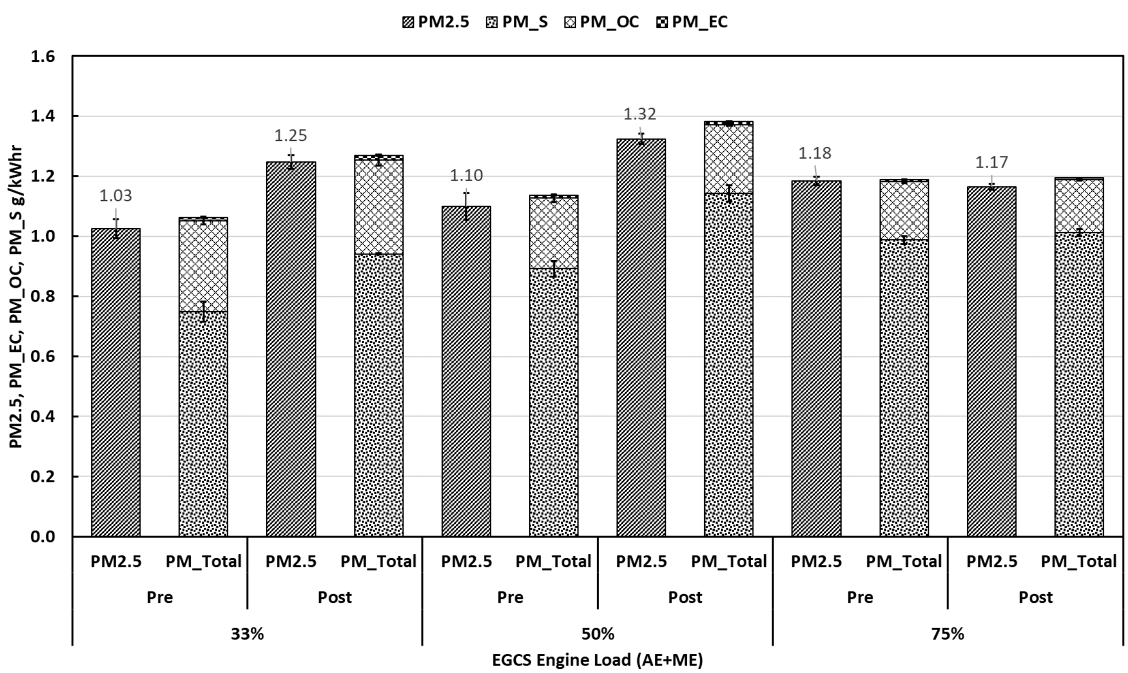


**Figure 3-5 $PM_{2.5}$ Emissions for the Pre- and Post-scrubber Tests in g/kWhr**

## 3.3 BC

The BC emissions results for the pre- and post-scrubber tests are shown in Figure 3-6 in units of g/kWhr for the MSS (eBC) and EC measurements. The results show that combined exhaust BC emissions ranged from 0.007 to 0.022 g/kWhr over the different loads. The pre-scrubber DG only result varied from 0.018 to 0.145 g/kWhr and from 0.006 to 0.01 g/kWhr for the ME. The eBC is consistent with the EC speciation results. These trends are consistent with other OGV studies where the slow speed 2-stroke engines have lower eBC compared to medium speed 4-stroke engines.

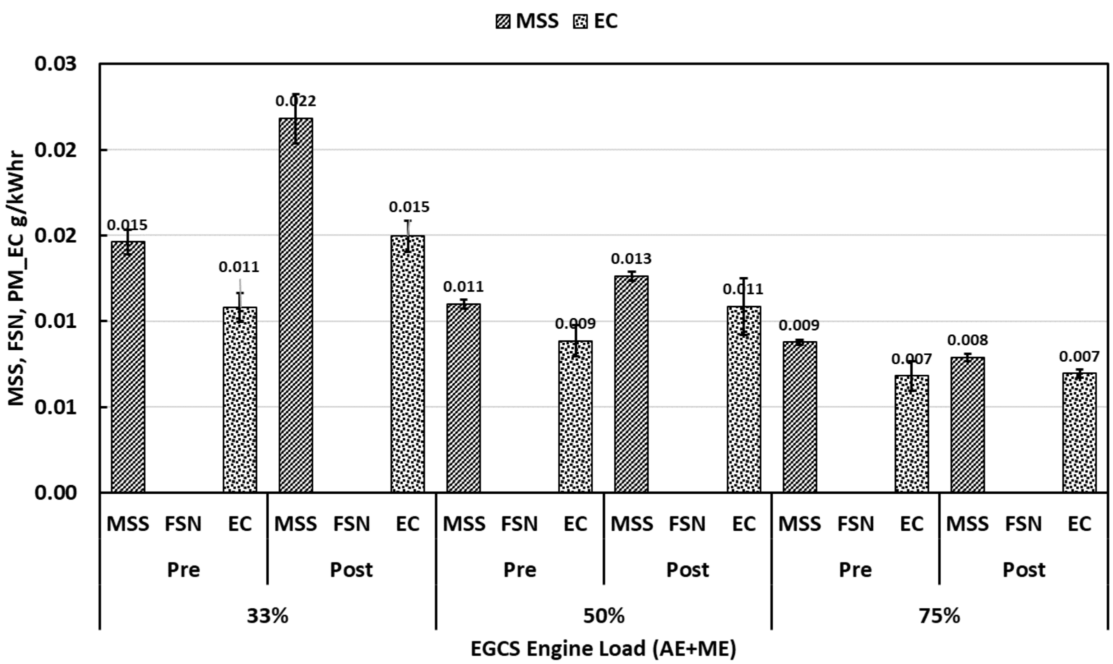


**Figure 3-6 MSS and FSN emissions for the pre- and post-scrubber tests in g/kWhr**

## 3.4 Particle Size Distributions

Number PSDs are shown in Figure 3-7 and Figure 3-8 for the pre and post-scrubber measurements. The number concentration PSDs were similar between loads at each of the sample points (AE only, ME only, and AE + ME) so only the average of the three modes is shown in Figure 3-7. The results for each mode was the average of at least 5 full SMPS scan and verified the stable engine load via stable MSS real time signal. The AE shows a higher PSD at 30 nm diameter compared to the ME. The post-scrubber PSD is much lower at 30 nm diameter compared to both the AE and ME, but the post-scrubber number PSD concentration is higher at the 75 nm diameter. The estimated mass PSD (density = 1.2 g/cm$^3$), is shown in Figure 3-9 (see foot notes for assumptions).

The mass of sulfate PM after the scrubber is slightly higher than before the scrubber. One possibility is that the sulfate particles may be removed in the scrubber, but an equal amount may be condensing into particles from the demister section. The post-scrubber mass concentration is showing a peak mass at 140 nm where before the scrubber the peak mass was 90 nm diameter for the ME and 40 nm for the DG. It is interesting that the ME peak mass diameter is almost double that of the DG. This may be a result of the high fraction of the ME exhaust is sulfate particles (85%) compared to the DG (50%).

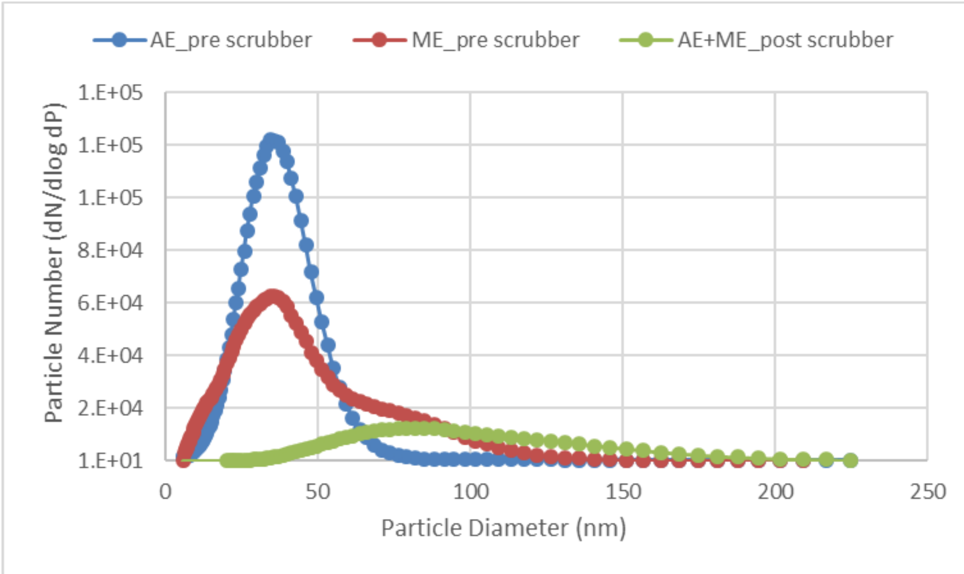


**Figure 3-7 Average number PSD for the pre and post-scrubber conditions: linear**

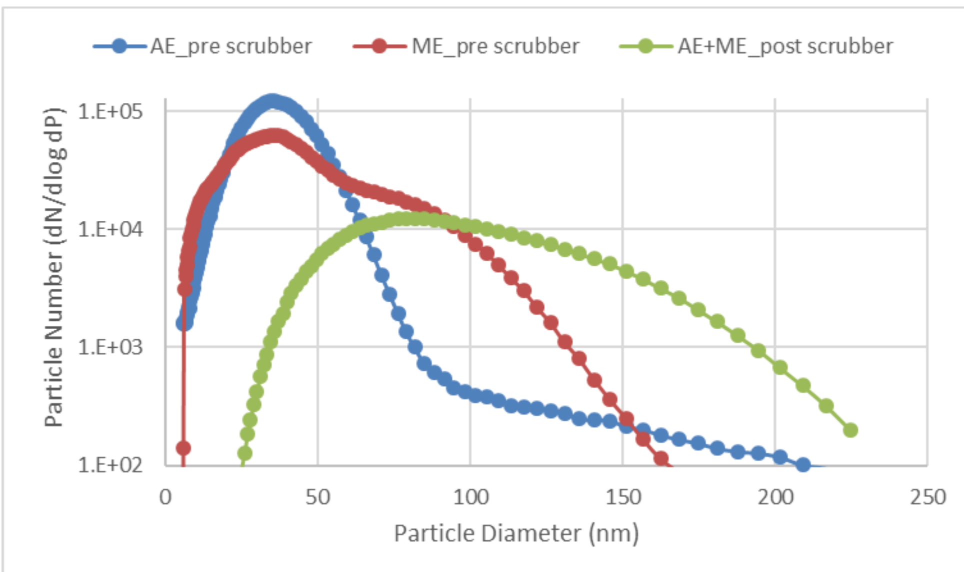


**Figure 3-8 Average number PSD for the pre and post-scrubber conditions: log.**

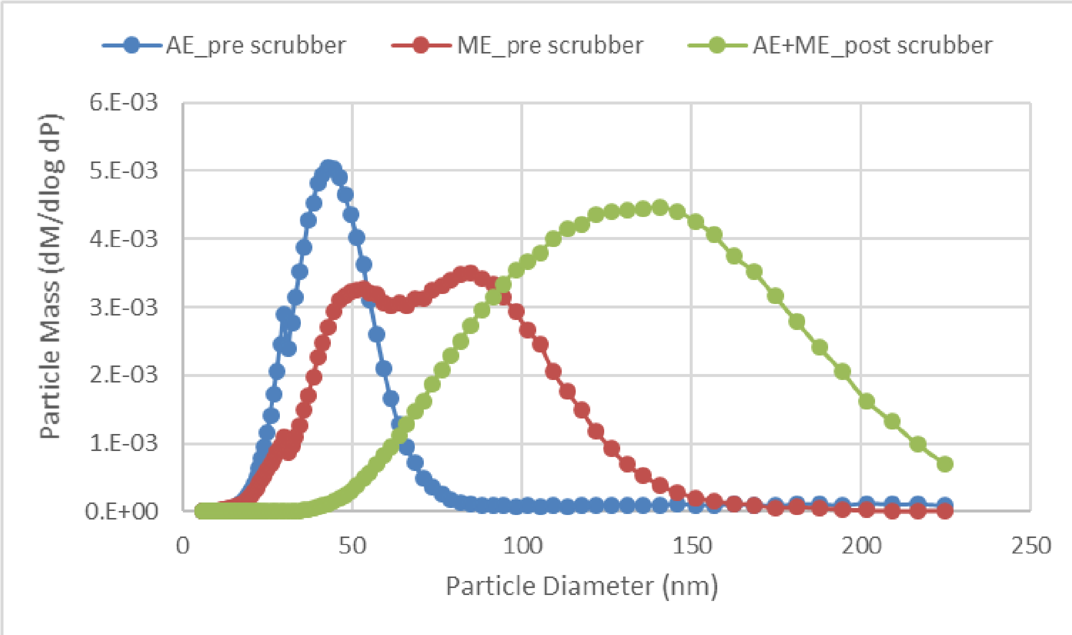


**Figure 3-9 Average mass PSD for the pre and post-scrubber measurements: linear plot**
[1] The figured is based on the calculation of the number based PSD by using Volume PSD_v as PSD_v=(4/3)*pi*r^3*PSD_n. For mass we assumed an average density of 1.2 g/cm[3].

## 3.5 Scrubber efficiency

The scrubber reduction efficiency for the regulated and selected PM composition species are provided in Table 3-1 with a sulfur analysis (g/kWHr) presented in Figure 3-10. The sulfur analysis considers the sulfur in the particle phase (hydrated sulfuric acid $H_2SO_4 6.65H_2O$)[2] and gaseous phase ($SO_2$). The largest percent reduction (97%) is for the gaseous $SO_2$ emissions as would be expected since scrubbers are designed for $SO_2$ reduction. The particle phase sulfur emissions varied from -2.5% to -28.2% (i.e., an increase in sulfur measurements after the scrubber). The increase in particle phase sulfur emissions post-scrubber was also found when testing other OGVs.

The organic PM reductions were fairly small compared to similar studies and ranged from 9% to -3% with an ISO weighted reduction of 6%. The organic PM reduction appears to be lower at higher loads, and higher at lower loads, which may be the result of lower residence times at higher load. The slight difference in $CO_2$ is not necessarily due to the scrubber, but due to measurement accuracy.

**Table 3-1 Percent reduction over baseline conditions (positive implies increase)**

| Mode | DR | Exh Flow | Engine Load | | Total Percent Change from baseline (pre-scrubber)/pre sample location | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | m3/hr | ME | AE | NOx | CO | CO2 | SO2 | PM2.5 | PM_OC | PM_S |
| 2 | 8 | 91,206 | 11.7 | 1.32 | -6.2% | 10.7% | -1.7% | 96.8% | 1.6% | 9.3% | -2.5% |
| 3 | 12 | 66,467 | 7.62 | 1.29 | -2.8% | 8.7% | -1.3% | 97.0% | -20.5% | 3.0% | -28.2% |
| 4 | 20 | 48,804 | 4.90 | 1.24 | -0.3% | -18.3% | -1.7% | 97.4% | -21.7% | -3.0% | -25.8% |
| ISO Wt | 10 | 82,160 | 10.23 | 1.30 | -4.6% | 5.4% | -1.6% | 96.9% | -4.2% | 6.1% | -8.6% |

[2] This is the level of hydration expected for typical filter exposure in a filter chamber. 40 CFR part 1065.1005 (f)(2)

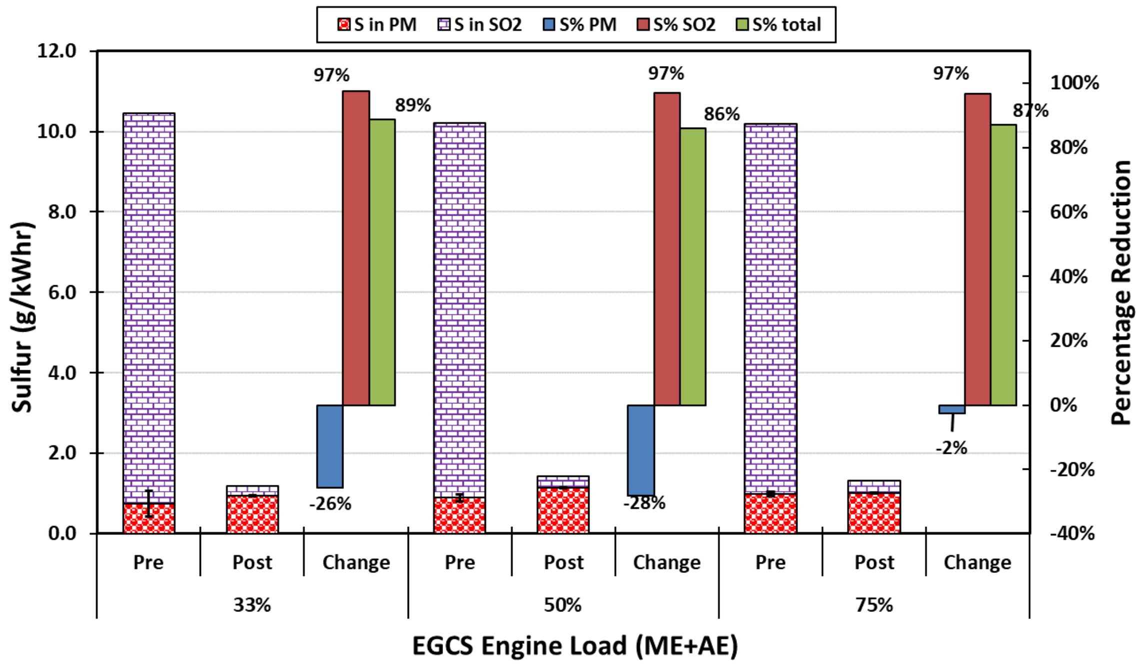


**Figure 3-10 Overall sulfur emissions (gas and particle phase) in g/kWhr**

Table 3-2 lists the BC percent reductions over the scrubber for the two methods evaluated. The BC scrubber reduction percentages varied between the methods and between the modes. The MSS and EC measurements showed a weighted BC reduction across the scrubber that varied from -12% (EC) to -5% (eBC_MSS). The weighted results compared well between the methods as well as from mode-to-mode. The changes for the EC method mode 4 (at 25% load) was -38% and for the eBC_MSS was -49% (both were negative implying an increase in BC emissions after the scrubber).

Previously, it was expected that the EC detection limits may be reached by the measurement methods. Although the EC method can detect down to 0.1 µg reliably, our tunnel blank measurements are around 0.5 µg. Additionally, EC/OC analysis could be impacted by the ratio of the material and low amount of EC present. Previous results with EC at less than 5% of the total PM mass and the EC mass less than 10 µg/filter suggested variable results. For these tests, the results were more consistent and the EC ranged from 5-6 µg/filter and was less than 5% of the total mass. It is unclear what may cause some EC/OC measurement to be more agreeable, but for these results the EC and eBC_MSS agree well.

In summary, BC appears to increase from the scrubber by around 5% using the MSS (eBC), and by around 12% using the EC method. Also, there is a clear trend of increasing BC emission reductions as the engine load increases, as has been reported previously by UCR.

**Table 3-2 BC scrubber efficiency results for all methods (with DG)**

| Mode | DR | Exh Flow | Engine Load | | Total Percent Change | | |
|---|---|---|---|---|---|---|---|
| | | m3/hr | ME | AE | EC | eBC_MSS | eBC_FSN |
| 2 | 8 | 43,635 | 12.5 | 0.90 | -2.1% | 10.1% | - |
| 3 | 12 | 31,394 | 8.28 | 0.90 | -22.5% | -14.7% | - |
| 4 | 20 | 2,698 | 0.00 | 0.79 | -38.5% | -49.2% | - |
| ISO Wt | 9 | 40,663 | 11.61 | 0.90 | -12.1% | -5.0% | - |

## 3.6 Scrubber sulfur balance

IMO regulations include caps on the sulfur content of fuel to 0.1% in ECAs. For vessels traveling from LA to Oakland, the majority of their operation is conducted within the ECA. Solutions to meet these low $SO_x$ emissions can be achieved with low sulfur fuels or other devices such scrubber systems designed to meet the equivalent of using 0.1% sulfur fuel in an ECA. This discussion compares the total sulfur balance to the IMO ECA fuel sulfur rule to see how well the tested scrubbers performed.

To perform this analysis, sulfur containing species in both gaseous and particle phases are considered. Figure 3-11 shows the pre-scrubber sulfur fraction (G and P), the post-scrubber gaseous sulfur contribution (G), and the combined gaseous plus particle (G+P) sulfur species for a total sulfur accounting. For each mode, the equivalent fuel sulfur percent was estimated at 0.08% at low load and 0.1% at high load, all of which are at or below the 0.1% ECA $SO_x$ requirement. The scrubber CEMS system, which only measures the gas phase sulfur species, reported an average $SO_2/CO_2$ ratio of ~2.4 which equates to a fuel sulfur level of 0.06% (ratio limit is 4.3). Both the UCR gaseous fuel sulfur measurement and the CEMS measurement are meeting the IMO requirement, but the CEMS is half of the UCR value. More investigation is required to help understand these differences, see Appendix D Figures D-8 through D-18 for details on the scrubber CEMS system.

When the particle phase sulfur species are included in the fuel balance we get a slightly higher equivalent sulfur balance. The post-scrubber total sulfur equivalence (P + G) ranged from 0.15% to 0.18% from low to high load. When the particle phase sulfate species are added to the gas phase species the total sulfur balance suggest the scrubber system is not as effective as the IMO ECA fuel sulfur rule and that particle phase sulfur emissions may be higher, as shown in Figure 3-11. It should also be noted that even though the combined sulfur balance exceeds the fuel sulfur rule, it does not mean the scrubber doesn't meet the ISO requirements, but it does show a possible discrepancy in the IMO definition. Research at UCR has also shown that some low sulfur HFO meeting the 0.1% sulfur rule show an increase in EC and OC emissions compared to HFO fuels, (Johnson et al, 2016). This suggests that more research is needed to understand the overall impact of the fuel sulfur rule as it is proposed.

