Evaluation of a Modern Tier 2 Ocean Going Vessel on Two Low Sulfur Fuels

Final Report

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Acronyms and Abbreviations

σ	standard deviation
AE	auxiliary engine (diesel generator)
BC	black carbon
BSFC	brake specific fuel consumption
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
cm/s	centimeters per second
CO	carbon monoxide
COV	coefficient of variation
CO_2	carbon dioxide
DF	dilution factor
eBC	equivalent black carbon
EC	elemental carbon by NIOSH thermal optical methods
EPA	United States Environmental Protection Agency
IMO	International Maritime Organization
IMPROVE	Interagency Monitoring of Protected Visual Environment
ISO	International Organization for Standardization
kPa	kilo Pascal
lpm	liters per minute
MCR	maximum continuous rating
MGO	marine gas oil
MDL	minimum detection limit
ME	main engine
MFC	mass flow controller
ms	milliseconds
MSS	Micro Soot Sensor
NCR	nominal continuous rating
NIOSH	National Institute of Occupational Safety and Health 5040 protocol
NIST	National Institute for Standards and Technology
NO_x	nitrogen oxides
OC	organic carbon by NIOSH thermal optical methods
o.d.	outer diameter
OEM	original equipment manufacturer
PM	particulate matter
$PM_{2.5}$	fine particles less than 2.5 µm (50% cut diameter)
PTFE	polytetrafluoroethylene
QC	quality control
RPM	revolutions per minute
scfm	standard cubic feet per minute
S	sulfur
SO_2	sulfur dioxide
SO_x	sulfur oxide
UCR	University of California at Riverside

ULSFO .... Ultra-low sulfur heavy fuel oil

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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 (OGV)) represent a significant contribution of