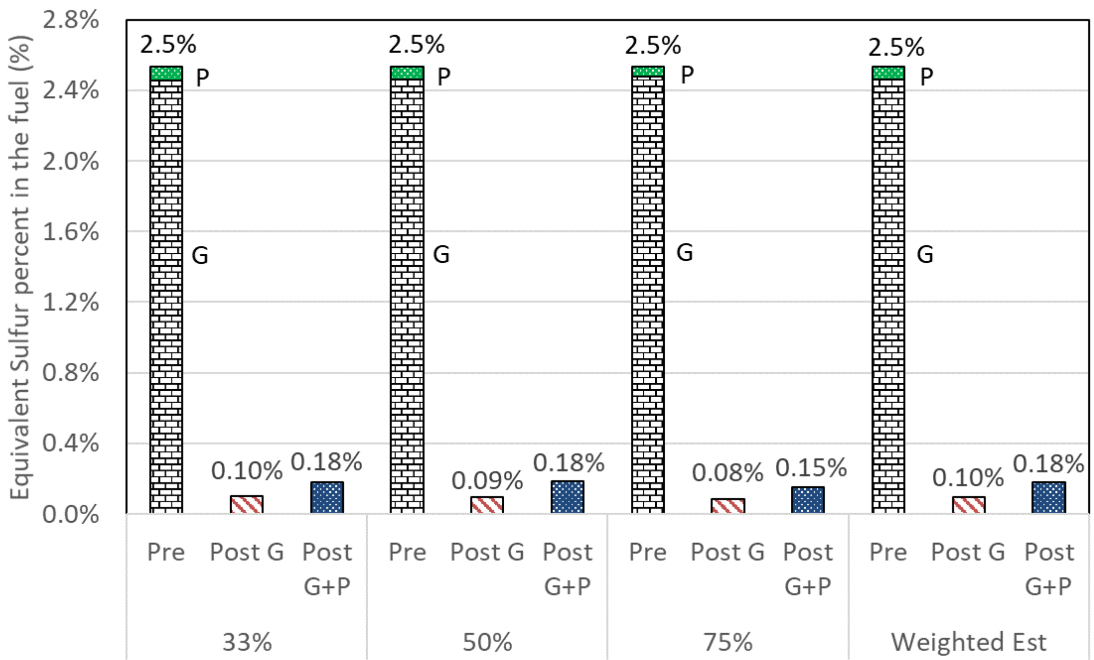


**Figure 3-11 Equivalent sulfur % in the test fuel (gas, gas plus particles)**

[1] This figure includes the gaseous $SO_2$ sulfur species and gaseous $SO_2$ plus the sulfate PM emissions species to estimate the sulfur percent equivalent fuel.

### 3.7 CEMS evaluation

Vessels equipped with scrubbers have implemented an onboard Continuous Emissions Monitoring System (CEMS) to verify the scrubber is meeting the compliance of the SO2/CO2 ratio of 4.3. The on board CEMS is an instrument that measures the in-situ exhaust plum CO2 and SO2 via Infrared (IR) spectroscopy methods, see Figure 3-12 and Appendix D. This data is then reported utilized to control the operation of the scrubber and alter the vessel operators. During testing the CEMS data was collected and compared against UCRs data.

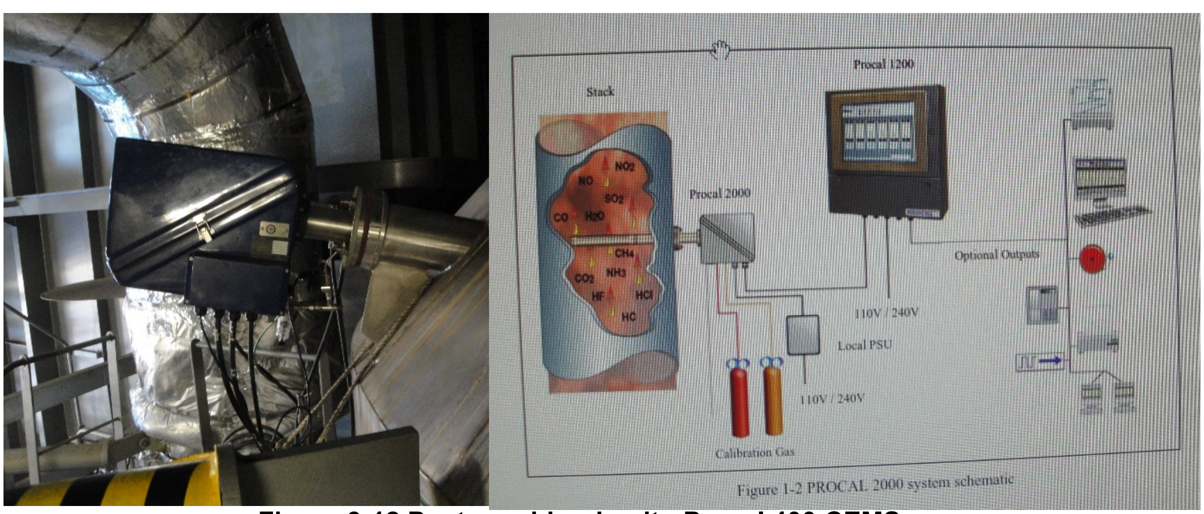


**Figure 3-12 Post-scrubber in-situ Procal 400 CEMS**

Figure 3-13 and Figure 3-14 show the difference in the UCR measured CO2 compared to ship CO2 for each of the test points collected by UCR. Figure 3-13 shows the points with the CEMS on the left axis and UCR PG350 on the right axis. Figure 3-14 shows a correlation figure of this data with the CEMS on the y-axis and UCR's PG350 on the x-axis. The slope is a factor of three higher for the CEMS which would suggest the SO2/CO2 ratio would be incorrect. It is unclear how this would impact the operation of the scrubber, but it is interesting to see this difference. Future scrubber tests need to include an evaluation of the CEMS, and if possible to perform a in-situ calibration of the on vessel SEMS with UCR's calibration bottles.

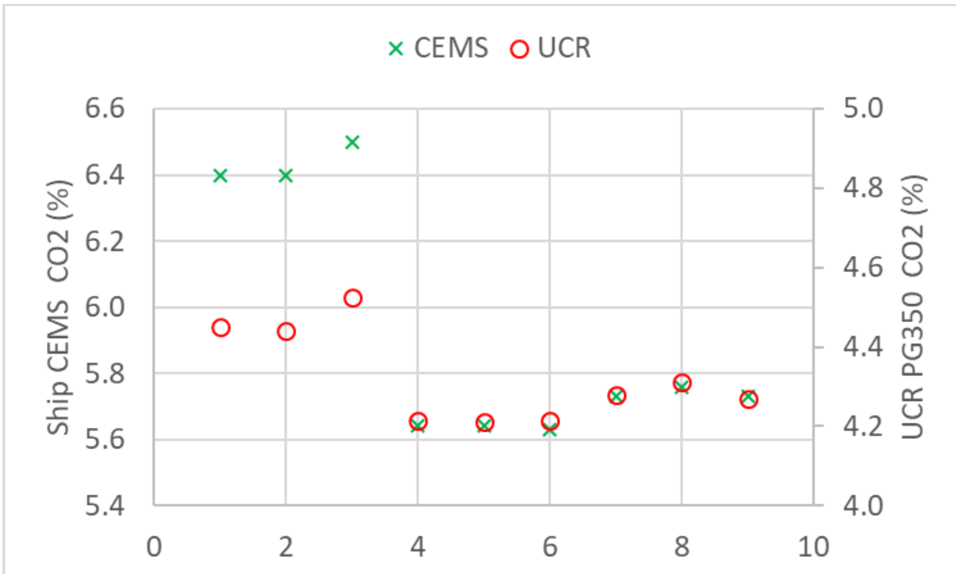


**Figure 3-13 $CO_2$ comparison between the UCR and the CEMS**

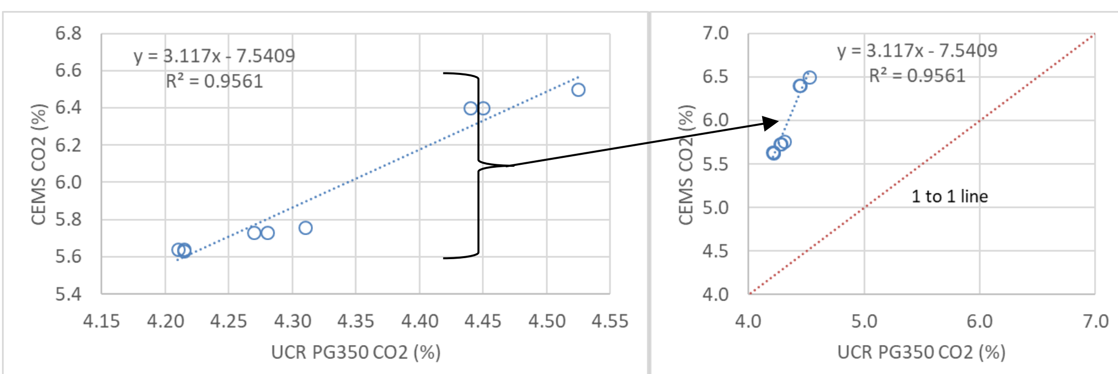


**Figure 3-14 $CO_2$ correlation between the UCR and the CEMS**

# Summary

Emissions measurements were made across an exhaust gas cleaning system for a main engine and a diesel generator on a cargo ship as it cruised from Los Angeles to Oakland, California. Testing followed the ISO-8178 E3 and D2 test cycles to determine the emissions rate of each engine for gaseous and particulate pollutants. Emissions were measured following ISO and CFR methods for gaseous, PM (total mass, elemental, and organic carbon species, sulfated PM) and PSD measurements. Upgrades were performed to meet EPA requested 1065 dilution ratios and filter temperatures on an exhaust that was cooled with sea water. Dilution ratios and filter temperatures as specified in 1065 were met during this testing.

Emissions measurements were also made of the combined main engine and DG exhaust before and after the scrubber at three load points that represented a combined scrubber load of 33%, 50%, and 75% load. The measured weighted emission reductions across the scrubber were high for $SO_2$ (97%), but PM tended to increase for most species and total mass.

A summary of the results for the scrubber testing is as follows:

- The emissions were stable for all days suggesting the results for this testing are representative of a properly operating OGV equipped with a scrubber.
- The ME pre-scrubber $NO_x$ emissions varied from 12 to 19.9 g/kWhr (weighted emissions of 14.2 g/kWhr), and the DG varied from 5.88 to 7.40 g/kWhr. These emission rates decreased at higher loads and are in good agreement with emission rates for other UCR studies
- The $PM_{2.5}$ pre- and post-scrubber emissions ranged from about 1.0 to 1.3 g/kWhr. The $PM_{2.5}$ emissions did not show a strong trend with respect to load. The PM composition was predominantly sulfate and agreed with the $PM_{2.5}$ measurement.
- The ME pre-scrubber composition was < 1% EC, ~ 14% OC, and 85% sulfate. The DG composition was around 5% EC to 45% OC and 50% sulfate.
- The combined BC emissions ranged from 0.007 to 0.022 g/kWhr over the different loads. The pre-scrubber DG only result varied from 0.018 to 0.145 g/kWhr and from 0.006 to 0.01 g/kWhr for the ME.
- The sulfate, total PM, and BC emissions were not reduced by the scrubber system. OC PM was the only PM fraction that decreased across the scrubber system.
- The scrubber provides significant reductions in $SO_2$ gaseous emissions of 97%. The gaseous reduction efficiency was sufficient to meet fuel sulfur requirements for scrubber systems. The $SO_2$ emission levels averaged around 0.28 g/kWhr, which is similar to levels seen for other OGVs operating on low sulfur fuels.
- The post-scrubber change in particle phase sulfur emissions varied from -2.5% to -28.2% (i.e., an increase in sulfur measurements after the scrubber). This has also been seen in tests of other OGVs equipped with scrubber systems.
- The gas phase equivalent fuel sulfur percent was estimated at 0.08% at low load and 0.1% at high load all of which are at or below the 0.1% ECA $SO_x$ requirement.

- The post-scrubber total sulfur equivalence (P + G) ranged from 0.15% to 0.18% from low to high load. This suggests a scrubber system will result in higher PM emissions than low sulfur MGO/MDO fuels.

## References

IMO International: IMO Marine Engine Regulations, http://www.dieselnet.com/standards/inter/imo.php

Berglen T.F., Berntsen T.K., Isaksen I.S.A., Sundet J.K. A global model of the coupled sulfur/oxidant chemistry in the troposphere: the sulfur cycle. Journal of Geophysical Research, 109 (2004), p. D19310

T. C. Bond, S. J. Doherty, D. W. Fahey, P. M. Forster, T. Berntsen, B. J. DeAngelo, M. G. Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, Bounding the role of black carbon in the climate system: A Scientific assessment, Journal of Geo. Res. Atm., VOL. 118, 1–173, doi:10.1002/jgrd.50171, 2013

Corbett J.J., Winebrake J.J., Green E.H., Kasibhatla P., Eyring V., Lauer A. Mortality from ship emissions: a global assessment Environmental Science and Technology, 41 (2007), pp. 8512–8518

Corbett J.J., Koehler H.W. Updated emissions from ocean shipping Journal of Geophysical Research: Atmospheres, 108 (2003)

Comer B., Ollmer, N., Mao, X., Roy B., and Rutherford D., 2017 Black Carbon Emissions and Fuel Use In Global Shipping 2015, Final report from ICCT, 2017

Dalsøren S. B. , Eide M. S. , Endresen Ø., Mjelde A. , Gravir G., and Isaksen I. S. A. Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports. Atmos. Chem. Phys., 9, 2171-2194, 2009

Endresen, Ø., Sørg̊ard, E., Behrens, H. L., and Brett, P. O.: A historical reconstruction of ships' fuel consumption and emissions, J. Geophys. Res., 112, D12301, doi:10.1029/2006JD007630, 2007

Endresen O, Bakke, J, Sorgardc E, Flatlandsmo Berglenb T, Holmvang P. Improved modelling of ship SO2 emissions-a fuel-based approach. Atmospheric Environment 2005, 39, 3621-3628.

Eyring, V., K̈ohler, H. W., van Aardenne, J., and Lauer, A.: Emissions from international shipping: 1. The last 50 years, J. Geophys. Res., 110, D17305, doi:10.1029/2004JD005619, 2005.

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, 1475090214543716.

Khan, M. Y.; Giordano, M.; Gutierrez, J.; Welch, W. A.; Asa-Awuku, A.; Miller, J. W.; Cocker, D. R., III, Benefits if Two Mitigation Strategies for Container Vessels: Cleaner Engines and Cleaner Fuels. Environ. Sci. Technol. 2012, 46, 5049−5056.

Johnson, K.C., Durbin, T.D., Cocker, D.R., JMiller, W., Bishnu, D.K., Maldonaldo, H., Moynahan, N., Ensfield, C., Laroo, C.A. 2009. On-road Comparisons of a Portable Emissions Measurement System with a Mobile Reference Laboratory for a Heavy-Duty diesel Vehicle. Atmospheric Environment. Vol. 43: p.2877-2833. (Refereed)

Johnson, K., Miller, W., Durbin, T., Jiang, Y., Karavalakis, G., Cocker, D., 2016, Black Carbon Measurement Methods and Emission Factors from Ship, Final Report submitted to the International Council on Clean Transportation, December 2016. (Refereed)

Kahn, Y., Johnson, K.C., Durbin, T., Cocker, D., Bishnu, D., Giannelli, R. 2012. Characterization of PM-PEMS for In-Use Measurements – Validation Testing for the PM-PEMS Measurement Allowance Program. Atmospheric Environment. p.311-318. 7p. (Refereed) https://doi.org/10.1016/j.atmosenv.2012.03.004

Lehtoranta K., Aakso-Saksa P., Murtonen T., Vesala H., Ntziachristos L., Rönkkö T., Karjalainen P., Kuittinen N., and Timonen H., Particulate Mass and Nonvolatile Particle Number Emissions from Marine Engines Using Low-Sulfur Fuels, Natural Gas or Scrubbers, Environental Science and Technology, 2019, 53, 3315-332

MARPOL (2017). MARPOL Consolidated Edition 2017. London: IMO.

Mikhail Sofiev, James J. Winebrake , Lasse Johansson, Edward W. Carr, Marje Prank, Joana Soares, Julius Vira, Rostislav Kouznetsov, Jukka-Pekka Jalkanen, and James J. Corbett, 2018 Cleaner fuels for ships provide public health benefits with climate tradeoffs, NATURE COMMUNICATIONS, (2018) 9:406

Smith, T. W. P. et al. Third IMO GHG Study 2014. (International Maritime Organization, London, UK, 2014).

United Nations Conference on Trade and Development (UNCTAD), Review of Maritime Transport 2015

United Nations Conference on Trade and Development (UNCTAD), Review of Maritime Transport 2017

Viana, M.; Hammingh, P.; Colette, A.; Querol, X.; Degraeuwe, B.; Vlieger, I. de; van Aardenne, J. Impact of Maritime Transport Emissions on Coastal Air Quality in Europe. *Atmos. Environ.* 2014, *90*, 96–105. https://doi.org/10.1016/J.ATMOSENV.2014.03.046

Winnes, H., & Fridell, E. (2009). Particle emissions from ships: dependence on fuel type. Journal of the Air & Waste Management Association, 59(12), 1391-1398.

# Appendix A – Sample Collection Methods

ISO-8178-1 [3] and ISO-8178-2 [4] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in ISO-8178- *Part 4: Test cycles for different engine applications*. The emission results represent the mass rate of emissions per unit of work accomplished. Specific emission factors are based on brake power measured at the crankshaft, the engine being equipped only with the standard auxiliaries necessary for its operation. Per ISO, auxiliary losses are <5 % of the maximum observed power. IMO ship pollution rules and measurement methods are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78 [5], and sets limits on $NO_x$ and $SO_x$ emissions from ship exhausts. The intent of this protocol was to conform as closely as practical to both the ISO and IMO standards.

## Gaseous and particulate emissions

A properly designed sampling system is essential for accurate collection of a representative sample from the exhaust and subsequent analysis. ISO points out that particulate must be collected in either a full flow or partial flow dilution system and UCR chose the partial flow dilution system as shown in Figure A-1.

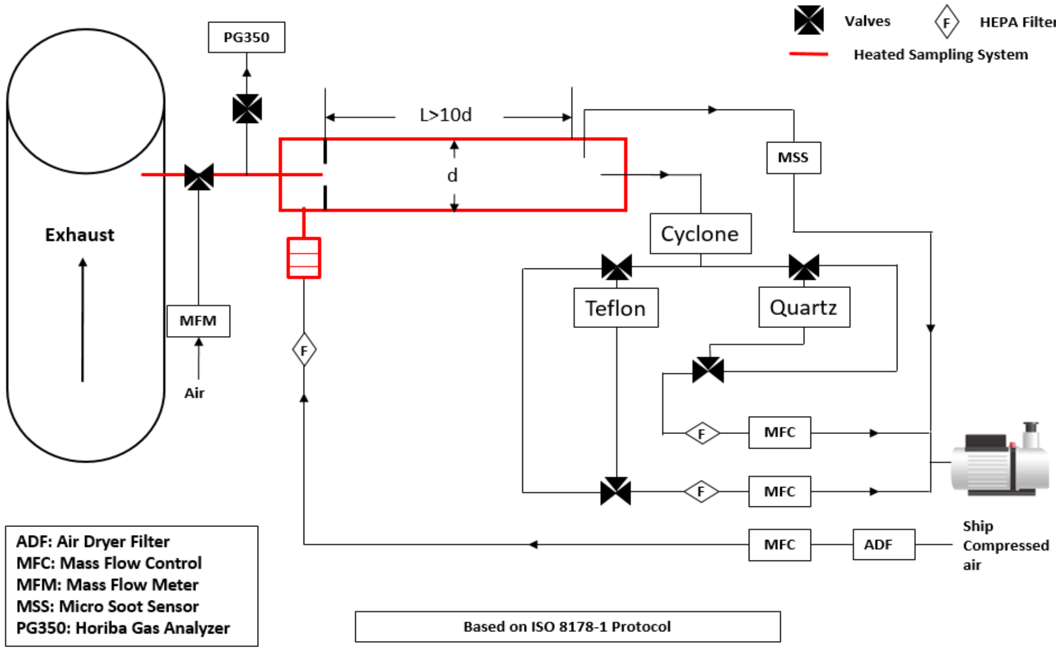


**Figure A-1 Partial flow dilution system**

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[3] International Standards Organization, IS0 8178-1, *Reciprocating internal combustion engines - Exhaust emission measurement -Part 1: Test-bed measurement of gaseous particulate exhaust emissions,* First edition 1996-08-l5

[4] International Standards Organization, IS0 8178-2, *Reciprocating internal combustion engines - Exhaust emission measurement -Part 2: Measurement of gaseous and particulate exhaust emissions at site,* First edition 1996-08-l5

[5] International Maritime Organization, *Annex VI of MARPOL 73/78 "Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*".

The flow in the dilution system eliminates water condensation in the dilution tunnel and sampling systems and maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions that the advantages of partial flow dilution systems can be lost to potential problems such as: losing particulates in the transfer tube, failing to take a representative sample from the engine exhaust and inaccurately determining the dilution ratio.

An overview of UCR's partial dilution system is shown in Figure A-2. Raw exhaust gas is transferred from the exhaust pipe (EP) through a sampling probe (SP) and the transfer tube (TT) to a dilution tunnel (DT) due to the negative pressure created by the venturi (VN) in DT. The gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the absolute temperature of the gas at the exit of TT. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. More detail on the key components is provided in Table A-1.

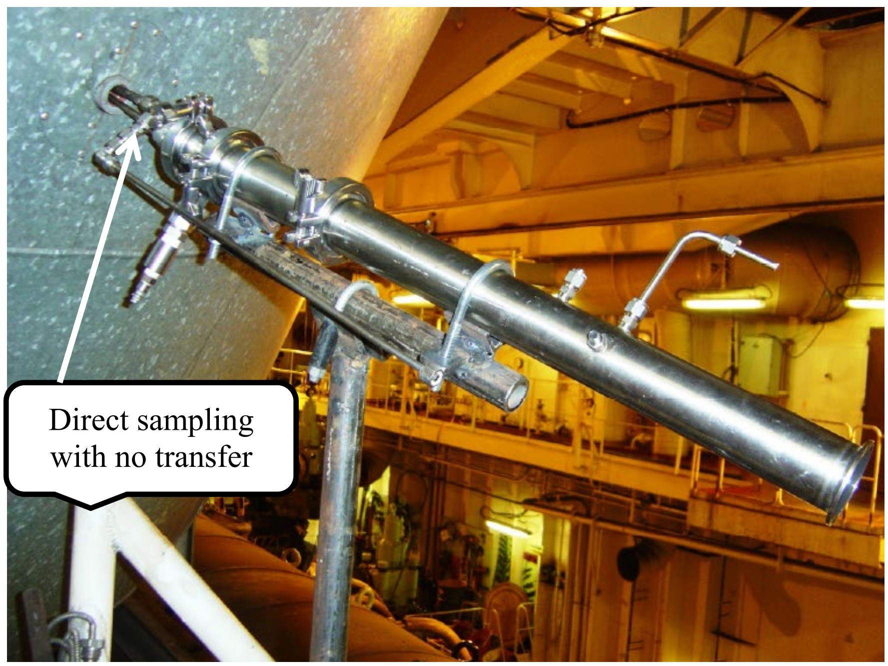



**Figure A-2 measurement layout on an engine exhaust stack**

**Dilution air system**

40 CFR Part 1065 recommends dilution air to be 20 to 30°C and ISO recommends 25 ±5°C. Both also recommend using filtered and charcoal scrubbed air to eliminate background hydrocarbons. The dilution air may be dehumidified. The system can be described as follows: The pressure is reduced to around 40 psig, a liquid knock-out vessel, desiccant to remove moisture with silica gel containing an indicator, hydrocarbon removal with activated charcoal, and a HEPA filter for the fine aerosols that might be present in the supply air. The silica gel and activated carbon are changed for each field campaign. Figure A-3 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit.

**Table A-1 Components of a sampling system: ISO criteria & UCR design**

| Section | Selected ISO and IMO criteria | UCR design |
|---|---|---|
| Exhaust Pipe (EP) | In the sampling section, the gas velocity is > 10 m/s, except at idle, and bends are minimized to reduce inertial deposition of PM. Sample collection of 10 pipe diameters of straight pipe upstream is recommended and performed where possible. For some tight configurations use good engineering judgment. | UCR follows the ISO recommendation, when practical. |
| Sampling Probe (SP) - | The minimum inside diameter is 4 mm and the probe is an open tube facing upstream on the exhaust pipe centerline. No IMO code. | UCR uses a stainless steel tube with diameter of 8mm placed near the center line. |
| Transfer Tube (TT) | • As short as possible and < 5 m in length;<br>• Equal to/greater than probe diameter & < 25 mm diameter;<br>• TTs insulated. For TTs > 1m, heat wall temperature to a minimum of 250°C or set for < 5% thermophoretic losses of PM. | UCR uses a transfer tube of 0.15 m (6 inches). Additionally the sample tube insertion length varies with stack diameter, but typically penetrates at least 10%, but not more than 50% of the stack diameter. |
| Dilution Tunnel (DT) | • shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions;<br>• shall be at least 75 mm inside diameter (ID) for the fractional sampling type, constructed of stainless steel with a thickness of > 1.5 mm. | UCR uses fractional sampling; stainless steel tunnel has an ID of 50mm and thickness of 1.5mm. |
| Venturi (VN) -- | The pressure drop across the venturi in the DT creates suction at the exit of the transfer tube TT and the gas flow rate through TT is basically proportional to the flow rate of the dilution air and pressure drop. | Venturi proprietary design provided by MAN B&W; provides turbulent mixing. |
| Exhaust Gas Analyzers (EGA) | One or several analyzers may be used to determine the concentrations. Calibration and accuracy for the analyzers are like those for measuring the gaseous emissions. | UCR uses a 5-gas analyzer meeting IMO/ISO specs |

**Figure A-3 Field processing unit for purifying dilution air in carrying case**

**Calculating the dilution ratio**

According to ISO-8178, "it is essential that the dilution ratio be determined very accurately" for a partial flow dilution system such as what UCR uses. The dilution ratio is simply calculated from measured gas concentrations of $CO_2$ and/or $NO_x$ in the raw exhaust gas, the diluted exhaust gas and the dilution air. UCR has found it useful to independently determine the dilution ratio from both $CO_2$ and $NO_x$ and compare the values to ensure that they are within ±10%. UCR's experience indicates the independently determined dilution ratios are usually within 5%. At systematic deviations within this range, the measured dilution ratio can be corrected, using the calculated dilution ratio. According to ISO, dilution air is set to obtain a maximum filter face temperature of <52°C and the dilution ratio shall be > 4.

**Dilution system integrity check**

ISO describes the necessity of measuring all flows accurately with traceable methods and provides a path and metric to quantifying the leakage in the analyzer circuits. UCR has adopted the leakage test and its metrics as a check for the dilution system. According to ISO the maximum allowable leakage rate on the vacuum side shall be 0.5 % of the in-use flow rate for the portion of the system being checked. Such a low leakage rate allows confidence in the integrity of the partial flow system and its dilution tunnel. Experience has taught UCR that the flow rate selected should be the lowest rate in the system under test.

**Measuring the gaseous emissions: CO, $CO_2$, HC, $NO_x$, $O_2$, $SO_2$**

Measurement of the concentration of the main gaseous constituents is one of the key activities in measuring emission factors. This section covers the ISO/IMO protocols and that used by UCR. For $SO_2$, ISO recommends and UCR concurs that the concentration of $SO_2$ is calculated based on the fact that 95+% of the fuel sulfur is converted to $SO_2$.

**Measuring gaseous emissions: ISO & IMO Criteria**

ISO specifies that either one or two sampling probes located in close proximity in the raw gas can be used and the sample split for different analyzers. However, in no case can condensation of exhaust components, including water and sulfuric acid, occur at any point of the analytical system. ISO specifies the analytical instruments for determining the gaseous concentration in either raw or diluted exhaust gases.

- Heated flame ionization detector (HFID) for the measurement of hydrocarbons;
- Non-dispersive infrared analyzer (NDIR) for the measurement of carbon monoxide and carbon dioxide;
- Heated chemiluminescent detector (HCLD) or equivalent for measurement of nitrogen oxides;
- Paramagnetic detector (PMD) or equivalent for measurement of oxygen.

ISO states the range of the analyzers shall accurately cover the anticipated concentration of the gases and recorded values between 15% and 100% of full scale. A calibration curve with five points is specified. However, with modern electronic recording devices, like a computer, ISO allows the range to be expanded with additional calibrations. ISO details instructions for establishing a calibration curve below 15%. In general, calibration curves must be < ±2 % of each calibration point and be < ±1 % of full scale zero.

ISO outlines their verification method. Each operating range is checked prior to analysis by using a zero gas and a span gas whose nominal value is more than 80 % of full scale of the measuring range. If, for the two points considered, the value found does not differ by more than ±4 % of full scale from the declared reference value, the adjustment parameters may be modified. If >4%, a new calibration curve is needed.

ISO, IMO, and CFR specify the operation of the HCLD. The efficiency of the converter used for the conversion of $NO_2$ into NO is tested prior to each calibration of the $NO_x$ analyzer. 40 CFR Part 1065 requires 95% and recommends 98%. The efficiency of the converter shall be >95 % and will be evaluated prior to testing.

ISO requires measurement of the effects of exhaust gases on the measured values of CO, $CO_2$, $NO_x$, and $O_2$. Interference can either be positive or negative. Positive interference occurs in NDIR and PMD instruments where the interfering gas gives rise to the same effect as the gas being measured, but to a lesser degree. Negative interference occurs in NDIR instruments due to the interfering gas broadening the absorption band of the measured gas, and in HCLD instruments due to the interfering gas quenching the radiation. Interference checks are recommended prior to an analyzer's initial use and after major service intervals.

**Measuring gaseous emissions: UCR design**

The concentrations of CO, $CO_2$, $NO_x$ and $O_2$ in the raw exhaust and in the dilution tunnel are measured with a Horiba PG-350 portable multi-gas analyzer, see Figure A-4. The PG-350 simultaneously measures five separate gas components with methods recommended by the ISO/IMO and USEPA. The signal output of the instrument is connected to a laptop computer through an RS-232C interface to continuously record measured values. Major features include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-350 was tested and verified under the U.S. EPA ETV program.

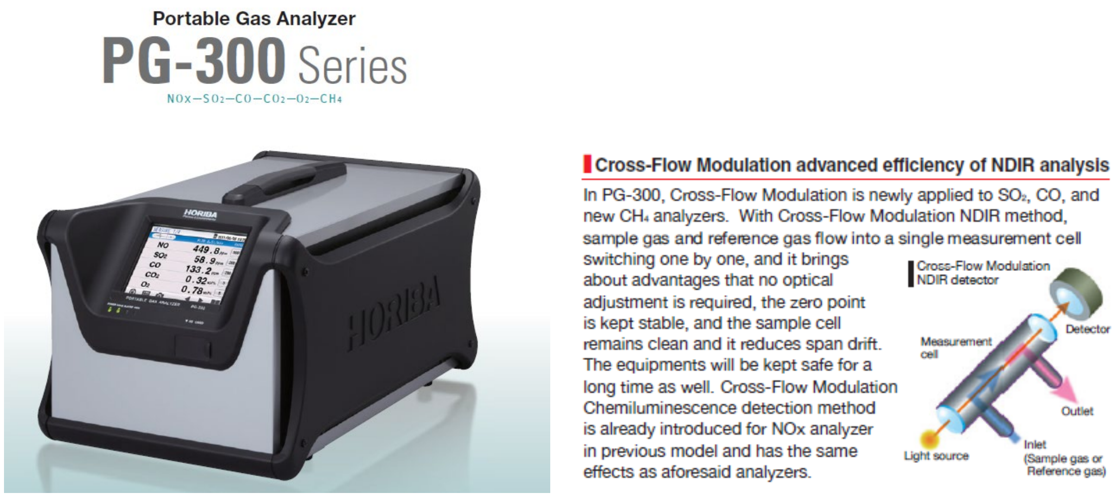



**Figure A-4 Gas analyzer setup with measurement cell description**

Details of the gases and the ranges for the Horiba instrument are shown in Table A-2. Note that the Horiba instrument measures sulfur oxides ($SO_2$); however, UCR follows the protocol in ISO which recommends calculation of the $SO_2$ level from the sulfur content of the fuel as the direct measurement for $SO_2$ is less precise than calculation. When an exhaust gas scrubber is present, UCR recommends measuring the $SO_2$ concentration after the scrubber since the fuel calculation approach will not be accurate due to scrubber $SO_2$ removal performance expectations.

**Table A-2 Detector method and concentration ranges for monitor**

| Component | Detector | Ranges |
|---|---|---|
| **Nitrogen Oxides (NOx)** | Heated Chemiluminescence Detector (HCLD) | 0-25, 50, 100, 250, 500, 1000, & 2500 ppmv |
| **Carbon Monoxide (CO)** | Non dispersive Infrared Absorption (NDIR). Cross flow modulation | 0-200, 500, 1000, 2000, & 5000 ppmv |
| **Carbon Dioxide ($CO_2$)** | Non dispersive Infrared Absorption (NDIR) | 0-5, 10, & 20 vol% |
| **Sulfur Dioxide ($SO_2$)** | Non dispersive Infrared Absorption (NDIR). Cross flow modulation | 0-200, 500, 1000, & 3000 ppmv |
| **Oxygen** | Zirconium oxide sensor | 0-5, 10, & 25 vol% |

For quality control, UCR carries out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases are a blend of several gases (super-blend) made to within 1% specifications. Experience has shown that the drift is within manufacturer specifications of ±1% full scale per day shown in Table A-3. The PG-250 meets the analyzer specifications in ISO-8178-1 Section 7.4 for repeatability, accuracy, noise, span drift, zero drift and gas drying. Maintenance recommendations are provided in Figure A-5

**Table A-3 Quality specifications for the Horiba PG-250**

| | |
|---|---|
| **Repeatability** | ±0.5% F.S. ($NO_x$: </= 100ppm range CO: </= 1,000ppm range)<br>±1.0% F. S. |
| **Linearity** | ±2.0% F.S. |
| **Drift** | ±1.0% F. S./day ($SO_2$: ±2.0% F.S./day) |

## Replacement parts

Replacement part intervals assume 8 hours of operation per day.
Replacement interval may be more frequent depending on measurement gas conditions and use conditions.

[Consumable Items]

| Name | Replace Every (general guideline) | Notes |
|---|---|---|
| Mist catcher | 3 months | MC-025 |
| Scrubber | 3 months | For reference line |
| Air filter element | 2 weeks | For reference line |

[Replacement Parts]

| Name | Replace Every (general guideline) | Notes |
|---|---|---|
| Pump | 1 year | Replace when broken |
| NOx converter catalyst | 1 year | For NOx analyzer* |
| Zero gas purifier unit catalyst | 1 year | * |
| Ozone generator | 1 year | For NOx analyzer* |
| Deozonizer | 1 year | For NOx analyzer* |
| CR2032 battery | 5 years | For clock backup |
| Galvanic $O_2$ cell | 1 year | Replace when broken* |

* Differs depending on model

**Figure A-5 Gas analyzer replacement parts and maintenance**

**Measuring the particulate matter (PM) emissions**

ISO-8178-1 defines particulates as any material collected on a specified filter medium after diluting exhaust gases with clean, filtered air at a temperature of ≤ 52ºC (40 CFR Part 1065 is 47±5 °C), as measured at a point immediately upstream of the PM filter. The particulate consists of primarily carbon, condensed hydrocarbons, sulfates, associated water, and ash. Measuring particulates requires a dilution system and UCR selected a partial flow dilution system. The dilution system design completely eliminates water condensation in the dilution/sampling systems and maintains the temperature of the diluted exhaust gas at < 52°C immediately upstream of the filter holders (and is typically below 47°C also). IMO does not offer a protocol for measuring PM and thus a combination of ISO and CFR practices are adopted. A comparison of the ISO and UCR practices for sampling PM is shown in Table A-4.

**Table A-4 Measuring particulate by ISO and UCR methods**

| | ISO | UCR |
|---|---|---|
| Dilution tunnel | Either full or partial flow | Partial flow |
| Tunnel & sampling system | Electrically conductive | Same |
| Pretreatment | None | Cyclone, removes >2.5µm |
| Filter material | PTFE coated glass fiber | Teflon (TFE) |
| Filter size, mm | 47 (37mm stain diameter) | Same |
| Number of filters in series | Two | One |
| Number of filters in parallel | Only single filter | Two; 1 TFE & 1 Quartz |
| Number of filters per mode | Single or multiple | Single is typical unless looking at artifacts |
| Filter face temp. °C | ≤ 52 | Same |
| Filter face velocity, cm/sec | 35 to 80. | ~33 |
| Pressure drop, kPa | For test <25 | Same |
| Filter loading, µg | >500 | 500-1,000 + water w/sulfate, post PM control ~ 100 |
| Weighing chamber | 22±3°C & RH= 45%± 8 | 22±1 °C & dewpoint of 9.5 °C±1°C (typically < ±0.6°C) |
| Analytical balance, LDL µg | 10 | LDL = 3 and resolution 0.1 |
| Flow measurement | Traceable method | Same |
| Flow calibration, months | < 3months | Every campaign |

**Sulfur content.** According to ISO, particulates measured using IS0 8178 are "conclusively proven" to be effective for fuel sulfur levels up to 0.8%. UCR is often faced with measuring PM for fuels with sulfur content exceeding 0.8% and has adopted the 40 CFR Part 1065 sampling methodologies as no other method is prescribed for fuels with a higher sulfur content.

**Calculating exhaust flow rates**

The calculated emission factor requires the measurement of the engine's exhaust flow rate. The exhaust gas flow can be determined by the following methods:

1. Direct Measurement Method
2. Carbon Balance Method
3. Air and Fuel Measurement Method
4. Air Pump method

*Method 1: Direct Measurement of Exhaust*
Actual exhaust mass flow rate can be determined from the exhaust velocity, cross sectional area of the stack, and moisture and pressure measurements. The direct measurement method is a difficult technique, and precautions must be taken to minimize measurement errors. Details of the direct measurement method are provided in ISO 5167-1.

*Method 2(a)-Carbon Balance*
Carbon Balance is used to calculate the exhaust mass flow based on the measurement of fuel consumption and the exhaust gas concentrations with regard to the fuel characteristics. The method given is only valid for fuels without oxygen and nitrogen content, based on procedures used for EPA and ECE calculations. Detailed calculation steps of the Carbon Balance method are provided in annex A of ISO-8178-1. Basically: In…lbs fuel/time * wt% carbon * 44/12 → input of grams CO2 per time Out… vol % CO2 * (grams exhaust/time * 1/density exhaust) → exhaust CO2 per time
Note that the density = (mole wt*P)/(R* Temp) where P, T are at the analyzer conditions. For highly diluted exhaust, M ~ of the atmosphere.

*Method 2(b)-Universal Carbon/Oxygen balance*
The Universal Carbon/Oxygen Balance is used for the calculation of the exhaust mass flow. This method can be used when the fuel consumption is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, 0, N in known proportions. Detailed calculation steps of Carbon/Oxygen Balance method is provided in annex A of ISO-8178-1.

*Method 3-Air and Fuel Measurement Method*
This involves measurement of the air flow and the fuel flow. The calculation of the exhaust gas flow is provided in Section 7.2 of ISO-8178-1.

*Method 4-Air Pump Method*
Exhaust flow rate is calculated by assuming the engine is an air pump, meaning that the exhaust flow is equal to the intake air flow. The flow rate is determined from the overall engine displacement, and rpm; corrected for temperature and pressure of the inlet air and pumping efficiency. In the case of turbocharged engines, this is the boost pressure and intake manifold temperature. This method should not be used for diesel engines equipped with additional air input for cylinder exhaust discharge, called purge or scavenger air, unless the additional flow rate is known or can be determined.

**Added comments about UCR's measurement of PM**
In the field UCR uses a raw particulate sampling probe fitted close to and upstream of the raw gaseous sample probe and directs the PM sample to the dilution tunnel. There are two gas streams leaving the dilution tunnel; the major flow vented outside the tunnel and the minor flow directed

to a cyclone separator, sized to remove particles >2.5um. The line leaving the cyclone separator is split into two lines; each line has a 47 mm Gelman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. UCR simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes the quartz filters utilizing the NIOSH or IMPROVE methods. UCR recommends the IMPROVE method over the NIOSH.

Briefly, total PM is collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflon filters and weighed using a Mettler Toledo UMX2 microbalance with a 0.1 µg resolution. Before and after collection, the filters are conditioned for 24 hours in an environmentally controlled room (22±1 °C and dewpoint of 9.5 °C) and weighed daily until two consecutive weight measurements are within 3 µg or 2%. It is important to note that the simultaneous collection of PM on quartz and Teflo™ filters provides a comparative check of PM mass measured by two independent methods for measuring PM mass.

Sulfur in the fuel produces $SO_2$ in the combustion process and some of the $SO_2$ becomes $SO_3$ in the exhaust and subsequently produces $H_2SO4 \bullet 6H_2O$ which is collected on the Teflon filter paper. After the final weights for the particulate laden Teflon filters have been determined a portion of the filter is punched out, extracted with High Performance Liquid Chromatography grade water and isopropyl alcohol and analyzed for sulfate ions by ion chromatography.

**Measuring real-time particulate matter (PM) emissions-DustTrak 8520**

In addition to the filter-based PM mass measurements, UCR uses a Nephelometer (TSI DustTrak 8520) for continuous measurements of steady-state and transient data, see Figure A-6. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout and has a built-in data logger. It measures light scattered (90 degree light scattering at 780nm near-infrared) by aerosol introduced into a sample chamber and displays the measured mass density in units of mg/m$^3$. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some question the accuracy of PM mass measurements. However, UCR always references the DustTrak results to filter based measurements and this approach has shown that mass scattering efficiencies for both on-road diesel exhaust and ambient fine particles have values around 3m$^2$/g.


**Figure A-6 Picture of TSI DustTrak**

**Measuring Non-Regulated Gaseous Emissions**

Neither ISO nor IMO provide a protocol for sampling and analyzing non-regulated emissions. UCR uses peer reviewed methods adapted to their PM dilution tunnel. The methods rely on added media to selectively collect hydrocarbons and PM fractions during the sampling process for subsequent off-line analysis. A secondary dilution is constructed to capture real time PM, see Figure A-7.

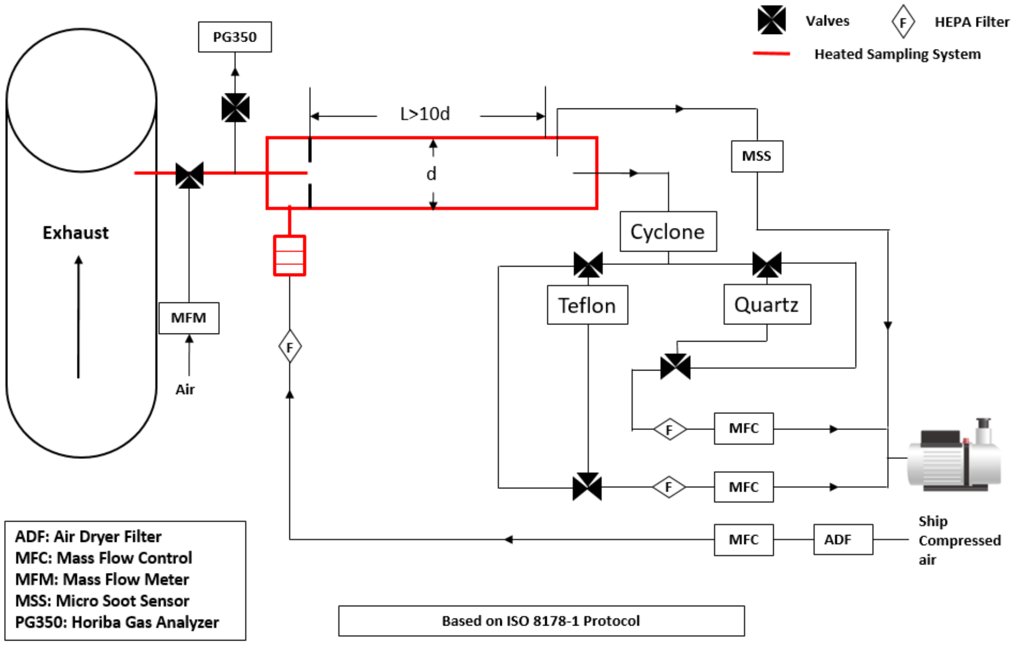



**Figure A-7 Extended setup of the PFDS for non-regulated emissions**

# Appendix B – Quality Control

**Pre-test calibrations**

Prior to departing from UCR all systems will be verified and cleaned for the testing campaign. This included all instruments used during this testing project. Sample filters are checked and replaced if necessary.

**On-site calibrations**

Pre- and post-test calibrations will be performed on the gaseous analyzer using NIST traceable calibration bottles. Dilution ratio was controlled and monitored with real time mass flow control. Hourly zero checks were performed with each of the real time PM instruments. Leak checks were performed for the total $PM_{2.5}$ system prior testing for each setup.

**Post-test and data validation**

Post-test evaluation includes verifying consistent dilution ratios between points, and verifying brake specific fuel consumption with reported manufacturer numbers. Typically this involves corresponding with the engine manufacturer to discuss the results on an emissions basis of interest. If the brake specific fuel consumption results are within reason this suggests that the load and mass of emissions measured are reasonable and representative.

The figure below (Figure B-1) is a chain of custody form. This is the form used to track filter weights from the test to the laboratory. One form for the filter weights, EC/OC, fuel sample, and sulfate analysis exists. This is just an example of media tracking that is used.

Figure B-2 is an example of UCR certified calibration bottles used for testing. Prior to using a new bottle the old one is verified with the new one as bottles can incorrect in their stated value. It is rare, but can happen.

**CE-CERT**

College of Engineering: Center for Environmental Research and Technology

**Analytical Laboratory**
University of California, Riverside
Data Results For TEFLON Filters

**Project Name: Original AEP River Operations - Kentuck** **Project Fund #:**
**PI/Contact: Wayne Miller** **Send Results: Nick Gysel**

| Sample ID | Serial ID | Date Received | Initial Weight (mg/filter) | Final Weight (mg/filter) | NET Weight (mg/filter) | Initials | COMMENTS |
|---|---|---|---|---|---|---|---|
| AT120473 | n/a | 2/x/2013 | 191.2060 | 192.6972 | 1.4912 | MV | |
| AT120474 | n/a | 2/x/2013 | 189.2139 | 191.2111 | 1.9972 | MV | |
| AT120475 | n/a | 2/x/2013 | 194.4568 | 196.2289 | 1.7721 | MV | |
| AT120476 | n/a | 2/x/2013 | 190.1723 | 191.7284 | 1.5561 | MV | |
| AT120477 | n/a | 2/x/2013 | 153.2872 | 154.4464 | 1.1592 | MV | |
| AT120478 | n/a | 2/x/2013 | 187.4435 | 188.9519 | 1.5084 | MV | |
| AT120479 | n/a | 2/x/2013 | 182.9071 | 184.0064 | 1.0993 | MV | |
| AT120481 | n/a | 2/x/2013 | 178.7453 | 179.3674 | 0.6221 | MV | |
| AT120482 | n/a | 2/x/2013 | 165.5829 | 166.2499 | 0.6670 | MV | |

**Figure B-1 Sample chain of custody form**

## CERTIFICATE OF ANALYSIS

***Primary Standard***

| Component | Requested Concentration | Certified Concentration | Analytical Principle | Analytical Accuracy |
|---|---|---|---|---|
| **Carbon dioxide** | **12 %** | **11.76 %** | **L** | **± 1%** |
| **Carbon monoxide** | **500 ppm** | **501 ppm** | **L** | **± 1%** |
| **Nitric oxide** | **2000 ppm** | **1929 ppm** | **U** | **± 1%** |
| **Propane** | **500 ppm** | **515 ppm** | **Q** | **± 1%** |
| **Nitrogen** | **balance** | **balance** | | |

Analytical Instruments: **Horiba Instruments Inc.~VIA-510~NDIR~Non-dispersive Infrared**
**Thermo Environmental~42i~Nitric Oxide Analyzer~Chemiluminescence**
**Horiba Instruments Inc.~FIA-510~THC- Total Hydrocarbon Analyzer~FID - Flame Ionization Detector**

Cylinder Style: **AS**
Cylinder Pressure @70F: **2000 psig**
Cylinder Volume: **140 ft3**
Valve Outlet Connection: **CGA-660**
Cylinder No(s). **CC92665**
Comments: **[NOx] = 1947 ppm for reference only.**
**All values not valid below 150 psig.**

Filling Method: **Gravimetric**
Date of Fill: **10/31/2012**
Expiration Date: **11/06/2014**

Analyst: **Chas Manning**

Approved Signer: **Nelson Ma**

**Figure B-2 Sample Protocol Gas Analysis**

# Appendix C –Test Modes and Load Estimates

## Test cycles and fuels for different engine applications

Heavy duty engines for non-road use are made in a much wider range of power output and used in more applications than engines for on-road use. The objective of IS0 8178[6] is to provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. ISO-81784 specifies the test cycles while measuring the gaseous and particulate exhaust emissions from reciprocating internal combustion engines coupled to a dynamometer or at the site. The tests are carried out under steady-state operation using test cycles which are representative of given applications. Standard terms and definitions are utilized, see Table C-1.

**Table C-1 Definitions used throughout ISO-8178**

| | |
|---|---|
| **Test cycle** | A sequence of engine test modes each with defined speed, torque and weighting factor, where the weighting factors only apply if the test results are expressed in g/kWh. |
| **Preconditioning the engine** | 1) Warming the engine at the rated power to stabilize the engine parameters and protect the measurement against deposits in the exhaust system.<br>2) Period between test modes which has been included to minimize point-to-point influences. |
| **Mode** | An engine operating point characterized by a speed and a torque. |
| **Mode length** | The time between leaving the speed and/or torque of the previous mode or the preconditioning phase and the beginning of the following mode. It includes the time during which speed and/or torque are changed and the stabilization at the beginning of each mode. |
| **Rated speed** | Speed declared by engine manufacturer where the rated power is delivered. |
| **Intermediate speed** | Speed declared by the manufacturer, taking into account the requirements of ISO-8178 clause 6. |

## Intermediate speed

For engines designed to operate over a speed range on a full-load torque curve, the intermediate speed shall be the maximum torque speed if it occurs between 60% and 75% of rated speed. If the maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed. If the maximum torque speed is greater than 75% of the rated speed then the intermediate speed shall be 75% of rated speed.

The intermediate speed will typically be between 60% and 70% of the maximum rated speed for engines not designed to operate over a speed range on the full-load torque curve at steady state

[1]International Standards Organization, IS0 8178-4*, Reciprocating internal combustion engines - Exhaust emission measurement - Part 4: Test cycles for different engine applications,* First edition IS0 8178-4:1996(E)

conditions. Intermediate speeds for engines used to propel vessels with a fixed propeller are defined based on that application.

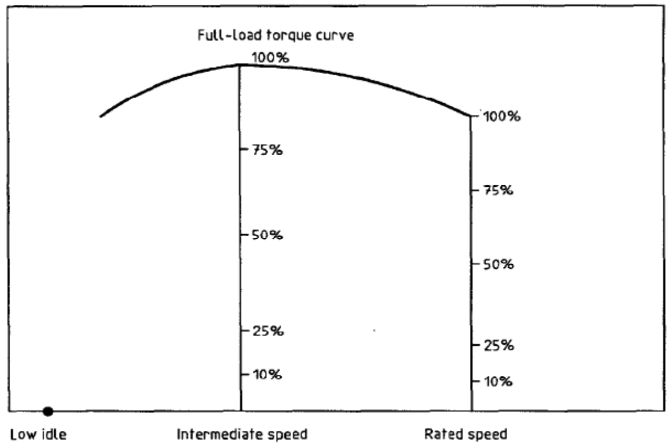



**Figure C-1 Torque as a Function of Engine Speed**

## Engine torque curves and test cycles

The percentage of torque figures given in the test cycles and Figure C-1 represent the ratio of the required torque to the maximum possible torque at the test speed. For marine test cycle E3, the power figures are percentage values of the maximum rated power at the rated speed as this cycle is based on a theoretical propeller characteristic curve for vessels driven by heavy duty engines. For marine test cycle E4 the torque figures are percentage values of the torque at rated power based on the theoretical propeller characteristic curve representing typical pleasure craft spark ignited engine operation. For marine cycle E5 the power figures are percentage values of the maximum rated power at the rated speed based on a theoretical propeller curve for vessels of less than 24 m in length driven by diesel engines. Figure C-2 shows the two representative curves.

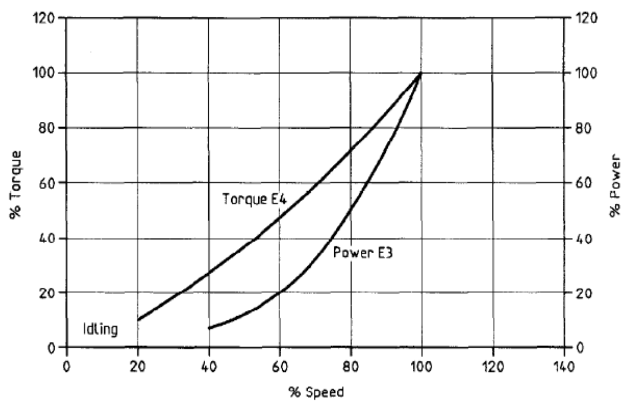



**Figure C-2 Examples of Power Scales**

## Modes and weighting factors for test cycles

Most test cycles are derived from the 13-mode steady state test cycle (UN-ECE R49). Apart from the test modes of cycles E3, E4 and E5, which are calculated from propeller curves, the test modes of the other cycles can be combined into a universal cycle (B) with emissions values calculated using the appropriate weighting factors, see Table C-2. Each test shall be performed in the given sequence with a minimum test mode length of 5 minutes or enough to collect sufficient particulate sample mass. The mode length shall be recorded and reported and the gaseous exhaust emission concentration values shall be measured and recorded for the last 3 min of the mode.

**Table C-2 Combined Table of Modes and Weighting Factors**

| **B-Type mode number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Torque** | 100 | 75 | 50 | 25 | 10 | 100 | 75 | 50 | 25 | 10 | 0 |
| **Speed** | Rated speed | | | | | Intermediate speed | | | | | Low idle |
| **Off-road vehicles** | | | | | | | | | | | |
| Cycle C1 | 0,15 | 0,15 | 0,15 | | 0,1 | 0,1 | 0,1 | 0,1 | | | 0,15 |
| Cycle C2 | | | | 0,06 | | 0,02 | 0,05 | 0,32 | 0,3 | 0,1 | 0,15 |
| **Constant speed** | | | | | | | | | | | |
| Cycle D1 | 0,3 | 0,5 | 0,2 | | | | | | | | |
| Cycle D2 | 0,05 | 0,25 | 0,3 | 0,3 | 0,1 | | | | | | |
| **Locomotives** | | | | | | | | | | | |
| Cycle F | 0,25 | | | | | | | 0,15 | | | 0,6 |
| **Utility, lawn and garden** | | | | | | | | | | | |
| Cycle G1 | | | | | | 0,09 | 0,2 | 0,29 | 0,3 | 0,07 | 0,05 |
| Cycle G2 | 0,09 | 0,2 | 0,29 | 0,3 | 0,07 | | | | | | 0,05 |
| Cycle G3 | 0,9 | | | | | | | | | | 0,1 |
| **Marine application** | | | | | | | | | | | |
| Cycle E1 | 0,08 | 0,11 | | | | | 0,19 | 0,32 | | | 0,3 |
| Cycle E2 | 0,2 | 0,5 | 0,15 | 0,15 | | | | | | | |

| **Marine application propeller law** | | | | | |
|---|---|---|---|---|---|
| **Mode number E3** | **1** | **2** | **3** | **4** | |
| **Power** (%) | 100 | 75 | 50 | 25 | |
| **Speed** (%) | 100 | 91 | 80 | 63 | |
| **Weighting factor** | 0,2 | 0,5 | 0,15 | 0,15 | |
| **Mode number E4** | **1** | **2** | **3** | **4** | **5** |
| **Speed** (%) | 100 | 80 | 60 | 40 | Idle |
| **Torque** (%) | 100 | 71,6 | 46,5 | 25,3 | 0 |
| **Weighting factor** | 0,06 | 0,14 | 0,15 | 0,25 | 0,4 |
| **Mode number E5** | **1** | **2** | **3** | **4** | **5** |
| **Power** (%) | 100 | 75 | 50 | 25 | 0 |
| **Speed** (%) | 100 | 91 | 80 | 63 | Idle |
| **Weighting factor** | 0,08 | 0,13 | 0,17 | 0,32 | 0,3 |

Cycle C1 (also known as the Non-Road Steady Cycle NRSC) and C2 are typically used for off-road vehicles and industrial equipment such as yard tractors and air compressors (C1 for diesel and C2 for spark ignition). D1 and D2 are used for constant speed engines such as generators (marine or land based) and power plants. D1 is for power plants and irrigation pumps, but D2 is for generators and other. The D2 cycle is typically used for marine auxiliary electrical generation. The "E" cycles are for marine application. E1 and E5 are for diesel engines craft less than 24 meters, E2 is for constant speed propulsion (variable prop applications), E3 is for large marine direct drive engines.

**Test fuels**

Fuel characteristics influence engine emissions so ISO-8178-1 provides guidance on the characteristics of the test fuel. Where fuels designated as reference fuels in IS0 8178-5 are used, the reference code and the analysis of the fuel shall be provided. For all other fuels the characteristics to be recorded are those listed in the appropriate universal data sheets in IS0 8178-5. The fuel temperature shall be in accordance with the manufacturer's recommendations. The fuel temperature shall be measured at the inlet to the fuel injection pump or as specified by the manufacturer, and the location of measurement recorded. The selection of the fuel for the test depends on the purpose of the test. Unless otherwise agreed by the parties the fuel shall be selected in accordance with Table C-3.

**Table C-3 Test fuels**

| Test purpose | Interested parties | Fuel selection |
|---|---|---|
| Type approval (Certification) | 1. Certification body<br>2. Manufacturer or supplier | Reference fuel, if one is defined<br>Commercial fuel if no reference fuel is defined |
| Acceptance test | 1. Manufacturer or supplier<br>2. Customer or inspector | Commercial fuel as specified by the manufacturer[1)] |
| Research/development | One or more of:<br>manufacturer, research organization, fuel and lubricant supplier, etc. | To suit the purpose of the test |

1) Customers and inspectors should note that the emission tests carried out using commercial fuel will not necessarily comply with limits specified when using reference fuels.

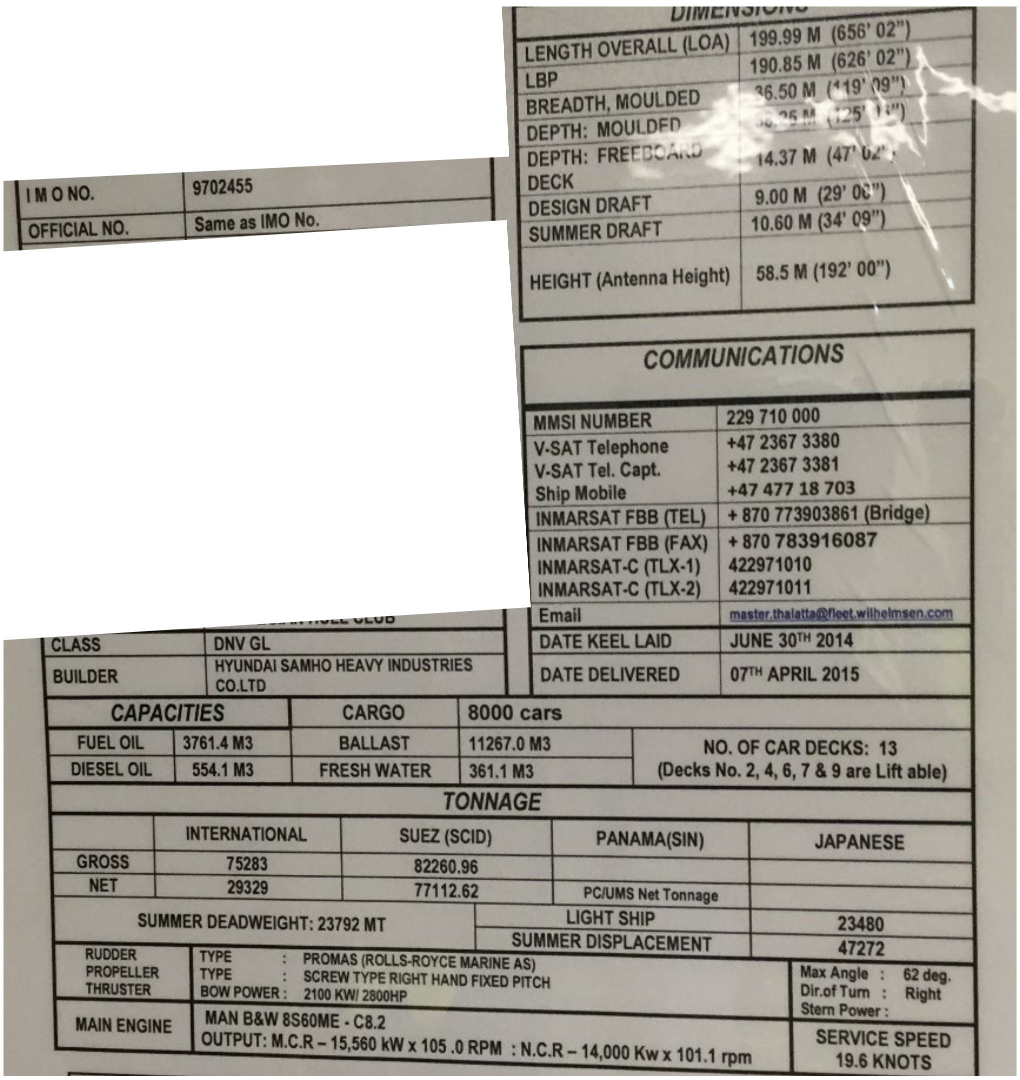
When a suitable reference fuel is not available, a fuel with properties very close to the reference fuel may be used. The characteristics of the fuel shall be declared.

# Appendix D –Vessel Details and Fuel Records

This Appendix includes vessel and fuel records 1) Maintenance Records, 2) Fuel Analysis, 3) Engine Screen Shots, and 4) scrubber Screen Shots. These records were recorded during testing.

**1: Engine maintenance records**

These records were collected only once during vessel testing to document the status of the ME and both DGs utilized for the emissions testing. The log book contained the current total recoded generator hours and the screen shows the individual maintenance specific records and plans for repairs. Figure D-1 shows the ship particulars.



| | |
|---|---|
| I M O NO. | 9702455 |
| OFFICIAL NO. | Same as IMO No. |

DIMENSIONS

| | |
|---|---|
| LENGTH OVERALL (LOA) | 199.99 M (656' 02") |
| LBP | 190.85 M (626' 02") |
| BREADTH, MOULDED | 36.50 M (119' 09") |
| DEPTH: MOULDED | [illegible] |
| DEPTH: FREEBOARD DECK | 14.37 M (47' 02") |
| DESIGN DRAFT | 9.00 M (29' 06") |
| SUMMER DRAFT | 10.60 M (34' 09") |
| HEIGHT (Antenna Height) | 58.5 M (192' 00") |

COMMUNICATIONS

| | |
|---|---|
| MMSI NUMBER | 229 710 000 |
| V-SAT Telephone | +47 2367 3380 |
| V-SAT Tel. Capt. | +47 2367 3381 |
| Ship Mobile | +47 477 18 703 |
| INMARSAT FBB (TEL) | + 870 773903861 (Bridge) |
| INMARSAT FBB (FAX) | + 870 783916087 |
| INMARSAT-C (TLX-1) | 422971010 |
| INMARSAT-C (TLX-2) | 422971011 |
| Email | master.thalatta@fleet.wilhelmsen.com |
| DATE KEEL LAID | JUNE 30TH 2014 |
| DATE DELIVERED | 07TH APRIL 2015 |

| | |
|---|---|
| CLASS | DNV GL |
| BUILDER | HYUNDAI SAMHO HEAVY INDUSTRIES CO.LTD |

| CAPACITIES | | CARGO | 8000 cars | |
|---|---|---|---|---|
| FUEL OIL | 3761.4 M3 | BALLAST | 11267.0 M3 | NO. OF CAR DECKS: 13 (Decks No. 2, 4, 6, 7 & 9 are Lift able) |
| DIESEL OIL | 554.1 M3 | FRESH WATER | 361.1 M3 | |

TONNAGE

| | INTERNATIONAL | SUEZ (SCID) | PANAMA(SIN) | JAPANESE |
|---|---|---|---|---|
| GROSS | 75283 | 82260.96 | | |
| NET | 29329 | 77112.62 | PC/UMS Net Tonnage | |

| | | |
|---|---|---|
| SUMMER DEADWEIGHT: 23792 MT | LIGHT SHIP | 23480 |
| | SUMMER DISPLACEMENT | 47272 |

| | | |
|---|---|---|
| RUDDER | TYPE : PROMAS (ROLLS-ROYCE MARINE AS) | Max Angle : 62 deg. |
| PROPELLER | TYPE : SCREW TYPE RIGHT HAND FIXED PITCH | Dir.of Turn : Right |
| THRUSTER | BOW POWER : 2100 KW/ 2800HP | Stern Power : |
| MAIN ENGINE | MAN B&W 8S60ME - C8.2 OUTPUT: M.C.R – 15,560 kW x 105 .0 RPM : N.C.R – 14,000 Kw x 101.1 rpm | SERVICE SPEED 19.6 KNOTS |

Figure D-1 Ship Particulars

**2. Fuel certificates**

A fuel sample was collected during our testing and sent out for analysis. The results are shown in the table below. The fuel sulfur was 2.53 % for the HFO fuel tested (fuel sample FS17001), see Table D-1. The on-vessel fuel sulfur concentration was reported at 2.5%, see Appendix E, Figure E-2. This matches UCR's analysis, see Table D-2. The heating value of the fuel was reported at 40.3 DG/kg and the sea-trial was performed at 42.26 DG/kg, see report copy Appendix E, Figure E2.

Table D-1 Fuel analysis measured results

| Method | ODDB 37938<br>FS17001<br>HFO Marine Fuel |
|---|---|
| ASTM D2622, Sulfur<br>Run 1, ppm<br>Run 2, ppm<br>Average, ppm | <br>25486<br>25182<br>25334 |
| ASTM D4052<br>API At 60F<br>Specific Gravity at 60F<br>Density at 15.56C, g/ml | <br>11.27<br>0.9911<br>0.9901 |
| ASTM D445<br>Viscosity at 50C, cSt | <br>370.3 |
| ASTM D524<br>Carbon Residue, mass % | <br>12.65 |

Table D-2 Fuel analysis measured results

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Vessel LHV | 40.30 | MJ/kg | | | | | |
| ShopTrial | 42.26 | MJ/kg | | | | | |
| BSFC_LHV | 1.049 | correction from shop trial using LHV as the basis | | | | | |
| BSFC_comp | 1.108 | correction from shop trial using meas BSFC from vessle | | | | | |
| BSFC Evaluation ship measurmetns vs shop trial report | | | | | | | |
| Eng Load | | BSFC (g/kWhr) | | | | | |
| % | MW | Indicated | Effective | ShopTrial | | | |
| 45.5 | 7.806 | 171.8 | 189.7 | 166.28 | 3.3% | 14.1% | |
| 72.5 | 12.13 | 171.8 | 184.6 | 166.63 | 3.1% | 10.8% | |
| 27.9 | 4.975 | 181.0 | 207.2 | 176.07 | 2.8% | 17.7% | see fig to right for data |
| | | | | | | | |
| Indicated | This is the power or fuel usage based on cylinder | | | | | | |
| effective | This is the power or fuel usage for power available at the crankshaft (very similar to break power). Use this when you can. | | | | | | |

The vessel as tested used Shell S6 300 for the cylinder oil, Shell Melinea S30 for the Circulating oil and Shell Melina S30 for the turbo oil, see Appendix E, Figure E-4. No oil sample was collected or analyzed as part of this testing.

**3. Engine screen shot**

UCR has discovered that collecting engine data from the control room using data logging files and records is difficult and can vary significantly between vessel age, crew, and technology. As such, UCR has developed a data collection system that relies on pictures. Engine load for the ME and DG will be collected from screen shot pictures showing information specific to the test. Each load test point will capture up to 4 screen shots to quantify stability of readings. More readings will be captured if the load is not stable. These pictures include a time reference to track things, then a repeated series of pictures for each load point. The time series is critical for the alignment of this data with our standard measured data. Duplicate information is recommended in order to verify results and ensure accuracy. Figure D-2 through D-6 show the engine details that were recorded for one test event.


Figure D-2 Ship clock index for picture data measurment system.

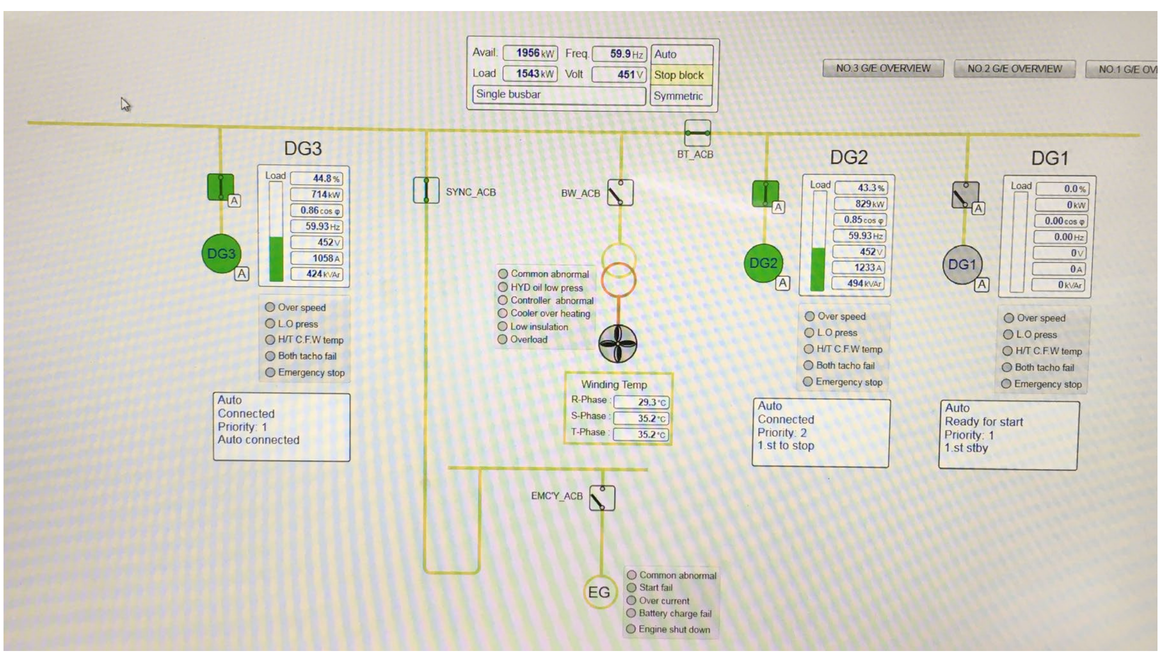



Figure D-3 Auxilary diesel generator electrical load DG1, DG2, and DG3.


Figure D-4 Auxiliar diesel generator #2 loads and particulateras (under test).

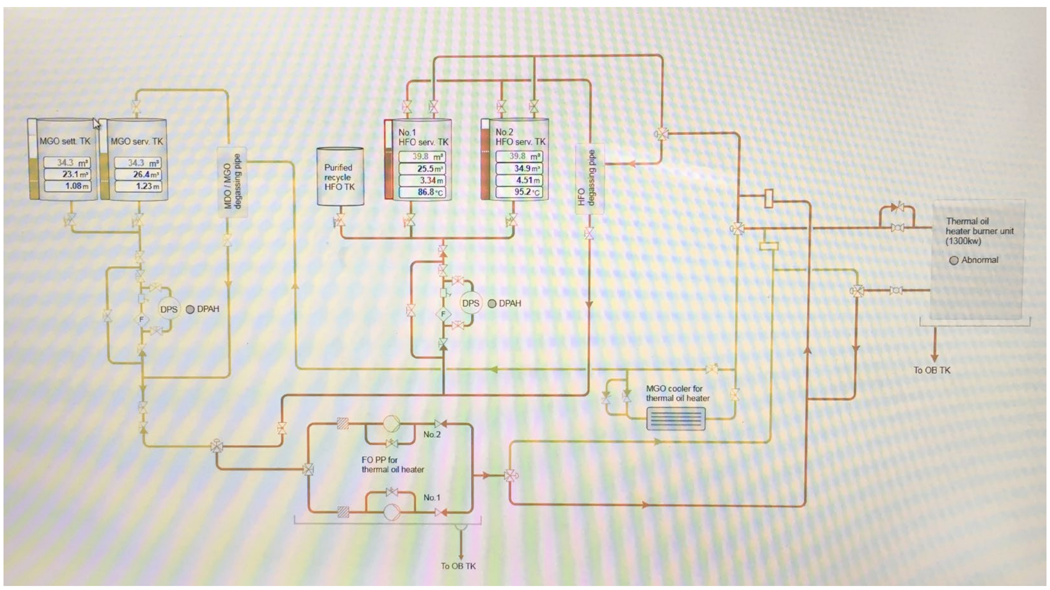



Figure D-5 DGO and HFO fuel tanks and particulars.

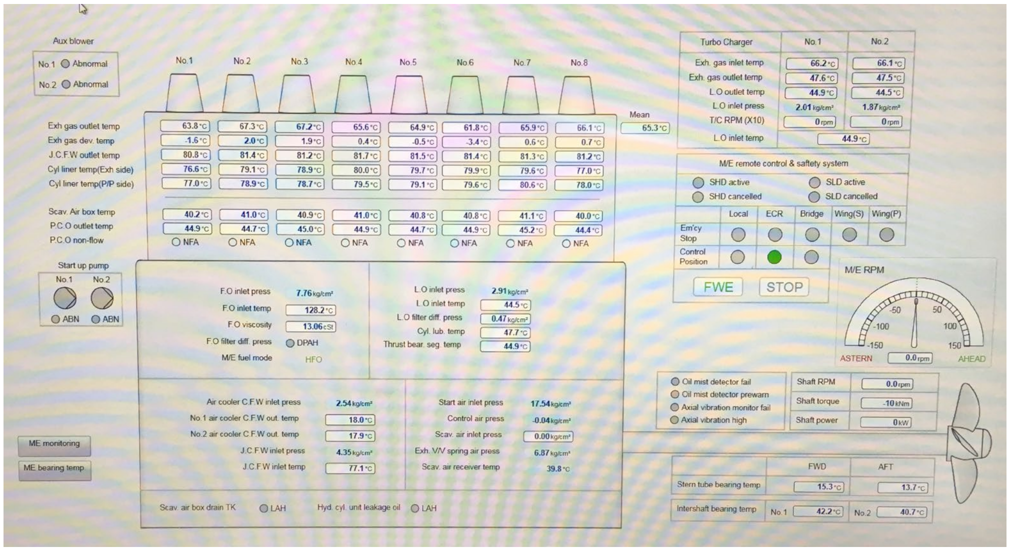



Figure D-6 Main engine particulars, load, temperatures, and other details.

**4. Scrubber screen shots**

The scrubber system operation will be documented during each load point. The following screen shots will be captured where selected information will be utilized in the final report to demonstrate proper operation of the scrubber during its evaluation. Figures D-7 and D-8 show the performance conditions of the scrubber for one load event. Figures D-9 through Figure D-13 show information on the CEMS operation and theory for this vessel.

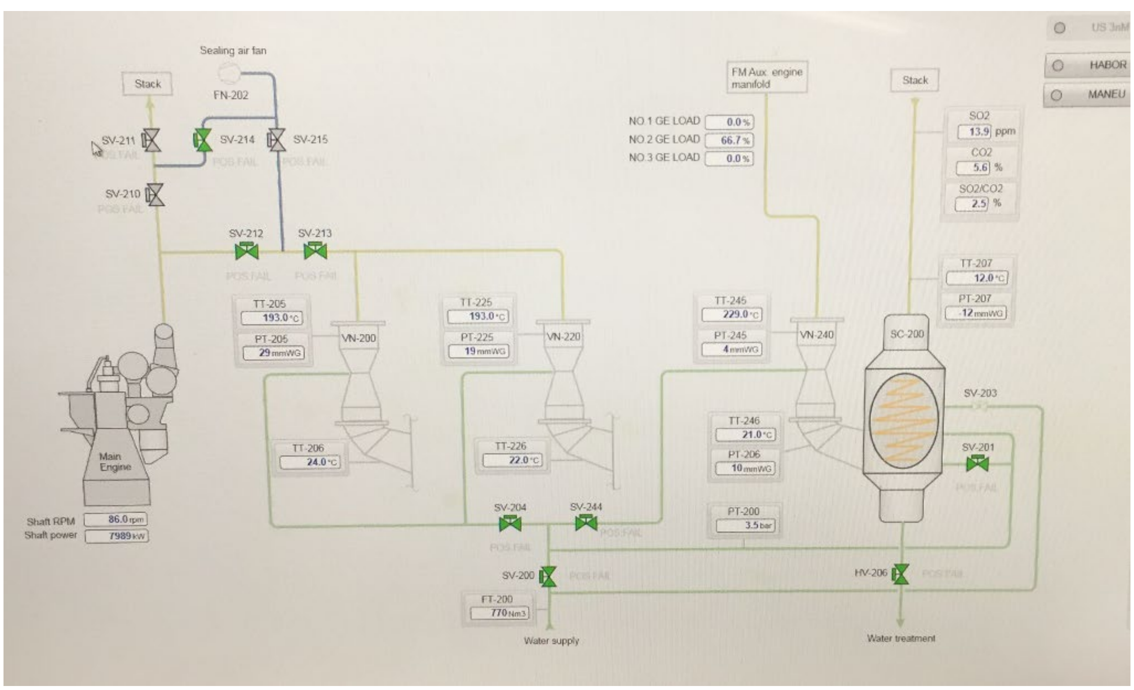



Figure D-7 Exhaust flow scrubber routing ME, and DG1, DG2, and DG3. (ME and DG2 via scrubber, others bypassed and operating on DGO).

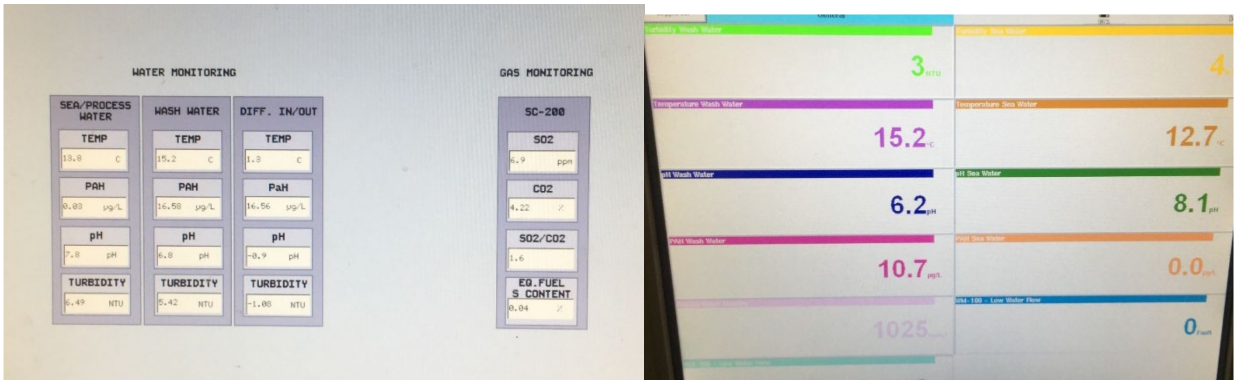



Figure D-8 Primary scrubber efficiency record (left) and redundent record (right).

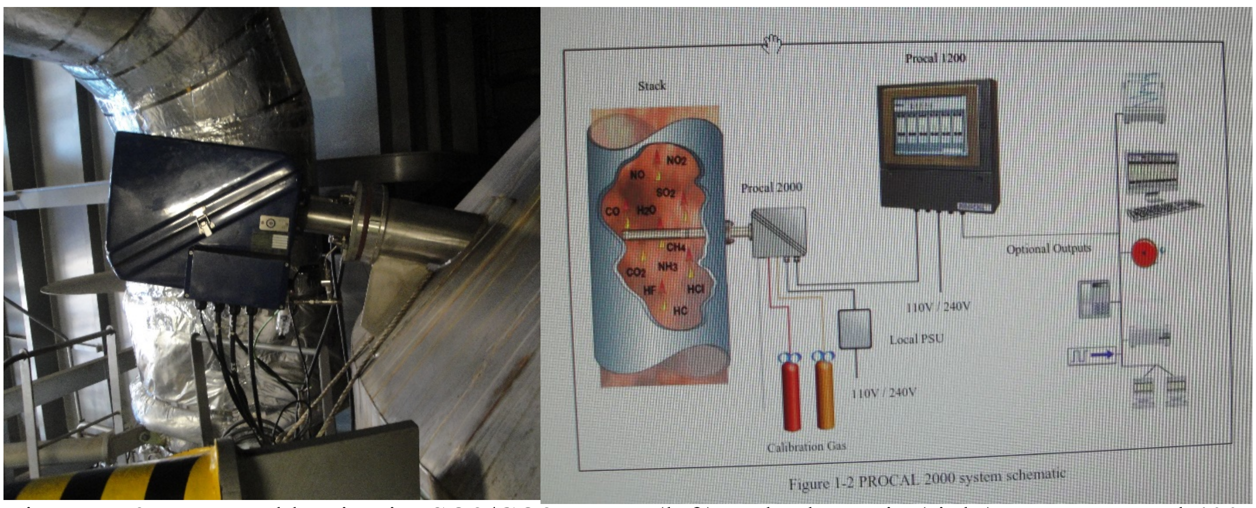
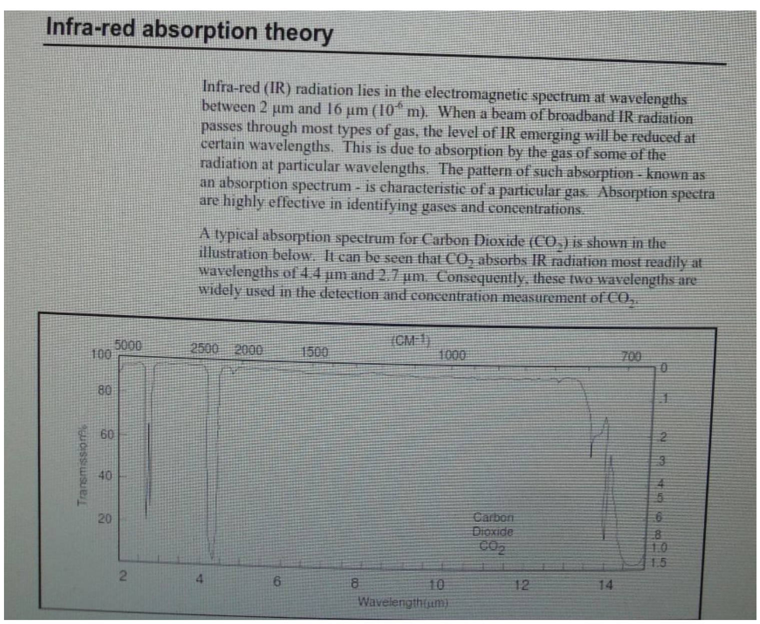



Figure D-9 Post-scrubber in-situ SO2/CO2 sensor (left) and schematic (right), source procal 400.



**Infra-red absorption theory**

Infra-red (IR) radiation lies in the electromagnetic spectrum at wavelengths between 2 µm and 16 µm ($10^{-6}$ m). When a beam of broadband IR radiation passes through most types of gas, the level of IR emerging will be reduced at certain wavelengths. This is due to absorption by the gas of some of the radiation at particular wavelengths. The pattern of such absorption - known as an absorption spectrum - is characteristic of a particular gas. Absorption spectra are highly effective in identifying gases and concentrations.

A typical absorption spectrum for Carbon Dioxide ($CO_2$) is shown in the illustration below. It can be seen that $CO_2$ absorbs IR radiation most readily at wavelengths of 4.4 µm and 2.7 µm. Consequently, these two wavelengths are widely used in the detection and concentration measurement of $CO_2$.



Figure D-10 The CO2 infra-red absorption theory specifics (source Procal 400 manual)

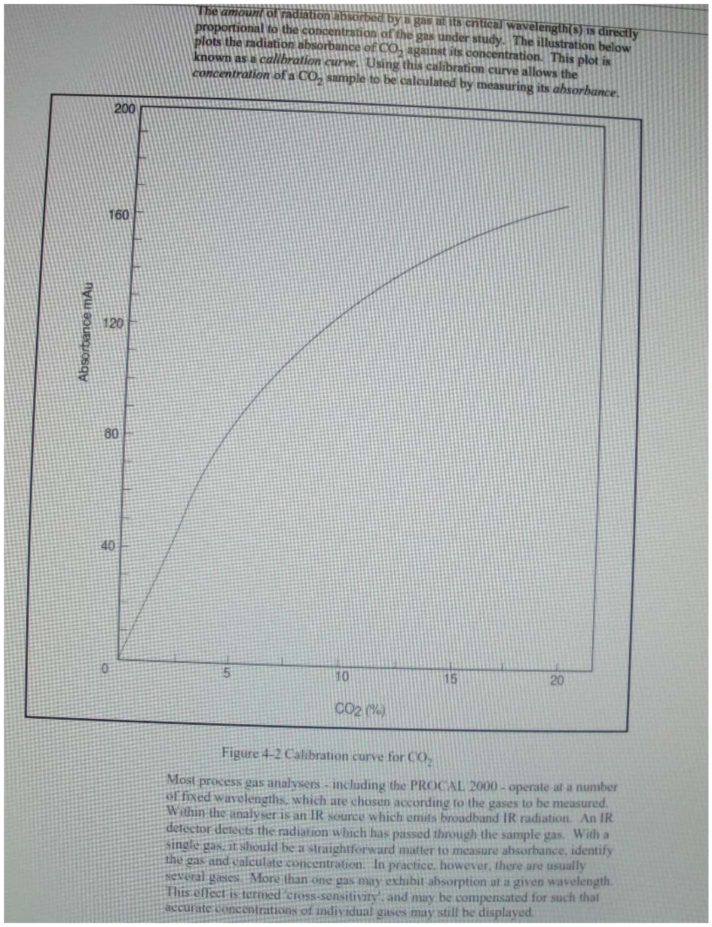

The *amount* of radiation absorbed by a gas at its critical wavelength(s) is directly
proportional to the concentration of the gas under study. The illustration below
plots the radiation absorbance of $CO_2$ against its concentration. This plot is
known as a *calibration curve*. Using this calibration curve allows the
*concentration* of a $CO_2$ sample to be calculated by measuring its *absorbance*.



Figure 4-2 Calibration curve for $CO_2$

Most process gas analysers - including the PROCAL 2000 - operate at a number of fixed wavelengths, which are chosen according to the gases to be measured. Within the analyser is an IR source which emits broadband IR radiation. An IR detector detects the radiation which has passed through the sample gas. With a single gas, it should be a straightforward matter to measure absorbance, identify the gas and calculate concentration. In practice, however, there are usually several gases. More than one gas may exhibit absorption at a given wavelength. This effect is termed 'cross-sensitivity', and may be compensated for such that accurate concentrations of individual gases may still be displayed.

Figure D-11 The CO2 infra-red calibration curve (source Procal 400 manual)

**In the PROCAL 2000, interference filters are placed in the path of the broadband IR radiation. Two filters are used per component. One selects a measuring wavelength, while the other selects a reference wavelength. The filters are mounted on a rotating disc immediately in front of the IR source. This arrangement gives rise to an IR beam alternating rapidly between measuring wavelength and reference wavelength for each component. This alternating beam passes through the gas to be measured, eventually striking the IR detector.**

**Filters have been selected such that if any of the gas to be measured is present, then a significant amount of radiation will be absorbed at the measuring wavelength, with very little or none at the reference wavelength.**

The quantity of radiation per unit time is a function of two factors: (1) the number of molecules within the optical path *and* (2) the extent to which these molecules absorb radiation, expressed as the absorption coefficient.

Absorbance may be defined in the following expression:

$$A = E.C.l = -\log_{10}(I_M/I_R) + O_Z$$

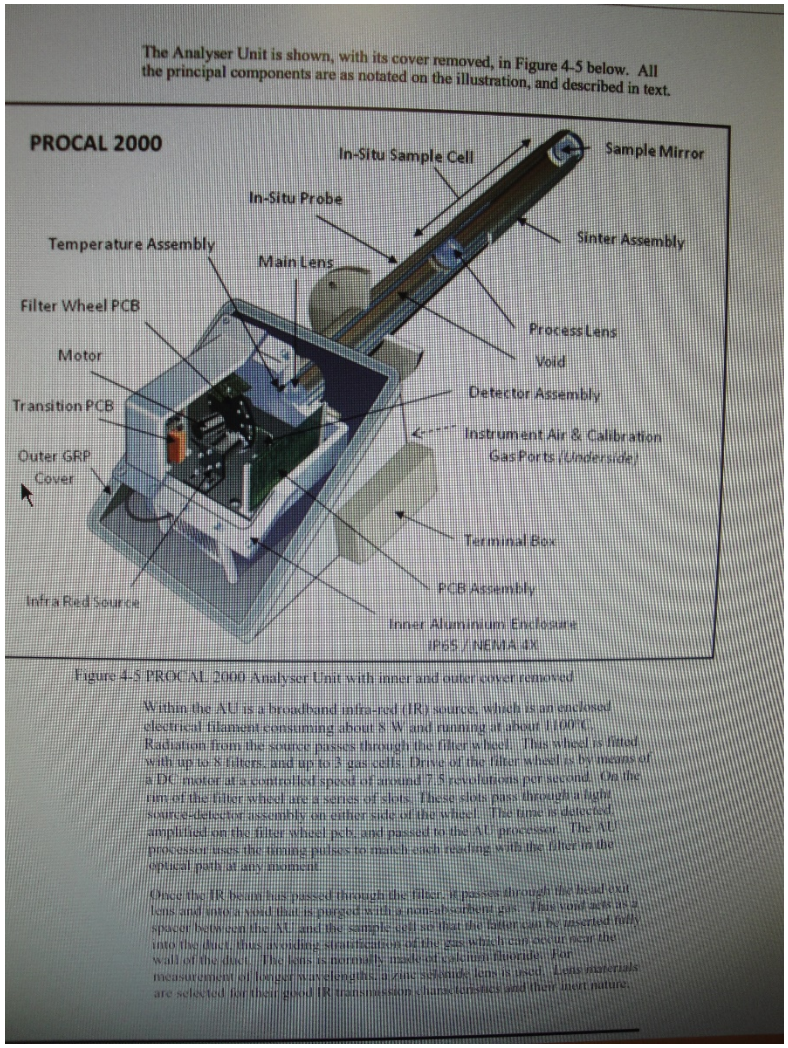
where:
- A is the absorbance
- E is the Extinction Coefficient
- C is the gas concentration
- l is the length of sample through which the beam has passed
- $I_M$ is the IR signal strength at the measuring wavelength
- $I_R$ is the IR signal strength at the reference frequency
- $O_Z$ is the zero offset.

It will be seen that there is a logarithmic relationship between the concentration and the ratio of the IR signal strengths at the measuring and reference wavelengths.

It is these two signal strengths which are shown on the TEST screen under the titles `measured value` and `reference value`.

During calibration of the analyser, the measured absorbance is recorded for known sample gas concentrations over the range required for the specific application. Results of this exercise are recorded within the system's memory in the form of a look-up table. During live operation of the analyser, the system calculates concentration levels from absorbance levels by continual reference to this look-up table.

Figure D-12 Theory for the SO2 and CO2 filter selectivity (source Procal 400 manual)



The Analyser Unit is shown, with its cover removed, in Figure 4-5 below. All the principal components are as notated on the illustration, and described in text.



Figure 4-5 PROCAL 2000 Analyser Unit with inner and outer cover removed

Within the AU is a broadband infra-red (IR) source, which is an enclosed electrical filament consuming about 8 W and running at about 1100°C. Radiation from the source passes through the filter wheel. This wheel is fitted with up to 8 filters, and up to 3 gas cells. Drive of the filter wheel is by means of a DC motor at a controlled speed of around 7.5 revolutions per second. On the rim of the filter wheel are a series of slots. These slots pass through a light source-detector assembly on either side of the wheel. The time is detected, amplified on the filter wheel pcb, and passed to the AU processor. The AU processor uses the timing pulses to match each reading with the filter in the optical path at any moment.

Once the IR beam has passed through the filter, it passes through the head exit lens and into a void that is purged with a non-absorbent gas. This void acts as a spacer between the AU and the sample cell so that the latter can be inserted fully into the duct, thus avoiding stratification of the gas which can occur near the wall of the duct. The lens is normally made of calcium fluoride. For measurement of longer wavelengths, a zinc selenide lens is used. Lens materials are selected for their good IR transmission characteristics and their inert nature.

Figure D-13 Sensor system layout and specifics (source Procal 400 manual)

# Appendix E –Engine Power and Exhaust Flow

This appendix present the engine related results utilized for the mass and brake-specific based emission values. These results rely on the data collected from the engine control room for actual load, sea-trial reference load, and fuel quality (heating value, sulfur levels and such). Thus, this appendix is a summary of the data collected and its use in this report. The engine percent load for each mode are presented in Table E-1, the actual loads and calculated exhaust flow are listed in Table E-2, and the sea-trial from the ship maker is presented in Figure E-1. The sea-trial BSFC report at 75% load was 166.6 g/kWhr, but the engine screen shot effective power was 184.6 g/kWhr[7]. These effective power is the power available to the crank shaft based on real in-use measurements with real in-use fuels at real in-use conditions. The BSFC fuel flow calculations were based on the measured effective fuel flow and not the sea-trial reported fuel flow. The effective fuel flow is the basis for the exhaust flow and fuel flow calculations with in this report.

The fuel flow and power were measured on the vessel with in-cylinder pressure systems. This vessel was equipped with in-cylinder pressure measurements that allowed the direct calculation of indicated power from which effective fuel consumption and engine load were derived. From review of the in-cylinder pressure vs crank angle diagrams (provided for various load points on the engine during testing) and the pressure volume diagrams for each cylinder, it can be reported the cylinder to cylinder variation was very small and the accuracy of the reported engine load is good. Both engine load and fuel consumption can be derived from the indicated pressure spikes.

Table E-1 Summary of engine load and fuel rate

| | | | | | | | Engine Load | | | | | | | ME | | | AE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Project Name | Fuel | ATS | Location | Test Mode | Start Time | ME | | | AE | | | | Fuel Rate cacl OEM | cor. Factor | cor. Fuel Rate | Fuel Rate cacl OEM | cor. Factor | cor. Fuel Rate |
| mm/dd/yyyy | name | | | | | hh:mm:ss | MW | % MCR | % NCR | MW | % MCR | % NCR | % total | kg/hr | n/a | kg/hr | kg/hr | n/a | kg/hr |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 13:35:00 | 0.00 | 0% | 0% | 0.83 | 44% | 57% | 5% | 0 | 1.00 | 0 | 191 | 1.00 | 191 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 13:45:00 | 0.00 | 0% | 0% | 0.85 | 45% | 58% | 5% | 0 | 1.00 | 0 | 194 | 1.00 | 194 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 13:55:00 | 0.00 | 0% | 0% | 0.87 | 46% | 60% | 5% | 0 | 1.00 | 0 | 198 | 1.00 | 198 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 14:55:00 | 0.00 | 0% | 0% | 1.28 | 68% | 88% | 7% | 0 | 1.00 | 0 | 276 | 1.00 | 276 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 15:05:00 | 0.00 | 0% | 0% | 1.31 | 69% | 90% | 7% | 0 | 1.00 | 0 | 281 | 1.00 | 281 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 15:20:00 | 0.00 | 0% | 0% | 1.29 | 68% | 89% | 7% | 0 | 1.00 | 0 | 277 | 1.00 | 277 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 16:20:00 | 0.00 | 0% | 0% | 0.58 | 31% | 40% | 3% | 0 | 1.00 | 0 | 144 | 1.00 | 144 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 16:30:00 | 0.00 | 0% | 0% | 0.60 | 31% | 41% | 3% | 0 | 1.00 | 0 | 147 | 1.00 | 147 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 16:40:00 | 0.00 | 0% | 0% | 0.55 | 29% | 38% | 3% | 0 | 1.00 | 0 | 139 | 1.00 | 139 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 10:00:00 | 12.82 | 82% | 108% | 0.00 | 0% | 0% | 73% | 2382 | 1.00 | 2382 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 10:15:00 | 11.95 | 77% | 100% | 0.00 | 0% | 0% | 68% | 2208 | 1.00 | 2208 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 10:30:00 | 12.23 | 79% | 103% | 0.00 | 0% | 0% | 70% | 2263 | 1.00 | 2263 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 14:40:00 | 11.69 | 75% | 98% | 0.00 | 0% | 0% | 67% | 2156 | 1.00 | 2156 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 14:55:00 | 11.74 | 75% | 99% | 0.00 | 0% | 0% | 67% | 2166 | 1.00 | 2166 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 15:10:00 | 11.84 | 76% | 99% | 0.00 | 0% | 0% | 68% | 2186 | 1.00 | 2186 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 16:15:00 | 7.36 | 47% | 62% | 0.00 | 0% | 0% | 42% | 1360 | 1.00 | 1360 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 16:30:00 | 7.43 | 48% | 62% | 0.00 | 0% | 0% | 43% | 1373 | 1.00 | 1373 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 16:45:00 | 7.35 | 47% | 62% | 0.00 | 0% | 0% | 42% | 1360 | 1.00 | 1360 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 18:30:00 | 4.77 | 31% | 40% | 0.00 | 0% | 0% | 27% | 913 | 1.00 | 913 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 18:45:00 | 4.63 | 30% | 39% | 0.00 | 0% | 0% | 27% | 889 | 1.00 | 889 | 0 | 1.00 | 0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 19:00:00 | 4.69 | 30% | 39% | 0.00 | 0% | 0% | 27% | 899 | 1.00 | 899 | 0 | 1.00 | 0 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 14:00:00 | 11.54 | 74% | 97% | 1.33 | 70% | 92% | 74% | 2126 | 1.00 | 2126 | 285 | 1.00 | 285 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 14:15:00 | 11.76 | 76% | 99% | 1.37 | 72% | 94% | 75% | 2169 | 1.00 | 2169 | 292 | 1.00 | 292 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 14:30:00 | 11.64 | 75% | 98% | 1.32 | 70% | 91% | 74% | 2146 | 1.00 | 2146 | 283 | 1.00 | 283 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 15:45:00 | 7.90 | 51% | 66% | 1.29 | 68% | 89% | 53% | 1455 | 1.00 | 1455 | 277 | 1.00 | 277 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 16:00:00 | 7.90 | 51% | 66% | 1.29 | 68% | 89% | 53% | 1456 | 1.00 | 1456 | 278 | 1.00 | 278 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 16:15:00 | 7.77 | 50% | 65% | 1.27 | 67% | 88% | 52% | 1432 | 1.00 | 1432 | 274 | 1.00 | 274 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 18:35:00 | 5.19 | 33% | 44% | 1.19 | 63% | 82% | 37% | 986 | 1.00 | 986 | 257 | 1.00 | 257 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 18:50:00 | 5.06 | 33% | 42% | 1.20 | 63% | 82% | 36% | 963 | 1.00 | 963 | 259 | 1.00 | 259 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 19:05:00 | 5.05 | 32% | 42% | 1.19 | 63% | 82% | 36% | 962 | 1.00 | 962 | 258 | 1.00 | 258 |

[7] Indicated power is the energy produced in the cylinder from the formula IP = P*A*L*N/1000. Where P is the mean effective pressure from in-cylinder pressure measurements, L is the stroke length, A is the cylinder area, and N is the power stroke rate per second. Effective power is the power available to the output side of the crankshaft which is connected to the flywheel. It can be determined by speed and torque measurements or from indicated power measurements. Effective power and fuel consumption should be used since that is what drives the emissions calculations for engines.

| Observation No.: | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Bunker Station: | | | | | | | Brand | | Type |
| Oil Brand: | | | | HFO 380 | Cylinder Oil | | Shell | | S6 |
| Viscosity at 50ºC: | -/- | cSt | Heat Value: | 40.35 MJ/kg | Circulating Oil | | Shell | | Melina S 30 |
| Density at 15°C: | 991 | kg/m³ | Sulphur: | 2.5 % | Turbo Oil | | SHELL | | MELINA S 30 |
| Test Date | Test hour hh:mm | Engine speed RPM | Load % | Indicated Power kW | Indicated Fuel Consumption g/kWh | Speed Setting | | Draft Fore 8.1 m | Log Speed 17.4 knot |
| 3/3/2017 | 4:16 PM | 93.1 | 72.5 | 12,130 | 171,800.0 | 101 | | Draft Aft. 8.8 m | Obs. Speed 17.6 knot |
| Total running hours hh:mm | Ref. Pmax bar | | Fuel index % | Effective Power kW | Eff. Fuel Consumption g/kWh | Ambient pressure mbar | | Wind 20.0 knot | Wind Direction 330 deg |
| 13932:30 | -/- | | 88.0 | 11,288 | 184,600.0 | 1,000 | | Wave Height 2.5 m | Wave Direction 0 deg |

Figure E-1 This figure shows the indicated and effective fuel consumption from the vessel. The effective brake specific fuel consumption here was used in place of the BSFC from the sea-trial. This figure also shows the specifics on the lubricating oils utilized.

| Official shop test result for Main Engine | Hull No. | | Owner | WALLENIUS WILHELMSEN LINES |
|---|---|---|---|---|
| | Engine No. | AA5516 | Class | DNV |
| | Engine Type | 8S60ME-C8.2 | Test Date | Apr. 28, 2014 |
| Summary Data of Load Test | Output(MCR) | 15560 kW | Engineer | |
| | Speed(MCR) | 105 rpm | Operator | |

| Data Sheet No. | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Load ( % ) | | 25 | 50 | 75 | 90 | 100(1) | 100(2) | 110 | |
| Measuring Time | | 10:45 | 11:15 | 11:45 | 12:15 | 12:45 | 13:15 | 13:45 | |
| Speed ( rpm ) | | 66.1 | 83.3 | 95.4 | 101.4 | 105.0 | 105.0 | 108.4 | |
| Brake Power ( kW ) | | | | | | | | | |
| Pmax. ( bar ) | | | | | | | | | |
| Pcomp. ( bar ) | | | | | | | | | |
| Fuel Index ECU( % ) | | | | | | | | | |
| Fuel Oil Con- | Measured | 177.38 | 168.38 | 168.81 | 171.81 | 173.78 | - | 177.32 | |
| sum.(g/kWh) | Corrected | 176.07 | 166.28 | 166.63 | 169.58 | 171.42 | - | 175.01 | |
| Exh. Gas | Cyl. Out | | | | | | | | |
| Temp. | Bef. T/C | | | | | | | | |
| ( ℃ ) | Aft. T/C | | | | | | | | |

Figure E-2 Shop trial data sheet for the Scrubber engine tested (ref LHV = 42.36) [8]

[8] Instructions Hyundai-MAN B&W Diesel Engines Operation. Operations 700-01, Edition 0001

| OFFICIAL NOx EMISSION TEST RESULT FOR DIESEL GENERATOR ENGINE | Project | | Owner | \ |
|---|---|---|---|---|
| | Eng. Type | 7H25/33 | Class | DNV |
| **MEASURING RECORD for NOx EMISSION TEST (NO. 2 G/E)** | Eng. No. | BA5312-2 | Test Date | 2014.03.11 |
| | Eng. MCR | 2000 KW | Evaluated by | |
| | Gen. MCR | 1900 KW | Operated by | |

| Test NO. | | 01 | | 02 | | 03 | | 04 | | 05 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | hh:mm | 09:30~09:50 | | 09:50~10:10 | | 10:10~10:30 | | 10:30~10:50 | | 10:50~11:10 | |
| Ambient Press. / Temp. | mbar/°c | 1025.0 | 10.8 | 1025.0 | 11.4 | 1025.0 | 11.6 | 1025.0 | 11.9 | 1025.0 | 12.5 |
| Intake Air Humidity / Temp. | %RH/°c | 33.3 | 13.6 | 32.3 | 14.8 | 32.0 | 15.5 | 31.5 | 16.8 | 30.1 | 17.4 |
| Load Point | % | 100% | | 75% | | 50% | | 25% | | 10% | |
| Engine Speed | rpm | 900 | | 900 | | 900 | | 900 | | 900 | |
| Generator Load | kW | 1932.2 | | 1449.8 | | 962.0 | | 469.2 | | 171.3 | |
| Generator Efficiency | % | [illegible] | | [illegible] | | [illegible] | | [illegible] | | [illegible] | |
| Engine Load | kW | [illegible] | | [illegible] | | [illegible] | | [illegible] | | [illegible] | |
| Fuel oil consumption | kg/h | 384.000 | | 291.600 | | 205.000 | | 117.600 | | 64.800 | |
| specific consumption | g/kW.h | 192.000 | | 194.400 | | 205.000 | | 235.200 | | 324.000 | |
| at ISO conditions | g/kW.h | 189.723 | | 192.037 | | 202.489 | | 232.284 | | 319.888 | |

Figure E-3 Shop trial data sheet for the Scrubber auxiliary generator tested [9]

Table E-2 Summary of engine exhaust flow by speed density and carbon balance

| | | | | | | | | | | ME | | | | | AE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Calc Dry Exh. Flow Rate | | | | Selected | Calc Dry Exh. Flow Rate | | | | Selected | |
| Date | Project Name | Fuel | ATS | Location | Test Mode | Start Time | Sample Duration | DR | Exh Temp | Exh Flow I | | Exh Flow II | | Exh Flow II | Exh Flow I | | Exh Flow II | | Exh Flow II | Exh Flow Total II |
| mm/dd/yyyy | name | | | | | hh:mm:ss | min | n/a | C | (scfm) | (m3/hr) | (scfm) | (m3/hr) | m3/hr | (scfm) | (m3/hr) | (scfm) | (m3/hr) | m3/hr | m3/hr |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 13:35:00 | 5.0 | 12.0 | 275.8 | 0 | 0 | 0 | 0 | 0 | 2600 | 5508 | 2551 | 5406 | 5406 | 5406 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 13:45:00 | 5.0 | 12.0 | 275.1 | 0 | 0 | 0 | 0 | 0 | 2661 | 5637 | 2611 | 5532 | 5532 | 5532 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 13:55:00 | 5.0 | 12.0 | 274.2 | 0 | 0 | 0 | 0 | 0 | 2743 | 5812 | 2659 | 5635 | 5635 | 5635 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 14:55:00 | 5.0 | 12.0 | 260.7 | 0 | 0 | 0 | 0 | 0 | 4222 | 8945 | 4210 | 8921 | 8921 | 8921 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 15:05:00 | 5.0 | 12.0 | 260.1 | 0 | 0 | 0 | 0 | 0 | 4329 | 9173 | 4270 | 9047 | 9047 | 9047 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 15:20:00 | 5.0 | 12.0 | 260.6 | 0 | 0 | 0 | 0 | 0 | 4237 | 8978 | 4207 | 8913 | 8913 | 8913 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 16:20:00 | 5.0 | 12.0 | 286.2 | 0 | 0 | 0 | 0 | 0 | 1913 | 4053 | 1900 | 4026 | 4026 | 4026 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 16:30:00 | 5.0 | 12.0 | 285.7 | 0 | 0 | 0 | 0 | 0 | 1952 | 4136 | 1939 | 4108 | 4108 | 4108 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 16:40:00 | 5.0 | 12.0 | 287.6 | 0 | 0 | 0 | 0 | 0 | 1844 | 3907 | 1854 | 3929 | 3929 | 3929 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 10:00:00 | 10.0 | 6.0 | 231.7 | 40,172 | 85,120 | 41055 | 86991 | 86991 | 0 | 0 | 0 | 0 | 0 | 86991 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 10:15:00 | 10.0 | 7.2 | 226.2 | 38,711 | 82,024 | 38997 | 82631 | 82631 | 0 | 0 | 0 | 0 | 0 | 82631 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 10:30:00 | 10.0 | 9.6 | 227.9 | 38,720 | 82,043 | 39717 | 84156 | 84156 | 0 | 0 | 0 | 0 | 0 | 84156 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 14:40:00 | 10.0 | 8.1 | 224.7 | 37,811 | 80,118 | 37937 | 80384 | 80384 | 0 | 0 | 0 | 0 | 0 | 80384 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 14:55:00 | 10.0 | 8.2 | 225.0 | 38,058 | 80,641 | 37582 | 79632 | 79632 | 0 | 0 | 0 | 0 | 0 | 79632 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 15:10:00 | 10.0 | 8.1 | 225.6 | 38,546 | 81,674 | 38371 | 81303 | 81303 | 0 | 0 | 0 | 0 | 0 | 81303 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 16:15:00 | 10.0 | 12.0 | 205.3 | 25,123 | 53,233 | 25304 | 53616 | 53616 | 0 | 0 | 0 | 0 | 0 | 53616 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 16:30:00 | 10.0 | 11.6 | 205.5 | 25,262 | 53,528 | 25131 | 53250 | 53250 | 0 | 0 | 0 | 0 | 0 | 53250 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 16:45:00 | 10.0 | 12.0 | 205.3 | 24,961 | 52,889 | 25231 | 53461 | 53461 | 0 | 0 | 0 | 0 | 0 | 53461 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 18:30:00 | 10.0 | 19.8 | 199.5 | 18,427 | 39,045 | 17937 | 38006 | 38006 | 0 | 0 | 0 | 0 | 0 | 38006 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 18:45:00 | 10.0 | 19.8 | 199.3 | 17,854 | 37,831 | 18021 | 38184 | 38184 | 0 | 0 | 0 | 0 | 0 | 38184 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 19:00:00 | 10.0 | 19.9 | 199.3 | 17,584 | 37,258 | 18817 | 39871 | 39871 | 0 | 0 | 0 | 0 | 0 | 39871 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 14:00:00 | 10.0 | 7.8 | 223.8 | - | - | 39686 | 84090 | 84090 | - | - | 4235 | 8973 | 8973 | 93063 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 14:15:00 | 10.0 | 7.8 | 225.1 | - | - | 39678 | 84072 | 84072 | - | - | 4344 | 9205 | 9205 | 93277 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 14:30:00 | 10.0 | 7.8 | 224.4 | - | - | 39518 | 83733 | 83733 | - | - | 4231 | 8965 | 8965 | 92698 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 15:45:00 | 10.0 | 12.1 | 207.0 | - | - | 28729 | 60873 | 60873 | - | - | 4210 | 8921 | 8921 | 69795 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 16:00:00 | 10.0 | 11.5 | 207.0 | - | - | 29890 | 63333 | 63333 | - | - | 4270 | 9047 | 9047 | 72380 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 16:15:00 | 10.0 | 11.9 | 206.6 | - | - | 28604 | 60609 | 60609 | - | - | 4158 | 8810 | 8810 | 69419 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 18:35:00 | 10.0 | 20.1 | 200.1 | - | - | 19685 | 41709 | 41709 | - | - | 4064 | 8610 | 8610 | 50319 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 18:50:00 | 10.0 | 19.8 | 199.9 | - | - | 19351 | 41003 | 41003 | - | - | 4121 | 8732 | 8732 | 49735 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 19:05:00 | 10.0 | 20.5 | 199.9 | - | - | 19455 | 41223 | 41223 | - | - | 4060 | 8602 | 8602 | 49826 |

[9] Instructions Book Volume II Engine Type H25/33 for Hyundai Himsen Auxiliary Generator.

# Appendix F –Raw Data and Analysis

The summary results in this Appendix include raw data used to generate the values in the report including outside laboratory results. The tables of data show the results that includes the combined emission factors for AE and ME emissions for the pre and post measurements. Figure 1 shows the results from the sulfate ion-chromatography results sent to an outside laboratory. Table F1 – Table F7 and Figure F-1 show all the UCR collected and summarized data used in this report.

| Lab ID | Client ID | Sample Date | Deposit Area (cm2) | Units | SO4 | SO4 MDL |
|---|---|---|---|---|---|---|
| 17-X146 | T170029 | 3/02/2017 | 11.3 | ug/filter | 148 | 0.5 |
| 17-X147 | T170030 | 3/02/2017 | 11.3 | ug/filter | 138 | 0.5 |
| 17-X148 | T170031 | 3/02/2017 | 11.3 | ug/filter | 139 | 0.5 |
| 17-X149 | T170032 | 3/02/2017 | 11.3 | ug/filter | 169 | 0.5 |
| 17-X150 | T170033 | 3/02/2017 | 11.3 | ug/filter | 160 | 0.5 |
| 17-X151 | T170034 | 3/02/2017 | 11.3 | ug/filter | 154 | 0.5 |
| 17-X152 | T170035 | 3/02/2017 | 11.3 | ug/filter | 158 | 0.5 |
| 17-X153 | T170036 | 3/02/2017 | 11.3 | ug/filter | 152 | 0.5 |
| 17-X154 | T170037 | 3/02/2017 | 11.3 | ug/filter | 122 | 0.5 |
| 17-X155 | T170058 | 3/03/2017 | 11.3 | ug/filter | 1830 | 0.5 |
| 17-X156 | T170059 | 3/03/2017 | 11.3 | ug/filter | 1140 | 0.5 |
| 17-X157 | T170060 | 3/03/2017 | 11.3 | ug/filter | 925 | 0.5 |
| 17-X158 | T170061 | 3/03/2017 | 11.3 | ug/filter | 1330 | 0.5 |
| 17-X159 | T170062 | 3/03/2017 | 11.3 | ug/filter | 1330 | 0.5 |
| 17-X160 | T170063 | 3/03/2017 | 11.3 | ug/filter | 1310 | 0.5 |
| 17-X161 | T170064 | 3/03/2017 | 11.3 | ug/filter | 803 | 0.5 |
| 17-X162 | T170065 | 3/03/2017 | 11.3 | ug/filter | 795 | 0.5 |
| 17-X163 | T170066 | 3/03/2017 | 11.3 | ug/filter | 785 | 0.5 |
| 17-X164 | T170067 | 3/03/2017 | 11.3 | ug/filter | 386 | 0.5 |
| 17-X165 | T170068 | 3/03/2017 | 11.3 | ug/filter | 343 | 0.5 |
| 17-X166 | T170069 | 3/03/2017 | 11.3 | ug/filter | 342 | 0.5 |
| 17-X167 | T170070 | 3/04/2017 | 11.3 | ug/filter | 1260 | 0.5 |
| 17-X168 | T170071 | 3/04/2017 | 11.3 | ug/filter | 1260 | 0.5 |
| 17-X169 | T170072 | 3/04/2017 | 11.3 | ug/filter | 1280 | 0.5 |
| 17-X170 | T170073 | 3/04/2017 | 11.3 | ug/filter | 892 | 0.5 |
| 17-X171 | T170074 | 3/04/2017 | 11.3 | ug/filter | 869 | 0.5 |
| 17-X172 | T170075 | 3/04/2017 | 11.3 | ug/filter | 865 | 0.5 |
| 17-X173 | T170076 | 3/04/2017 | 11.3 | ug/filter | 417 | 0.5 |
| 17-X174 | T170077 | 3/04/2017 | 11.3 | ug/filter | 418 | 0.5 |
| 17-X175 | T170078 | 3/04/2017 | 11.3 | ug/filter | 402 | 0.5 |

| Name | Paul Duda |
|---|---|
| Phone | |
| Company | CHESTER LabNet |
| Address | 12242 SW Garden Place |
| City | Tigard |
| State | OR |
| Zip | 97223 |
| Date Shipped | 7/12/2016 |
| Date Lab Received | 7/13/2016 |
| Data Analyzed (Reported) | 7/27/2016 |
| Comments | |
| Fuel Used | HFO, normal sulfur (S~2.5%) |
| Preliminary Filter Weights | 1-10mg |

**Figure F-1 Analytical results from sulfate analysis (SO4 ions).**

Table F-1 Average emission factor results (g/kWhr)

| Mode | Location [1] | DR | Exh Flow | Engine Load | | Total Average Emissions Measured (g/kWhr) - triplicate | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | m3/hr | ME | AE | NOx | CO | CO2 | SO2 | PM2.5 | PM_EC | PM_OC | PM_S | PM_TC | PM_OCcor | PM_TCcor | MSS |
| 2 | pre | 8 | 89,400 | 11.76 | 1.29 | 11.6 | 0.419 | 578.4 | 9.200 | 1.18 | 0.007 | 0.193 | 0.988 | 1.188 | 0.232 | 1.226 | 0.0088 |
| 3 | pre | 12 | 62,403 | 7.38 | 1.29 | 16.7 | 0.347 | 587.3 | 9.313 | 1.10 | 0.009 | 0.235 | 0.892 | 1.135 | 0.282 | 1.182 | 0.0110 |
| 4 | pre | 20 | 47,648 | 4.70 | 1.29 | 17.6 | 0.638 | 613.7 | 9.701 | 1.03 | 0.011 | 0.304 | 0.748 | 1.063 | 0.364 | 1.124 | 0.0146 |
| 2 | post | 8 | 93,013 | 11.64 | 1.34 | 12.3 | 0.374 | 588.2 | 0.327 | 1.17 | 0.007 | 0.175 | 1.013 | 1.195 | 0.210 | 1.230 | 0.0079 |
| 3 | post | 11 | 70,531 | 7.86 | 1.29 | 17.2 | 0.316 | 595.1 | 0.303 | 1.32 | 0.011 | 0.228 | 1.143 | 1.382 | 0.273 | 1.427 | 0.0126 |
| 4 | post | 20 | 49,960 | 5.10 | 1.19 | 17.6 | 0.755 | 624.0 | 0.251 | 1.25 | 0.015 | 0.313 | 0.941 | 1.269 | 0.376 | 1.332 | 0.0218 |
| ISO Weighted | pre | 10 | 80,070 | 10.21 | 1.29 | 13.1 | 0.434 | 584.1 | 9.278 | 1.15 | 0.008 | 0.213 | 0.944 | 1.164 | 0.256 | 1.207 | 0.0098 |
| ISO Weighted | post | 10 | 84,249 | 10.25 | 1.31 | 13.7 | 0.411 | 593.6 | 0.314 | 1.20 | 0.009 | 0.200 | 1.025 | 1.234 | 0.240 | 1.274 | 0.0103 |

[1] SO2 estimated from fuel rate and sulfur percent in the fuel minus the sulfur fraction in the PM phase. SO2 measurements from UCR NDIR system did not agree well and are not used in this report.

Table F- 2 Single standard deviation emission factor results (g/kWhr)

| Mode | Location [1] | DR | Exh Flow | Engine Load | | Total stdev Emissions Measured (g/kWhr) - triplicate | | | | | | | | | | | | S_kg/fuel_kg | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | m3/hr | ME | AE | NOx | CO | CO2 | SO2 | PM2.5 | PM_EC | PM_OC | PM_S | PM_TC | PM_OCcor | PM_TCcor | MSS | S_PM | S_gas |
| 2 | pre | 8 | 89,400 | 11.76 | 1.29 | 0.24 | 0.01 | 4.5 | 0.051 | 0.0 | 0.001 | 0.00 | 0.013 | 0.014 | 0.005 | 0.014 | 0.000 | 0.0020 | 0.0255 |
| 3 | pre | 12 | 62,403 | 7.38 | 1.29 | 0.17 | 0.01 | 4.9 | 0.090 | 0.0 | 0.001 | 0.01 | 0.026 | 0.038 | 0.015 | 0.040 | 0.000 | 0.0038 | 0.0451 |
| 4 | pre | 20 | 47,648 | 4.70 | 1.29 | 0.79 | 0.12 | 24.9 | 0.327 | 0.0 | 0.001 | 0.01 | 0.033 | 0.044 | 0.015 | 0.047 | 0.001 | 0.0049 | 0.1637 |
| 2 | post | 8 | 93,013 | 11.64 | 1.34 | 0.12 | 0.01 | 8.0 | 0.013 | 0.0 | 0.000 | 0.00 | 0.012 | 0.010 | 0.002 | 0.010 | 0.000 | 0.0017 | 0.0066 |
| 3 | post | 11 | 70,531 | 7.86 | 1.29 | 0.18 | 0.01 | 10.6 | 0.007 | 0.0 | 0.002 | 0.00 | 0.027 | 0.027 | 0.004 | 0.027 | 0.000 | 0.0040 | 0.0036 |
| 4 | post | 20 | 49,960 | 5.10 | 1.19 | 0.20 | 0.06 | 4.9 | 0.011 | 0.0 | 0.001 | 0.02 | 0.002 | 0.019 | 0.022 | 0.023 | 0.001 | 0.0003 | 0.0053 |
| ISO Weighted | pre | 10 | 80,070 | 10.21 | 1.29 | 0.29 | 0.03 | 7.0 | 0.090 | 0.0 | 0.001 | 0.01 | 0.018 | 0.022 | 0.008 | 0.022 | 0.000 | 0.0026 | 0.0452 |
| ISO Weighted | post | 10 | 84,249 | 10.25 | 1.31 | 0.14 | 0.02 | 8.0 | 0.012 | 0.0 | 0.001 | 0.00 | 0.013 | 0.014 | 0.005 | 0.014 | 0.000 | 0.0019 | 0.0059 |

[1] SO2 estimated from fuel rate and sulfur percent in the fuel minus the sulfur fraction in the PM phase. SO2 measurements from UCR NDIR system did not agree well and are not used in this report.

Table F-3 Combined emission reductions across the scrubber (positive value implies a reduction across the scrubber)

| Mode | DR | Exh Flow | Engine Load | | Total Percent Change from baseline (pre-scrubber)/pre sample location | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | m3/hr | ME | AE | NOx | CO | CO2 | SO2 | PM2.5 | PM_OC | PM_S | PM_TC | PM_OCcor | PM_TCcor | EC | eBC_MSS |
| 2 | 8 | 91,206 | 11.7 | 1.32 | -6.2% | 10.7% | -1.7% | 96.8% | 1.6% | 9.3% | -2.5% | -0.6% | 9.3% | -0.3% | -2.1% | 10.1% |
| 3 | 12 | 66,467 | 7.62 | 1.29 | -2.8% | 8.7% | -1.3% | 97.0% | -20.5% | 3.0% | -28.2% | -21.7% | 3.0% | -20.7% | -22.5% | -14.7% |
| 4 | 20 | 48,804 | 4.90 | 1.24 | -0.3% | -18.3% | -1.7% | 97.4% | -21.7% | -3.0% | -25.8% | -19.4% | -3.0% | -18.5% | -38.5% | -49.2% |
| ISO Wt | 10 | 82,160 | 10.23 | 1.30 | -4.6% | 5.4% | -1.6% | 96.9% | -4.2% | 6.1% | -8.6% | -5.9% | 6.1% | -5.5% | -12.1% | -5.0% |

[1] SO2 estimated from fuel rate and sulfur percent in the fuel minus the sulfur fraction in the PM phase. SO2 measurements from UCR NDIR system did not agree well and are not used in this report.

## Table F-4 Average emissions at each of the measured conditions (average of triplicates)

| Date | Project Name | Fuel | ATS | Location | Test Mode | Total Load | Total Fuel | Sample Duration | DR | Exh Temp | Exh Flow Total II | g/kWhr | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm/dd/yyyy | name | | | | | MW | kg/hr | min | n/a | C | m3/hr | NOx | CO | $CO_2$ | $SO_2$ | O2 | $PM_{2.5}$ | PM_EC | PM_OC | PM_S | PM_TC | $PM\_OC_{cor}$ | $PM\_TC_{cor}$ |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 0.85 | 194.2 | 5.00 | 12.00 | 275.01 | 5524.31 | 6.67 | 0.89 | 698.42 | 9.14 | 1113.04 | 0.63 | 0.035 | 0.40 | 0.32 | 0.75 | 0.48 | 0.83 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 1.29 | 277.7 | 5.00 | 12.00 | 260.47 | 8960.57 | 7.40 | 1.00 | 661.77 | 8.11 | 1249.89 | 0.68 | 0.015 | 0.43 | 0.38 | 0.82 | 0.51 | 0.90 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 0.58 | 143.2 | 5.00 | 12.00 | 286.48 | 4021.01 | 5.88 | 1.57 | 770.67 | 9.88 | 1164.16 | 0.77 | 0.145 | 0.41 | 0.34 | 0.89 | 0.49 | 0.97 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 12.34 | 2284.1 | 10.00 | 7.60 | 228.62 | 84592.50 | 12.03 | 0.36 | 584.76 | 6.67 | 1286.31 | 1.09 | 0.006 | 0.16 | 0.93 | 1.10 | 0.19 | 1.13 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 11.76 | 2169.3 | 10.00 | 8.13 | 225.07 | 80439.65 | 12.08 | 0.35 | 569.15 | 5.87 | 1283.53 | 1.24 | 0.006 | 0.17 | 1.06 | 1.23 | 0.20 | 1.26 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 7.38 | 1364.3 | 10.00 | 11.86 | 205.34 | 53442.26 | 18.25 | 0.24 | 574.82 | 4.86 | 1381.11 | 1.17 | 0.008 | 0.20 | 0.98 | 1.19 | 0.24 | 1.23 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 4 | 4.70 | 900.4 | 10.00 | 19.84 | 199.36 | 38687.44 | 19.94 | 0.55 | 602.53 | 5.61 | 1608.14 | 1.11 | 0.010 | 0.28 | 0.83 | 1.12 | 0.33 | 1.17 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 12.99 | 2433.6 | 10.00 | 7.81 | 224.40 | 93012.65 | 12.33 | 0.37 | 588.17 | 0.33 | 1305.60 | 1.17 | 0.007 | 0.18 | 1.01 | 1.19 | 0.21 | 1.23 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 9.14 | 1723.9 | 10.00 | 11.82 | 206.90 | 70531.24 | 17.16 | 0.32 | 595.14 | 0.30 | 1425.75 | 1.32 | 0.011 | 0.23 | 1.14 | 1.38 | 0.27 | 1.43 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 6.29 | 1228.2 | 10.00 | 20.12 | 199.96 | 49959.94 | 17.63 | 0.75 | 623.98 | 0.25 | 1435.79 | 1.25 | 0.015 | 0.31 | 0.94 | 1.27 | 0.38 | 1.33 |

## Table F-5 Detailed emissions summary of all measured test points (g/hr), total load, fuel flow, and exhaust flow.

| Date | Project Name | Fuel | ATS | Location | Test Mode | Start Time | Engine Load | Fuel Rate Total | Sample Duration | DR | Exh Temp | Exh Flow Total II | g/hr | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm/dd/yyyy | name | | | | | hh:mm:ss | % total | kg/hr | min | n/a | C | m3/hr | NOx | CO | $CO_2$ | $SO_2$ | O2 | $PM_{2.5}$ | PM_EC | PM_OC | PM_S | PM_TC | $PM\_OC_{cor}$ | $PM\_TC_{cor}$ |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 13:35:00 | 5% | 191 | 5.0 | 12.0 | 275.8 | 5406 | 5,474 | 758 | 582,977 | 7,558 | 919,306 | 538.2 | 35.7 | 346.6 | 274.9 | 657.2 | 416.0 | 726.5 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 13:45:00 | 5% | 194 | 5.0 | 12.0 | 275.1 | 5532 | 5,661 | 736 | 593,322 | 7,763 | 943,839 | 537.9 | 28.1 | 333.6 | 262.1 | 623.8 | 400.3 | 690.5 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 13:55:00 | 5% | 198 | 5.0 | 12.0 | 274.2 | 5635 | 5,828 | 759 | 598,994 | 7,903 | 966,599 | 522.0 | 25.6 | 342.4 | 265.2 | 633.2 | 410.9 | 701.7 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 14:55:00 | 7% | 276 | 5.0 | 12.0 | 260.7 | 8921 | 9,521 | 1,262 | 855,148 | 10,407 | 1,610,018 | 901.8 | 16.5 | 573.8 | 519.3 | 1,109.6 | 688.5 | 1,224.3 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 15:05:00 | 7% | 281 | 5.0 | 12.0 | 260.1 | 9047 | 9,707 | 1,316 | 860,248 | 10,569 | 1,636,326 | 885.6 | 20.9 | 547.1 | 485.7 | 1,053.6 | 656.5 | 1,163.0 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 15:20:00 | 7% | 277 | 5.0 | 12.0 | 260.6 | 8913 | 9,490 | 1,292 | 854,365 | 10,529 | 1,607,358 | 860.2 | 19.0 | 531.2 | 457.8 | 1,008.1 | 637.5 | 1,114.3 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 16:20:00 | 3% | 144 | 5.0 | 12.0 | 286.2 | 4026 | 3,390 | 904 | 447,345 | 5,705 | 672,717 | 482.1 | 82.4 | 236.7 | 214.4 | 533.5 | 284.0 | 580.8 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 16:30:00 | 3% | 147 | 5.0 | 12.0 | 285.7 | 4108 | 3,531 | 873 | 454,529 | 5,825 | 687,747 | 471.4 | 78.3 | 255.2 | 206.4 | 539.9 | 306.2 | 590.9 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 16:40:00 | 3% | 139 | 5.0 | 12.0 | 287.6 | 3929 | 3,273 | 948 | 434,509 | 5,596 | 658,184 | 390.7 | 90.3 | 218.3 | 164.2 | 472.9 | 262.0 | 516.5 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 10:00:00 | 73% | 2382 | 10.0 | 6.0 | 231.7 | 86991 | 150,387 | 4,452 | 7,552,527 | 86,178 | 16,204,333 | 15,803.7 | 71.0 | 2,117.5 | 13,681.5 | 15,870.0 | 2,541.0 | 16,293.5 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 10:15:00 | 68% | 2208 | 10.0 | 7.2 | 226.2 | 82631 | 144,633 | 4,122 | 6,893,381 | 78,119 | 15,626,632 | 11,344.9 | 62.3 | 1,742.6 | 9,695.5 | 11,500.4 | 2,091.2 | 11,848.9 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 10:30:00 | 70% | 2263 | 10.0 | 9.6 | 227.9 | 84156 | 150,081 | 4,584 | 7,198,543 | 82,637 | 15,750,850 | 13,372.6 | 70.9 | 1,981.5 | 11,314.8 | 13,367.2 | 2,377.8 | 13,763.5 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 14:40:00 | 67% | 2156 | 10.0 | 8.1 | 224.7 | 80384 | 140,471 | 4,301 | 6,705,950 | 69,067 | 15,076,993 | 14,539.6 | 76.7 | 1,925.8 | 12,428.9 | 14,431.5 | 2,311.0 | 14,816.6 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 14:55:00 | 67% | 2166 | 10.0 | 8.2 | 225.0 | 79632 | 139,233 | 4,205 | 6,627,907 | 68,213 | 14,935,941 | 14,715.4 | 73.4 | 1,967.6 | 12,481.3 | 14,522.3 | 2,361.1 | 14,915.8 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 15:10:00 | 68% | 2186 | 10.0 | 8.1 | 225.6 | 81303 | 146,413 | 4,011 | 6,743,537 | 69,750 | 15,265,562 | 14,510.6 | 59.8 | 2,002.7 | 12,343.1 | 14,405.7 | 2,403.2 | 14,806.2 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 16:15:00 | 42% | 1360 | 10.0 | 12.0 | 205.3 | 53616 | 134,847 | 1,804 | 4,240,939 | 36,126 | 10,238,110 | 8,983.7 | 52.9 | 1,551.3 | 7,376.1 | 8,980.2 | 1,861.6 | 9,290.5 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 16:30:00 | 43% | 1373 | 10.0 | 11.6 | 205.5 | 53250 | 133,876 | 1,730 | 4,227,369 | 35,253 | 10,150,576 | 8,362.4 | 57.9 | 1,407.9 | 7,060.6 | 8,526.4 | 1,689.5 | 8,808.0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 16:45:00 | 42% | 1360 | 10.0 | 12.0 | 205.3 | 53461 | 135,121 | 1,727 | 4,254,431 | 36,161 | 10,180,215 | 8,530.1 | 64.5 | 1,530.2 | 7,210.9 | 8,805.6 | 1,836.2 | 9,111.6 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 18:30:00 | 27% | 913 | 10.0 | 19.8 | 199.5 | 38006 | 91,607 | 1,821 | 2,743,270 | 24,715 | 7,441,998 | 5,443.1 | 45.4 | 1,352.4 | 4,161.4 | 5,559.2 | 1,622.9 | 5,829.7 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 18:45:00 | 27% | 889 | 10.0 | 19.8 | 199.3 | 38184 | 90,691 | 2,909 | 2,770,807 | 27,573 | 7,471,801 | 4,974.1 | 49.5 | 1,216.9 | 3,720.2 | 4,986.6 | 1,460.3 | 5,230.0 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 19:00:00 | 27% | 899 | 10.0 | 19.9 | 199.3 | 39871 | 98,685 | 3,068 | 2,973,695 | 26,709 | 7,740,918 | 5,157.8 | 45.0 | 1,313.1 | 3,880.5 | 5,238.6 | 1,575.7 | 5,501.2 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 14:00:00 | 74% | 2411 | 10.0 | 7.8 | 223.8 | 93063 | 160,412 | 4,744 | 7,602,668 | 4,156 | 17,009,385 | 15,111.5 | 86.4 | 2,236.4 | 13,043.8 | 15,366.6 | 2,683.7 | 15,813.9 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 14:15:00 | 75% | 2461 | 10.0 | 7.8 | 225.1 | 93277 | 160,603 | 4,816 | 7,602,226 | 4,336 | 17,042,306 | 15,151.0 | 94.2 | 2,327.7 | 13,131.0 | 15,552.9 | 2,793.3 | 16,018.5 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 14:30:00 | 74% | 2429 | 10.0 | 7.8 | 224.4 | 92698 | 159,165 | 5,014 | 7,706,526 | 4,261 | 16,807,124 | 15,133.8 | 90.4 | 2,255.8 | 13,272.3 | 15,618.5 | 2,707.0 | 16,069.7 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 15:45:00 | 53% | 1733 | 10.0 | 12.1 | 207.0 | 69795 | 156,130 | 2,857 | 5,386,526 | 2,679 | 12,914,405 | 12,336.2 | 90.8 | 2,093.8 | 10,790.2 | 12,974.8 | 2,512.5 | 13,393.6 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 16:00:00 | 53% | 1733 | 10.0 | 11.5 | 207.0 | 72380 | 159,433 | 3,010 | 5,579,129 | 2,873 | 13,378,415 | 12,034.9 | 91.3 | 2,062.0 | 10,345.6 | 12,498.9 | 2,474.4 | 12,911.3 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 16:15:00 | 52% | 1706 | 10.0 | 11.9 | 206.6 | 69419 | 155,157 | 2,809 | 5,357,534 | 2,756 | 12,812,576 | 11,955.2 | 115.5 | 2,093.6 | 10,213.5 | 12,422.6 | 2,512.3 | 12,841.4 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 18:35:00 | 37% | 1243 | 10.0 | 20.1 | 200.1 | 50319 | 110,983 | 4,912 | 3,946,361 | 1,630 | 9,113,360 | 7,800.4 | 94.0 | 1,865.9 | 5,994.2 | 7,954.2 | 2,239.1 | 8,327.4 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 18:50:00 | 36% | 1222 | 10.0 | 19.8 | 199.9 | 49735 | 111,257 | 4,291 | 3,929,206 | 1,494 | 8,971,127 | 7,824.7 | 99.6 | 1,995.9 | 5,902.0 | 7,997.5 | 2,395.1 | 8,396.7 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 19:05:00 | 36% | 1219 | 10.0 | 20.5 | 199.9 | 49826 | 110,415 | 5,036 | 3,898,054 | 1,614 | 9,007,353 | 7,915.5 | 88.5 | 2,040.2 | 5,865.9 | 7,994.5 | 2,448.2 | 8,402.6 |

[1] for details on specific AE and ME engine loads, fuel rates, and exhaust flows see Appendix E.

Table F-6 Detailed emissions summary of all measured test points (g/kWhr), total load, fuel flow, and exhaust flow.

| Date | Project Name | Fuel | ATS | Location | Test Mode | Start Time | Engine Load | Fuel Rate Total | Sample Duration | DR | Exh Temp | Exh Flow Total II | g/kWhr | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm/dd/yyyy | name | | | | | hh:mm:ss | % total | kg/hr | min | n/a | C | m3/hr | NOx | CO | $CO_2$ | $SO_2$ | O2 | $PM_{2.5}$ | PM_EC | PM_OC | PM_S | PM_TC | $PM\_OC_{cor}$ | $PM\_TC_{cor}$ |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 13:35:00 | 5% | 191 | 5.0 | 12.0 | 275.8 | 5406 | 6.62 | 0.92 | 705 | 9.14 | 1111 | 0.651 | 0.043 | 0.419 | 0.332 | 0.794 | 0.503 | 0.878 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 13:45:00 | 5% | 194 | 5.0 | 12.0 | 275.1 | 5532 | 6.69 | 0.87 | 701 | 9.18 | 1116 | 0.636 | 0.033 | 0.394 | 0.310 | 0.737 | 0.473 | 0.816 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 13:55:00 | 5% | 198 | 5.0 | 12.0 | 274.2 | 5635 | 6.71 | 0.87 | 689 | 9.09 | 1112 | 0.601 | 0.029 | 0.394 | 0.305 | 0.729 | 0.473 | 0.807 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 14:55:00 | 7% | 276 | 5.0 | 12.0 | 260.7 | 8921 | 7.41 | 0.98 | 666 | 8.10 | 1254 | 0.702 | 0.013 | 0.447 | 0.404 | 0.864 | 0.536 | 0.953 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 15:05:00 | 7% | 281 | 5.0 | 12.0 | 260.1 | 9047 | 7.41 | 1.01 | 657 | 8.07 | 1250 | 0.676 | 0.016 | 0.418 | 0.371 | 0.805 | 0.501 | 0.888 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 15:20:00 | 7% | 277 | 5.0 | 12.0 | 260.6 | 8913 | 7.36 | 1.00 | 662 | 8.16 | 1246 | 0.667 | 0.015 | 0.412 | 0.355 | 0.782 | 0.494 | 0.864 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 16:20:00 | 3% | 144 | 5.0 | 12.0 | 286.2 | 4026 | 5.80 | 1.55 | 766 | 9.77 | 1152 | 0.826 | 0.141 | 0.405 | 0.367 | 0.914 | 0.486 | 0.995 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 16:30:00 | 3% | 147 | 5.0 | 12.0 | 285.7 | 4108 | 5.92 | 1.47 | 763 | 9.77 | 1154 | 0.791 | 0.131 | 0.428 | 0.346 | 0.906 | 0.514 | 0.991 |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 16:40:00 | 3% | 139 | 5.0 | 12.0 | 287.6 | 3929 | 5.90 | 1.71 | 783 | 10.09 | 1187 | 0.704 | 0.163 | 0.394 | 0.296 | 0.853 | 0.472 | 0.931 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 10:00:00 | 73% | 2382 | 10.0 | 6.0 | 231.7 | 86991 | 11.73 | 0.35 | 589 | 6.72 | 1264 | 1.233 | 0.006 | 0.165 | 1.067 | 1.238 | 0.198 | 1.271 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 10:15:00 | 68% | 2208 | 10.0 | 7.2 | 226.2 | 82631 | 12.10 | 0.34 | 577 | 6.54 | 1307 | 0.949 | 0.005 | 0.146 | 0.811 | 0.962 | 0.175 | 0.991 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 10:30:00 | 70% | 2263 | 10.0 | 9.6 | 227.9 | 84156 | 12.27 | 0.37 | 589 | 6.76 | 1288 | 1.093 | 0.006 | 0.162 | 0.925 | 1.093 | 0.194 | 1.125 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 14:40:00 | 67% | 2156 | 10.0 | 8.1 | 224.7 | 80384 | 12.01 | 0.37 | 574 | 5.91 | 1289 | 1.243 | 0.007 | 0.165 | 1.063 | 1.234 | 0.198 | 1.267 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 14:55:00 | 67% | 2166 | 10.0 | 8.2 | 225.0 | 79632 | 11.86 | 0.36 | 565 | 5.81 | 1272 | 1.253 | 0.006 | 0.168 | 1.063 | 1.237 | 0.201 | 1.271 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 15:10:00 | 68% | 2186 | 10.0 | 8.1 | 225.6 | 81303 | 12.36 | 0.34 | 569 | 5.89 | 1289 | 1.225 | 0.005 | 0.169 | 1.042 | 1.216 | 0.203 | 1.250 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 16:15:00 | 42% | 1360 | 10.0 | 12.0 | 205.3 | 53616 | 18.33 | 0.25 | 577 | 4.91 | 1392 | 1.221 | 0.007 | 0.211 | 1.003 | 1.221 | 0.253 | 1.263 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 16:30:00 | 43% | 1373 | 10.0 | 11.6 | 205.5 | 53250 | 18.03 | 0.23 | 569 | 4.75 | 1367 | 1.126 | 0.008 | 0.190 | 0.951 | 1.148 | 0.227 | 1.186 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 16:45:00 | 42% | 1360 | 10.0 | 12.0 | 205.3 | 53461 | 18.38 | 0.23 | 579 | 4.92 | 1385 | 1.160 | 0.009 | 0.208 | 0.981 | 1.198 | 0.250 | 1.239 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 18:30:00 | 27% | 913 | 10.0 | 19.8 | 199.5 | 38006 | 19.21 | 0.38 | 575 | 5.18 | 1561 | 1.142 | 0.010 | 0.284 | 0.873 | 1.166 | 0.340 | 1.223 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 18:45:00 | 27% | 889 | 10.0 | 19.8 | 199.3 | 38184 | 19.58 | 0.63 | 598 | 5.95 | 1613 | 1.074 | 0.011 | 0.263 | 0.803 | 1.077 | 0.315 | 1.129 |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 19:00:00 | 27% | 899 | 10.0 | 19.9 | 199.3 | 39871 | 21.04 | 0.65 | 634 | 5.69 | 1651 | 1.100 | 0.010 | 0.280 | 0.827 | 1.117 | 0.336 | 1.173 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 14:00:00 | 74% | 2411 | 10.0 | 7.8 | 223.8 | 93063 | 12.46 | 0.37 | 591 | 0.32 | 1322 | 1.174 | 0.007 | 0.174 | 1.013 | 1.194 | 0.209 | 1.229 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 14:15:00 | 75% | 2461 | 10.0 | 7.8 | 225.1 | 93277 | 12.24 | 0.37 | 579 | 0.33 | 1299 | 1.154 | 0.007 | 0.177 | 1.001 | 1.185 | 0.213 | 1.221 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 14:30:00 | 74% | 2429 | 10.0 | 7.8 | 224.4 | 92698 | 12.28 | 0.39 | 595 | 0.33 | 1297 | 1.168 | 0.007 | 0.174 | 1.024 | 1.205 | 0.209 | 1.240 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 15:45:00 | 53% | 1733 | 10.0 | 12.1 | 207.0 | 69795 | 16.99 | 0.31 | 586 | 0.29 | 1405 | 1.342 | 0.010 | 0.228 | 1.174 | 1.412 | 0.273 | 1.457 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 16:00:00 | 53% | 1733 | 10.0 | 11.5 | 207.0 | 72380 | 17.34 | 0.33 | 607 | 0.31 | 1455 | 1.309 | 0.010 | 0.224 | 1.125 | 1.359 | 0.269 | 1.404 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 16:15:00 | 52% | 1706 | 10.0 | 11.9 | 206.6 | 69419 | 17.16 | 0.31 | 593 | 0.30 | 1417 | 1.322 | 0.013 | 0.232 | 1.130 | 1.374 | 0.278 | 1.420 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 18:35:00 | 37% | 1243 | 10.0 | 20.1 | 200.1 | 50319 | 17.40 | 0.77 | 619 | 0.26 | 1429 | 1.223 | 0.015 | 0.293 | 0.940 | 1.247 | 0.351 | 1.306 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 18:50:00 | 36% | 1222 | 10.0 | 19.8 | 199.9 | 49735 | 17.79 | 0.69 | 628 | 0.24 | 1435 | 1.251 | 0.016 | 0.319 | 0.944 | 1.279 | 0.383 | 1.343 |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 19:05:00 | 36% | 1219 | 10.0 | 20.5 | 199.9 | 49826 | 17.70 | 0.81 | 625 | 0.26 | 1444 | 1.269 | 0.014 | 0.327 | 0.940 | 1.281 | 0.392 | 1.347 |

[1] for details on specific AE and ME engine loads, fuel rates, and exhaust flows see Appendix E.

Table F-7 Detailed emissions summary additional metrics BSFC, water fraction, and sulfate fractions.

| Date | Project Name | Fuel | ATS | Location | Test Mode | Start Time | Engine Load | Fuel Rate Total | Sample Duration | DR | Exh Temp | Exh Flow Total II | bsFC FuelRate | bsFC FuelRate | $H_20$ Fraction | $O_2$ Conc | Fuel Sulfur $SO_2$ calc | | PM soot | | Sulfur Equivalent | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm/dd/yyyy | name | | | | | hh:mm:ss | % total | kg/hr | min | n/a | C | m3/hr | g/kWhr | g/kWhr | % | % | g/h | g/kWhr | g/hr | g/kWhr | S_PM | S_Gas |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 13:35:00 | 5% | 191 | 5.0 | 12.0 | 275.8 | 5406 | 0 | 230 | 4.89 | 12.8 | 4827 | 11.559 | 30.965 | 0.0374 | 0.02% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 13:45:00 | 5% | 194 | 5.0 | 12.0 | 275.1 | 5532 | 0 | 229 | 4.87 | 12.8 | 4914 | 11.515 | 27.620 | 0.0326 | 0.02% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 13:55:00 | 5% | 198 | 5.0 | 12.0 | 274.2 | 5635 | 0 | 228 | 4.82 | 12.9 | 5021 | 11.456 | 25.615 | 0.0295 | 0.02% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 14:55:00 | 7% | 276 | 5.0 | 12.0 | 260.7 | 8921 | 0 | 215 | 4.32 | 13.6 | 6985 | 10.747 | 21.739 | 0.0169 | 0.03% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 15:05:00 | 7% | 281 | 5.0 | 12.0 | 260.1 | 9047 | 0 | 214 | 4.29 | 13.6 | 7107 | 10.736 | 24.355 | 0.0186 | 0.03% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 15:20:00 | 7% | 277 | 5.0 | 12.0 | 260.6 | 8913 | 0 | 215 | 4.32 | 13.6 | 7011 | 10.757 | 23.077 | 0.0179 | 0.02% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 1 | 16:20:00 | 3% | 144 | 5.0 | 12.0 | 286.2 | 4026 | 0 | 247 | 5.05 | 12.6 | 3658 | 12.405 | 81.541 | 0.1396 | 0.02% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 2 | 16:30:00 | 3% | 147 | 5.0 | 12.0 | 285.7 | 4108 | 0 | 246 | 5.03 | 12.6 | 3717 | 12.360 | 74.008 | 0.1242 | 0.02% | 2.51% |
| 3/02/2017 | WWL Scrubber | HFO | n/a | AE Pre Scrubber | 3 | 16:40:00 | 3% | 139 | 5.0 | 12.0 | 287.6 | 3929 | 0 | 250 | 5.03 | 12.6 | 3510 | 12.556 | 95.103 | 0.1715 | 0.02% | 2.52% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 10:00:00 | 73% | 2382 | 10.0 | 6.0 | 231.7 | 86991 | 186 | 0 | 3.90 | 14.0 | 60343 | 9.090 | 70.268 | 0.0055 | 0.08% | 2.45% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 10:15:00 | 68% | 2208 | 10.0 | 7.2 | 226.2 | 82631 | 185 | 0 | 3.74 | 14.2 | 55931 | 9.110 | 64.700 | 0.0054 | 0.06% | 2.47% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 10:30:00 | 70% | 2263 | 10.0 | 9.6 | 227.9 | 84156 | 185 | 0 | 3.84 | 14.1 | 57325 | 9.093 | 69.876 | 0.0057 | 0.07% | 2.46% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 14:40:00 | 67% | 2156 | 10.0 | 8.1 | 224.7 | 80384 | 184 | 0 | 3.74 | 14.1 | 54631 | 9.022 | 71.513 | 0.0061 | 0.08% | 2.45% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 14:55:00 | 67% | 2166 | 10.0 | 8.2 | 225.0 | 79632 | 184 | 0 | 3.73 | 14.1 | 54864 | 9.025 | 70.920 | 0.0060 | 0.08% | 2.45% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 15:10:00 | 68% | 2186 | 10.0 | 8.1 | 225.6 | 81303 | 185 | 0 | 3.72 | 14.1 | 55379 | 9.036 | 71.142 | 0.0060 | 0.08% | 2.45% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 16:15:00 | 42% | 1360 | 10.0 | 12.0 | 205.3 | 53616 | 185 | 0 | 3.54 | 14.4 | 34465 | 9.066 | 54.995 | 0.0075 | 0.08% | 2.45% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 16:30:00 | 43% | 1373 | 10.0 | 11.6 | 205.5 | 53250 | 185 | 0 | 3.55 | 14.3 | 34779 | 9.077 | 52.964 | 0.0071 | 0.08% | 2.46% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 16:45:00 | 42% | 1360 | 10.0 | 12.0 | 205.3 | 53461 | 185 | 0 | 3.56 | 14.3 | 34445 | 9.073 | 53.240 | 0.0072 | 0.08% | 2.46% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 1 | 18:30:00 | 27% | 913 | 10.0 | 19.8 | 199.5 | 38006 | 191 | 0 | 3.22 | 14.7 | 23128 | 9.434 | 52.889 | 0.0111 | 0.07% | 2.47% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 2 | 18:45:00 | 27% | 889 | 10.0 | 19.8 | 199.3 | 38184 | 192 | 0 | 3.24 | 14.7 | 22524 | 9.480 | 46.446 | 0.0100 | 0.06% | 2.47% |
| 3/03/2017 | WWL Scrubber | HFO | n/a | ME Pre Scrubber | 3 | 19:00:00 | 27% | 899 | 10.0 | 19.9 | 199.3 | 39871 | 192 | 0 | 3.33 | 14.6 | 22782 | 9.462 | 46.101 | 0.0098 | 0.06% | 2.47% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 14:00:00 | 74% | 2411 | 10.0 | 7.8 | 223.8 | 93063 | 184 | 214 | 3.66 | 13.7 | 61083 | 8.834 | 103.448 | 0.0080 | 0.08% | 0.11% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 14:15:00 | 75% | 2461 | 10.0 | 7.8 | 225.1 | 93277 | 184 | 213 | 3.65 | 13.7 | 62342 | 8.841 | 102.174 | 0.0078 | 0.08% | 0.11% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 14:30:00 | 74% | 2429 | 10.0 | 7.8 | 224.4 | 92698 | 184 | 214 | 3.73 | 13.6 | 61535 | 8.836 | 101.717 | 0.0078 | 0.08% | 0.11% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 15:45:00 | 53% | 1733 | 10.0 | 12.1 | 207.0 | 69795 | 184 | 215 | 3.45 | 13.9 | 43896 | 8.889 | 116.720 | 0.0127 | 0.09% | 0.10% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 16:00:00 | 53% | 1733 | 10.0 | 11.5 | 207.0 | 72380 | 184 | 215 | 3.45 | 13.9 | 43908 | 8.889 | 114.142 | 0.0124 | 0.09% | 0.11% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 16:15:00 | 52% | 1706 | 10.0 | 11.9 | 206.6 | 69419 | 184 | 215 | 3.45 | 13.9 | 43218 | 8.897 | 115.299 | 0.0128 | 0.09% | 0.10% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 1 | 18:35:00 | 37% | 1243 | 10.0 | 20.1 | 200.1 | 50319 | 190 | 217 | 3.51 | 13.6 | 31501 | 9.193 | 129.536 | 0.0203 | 0.07% | 0.08% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 2 | 18:50:00 | 36% | 1222 | 10.0 | 19.8 | 199.9 | 49735 | 190 | 216 | 3.54 | 13.6 | 30954 | 9.214 | 135.764 | 0.0217 | 0.07% | 0.08% |
| 3/04/2017 | WWL Scrubber | HFO | n/a | ME AE Post Scrubber | 3 | 19:05:00 | 36% | 1219 | 10.0 | 20.5 | 199.9 | 49826 | 190 | 217 | 3.50 | 13.6 | 30892 | 9.216 | 146.142 | 0.0234 | 0.07% | 0.08% |

[1] for details on specific AE and ME engine loads, fuel rates, and exhaust flows see Appendix E.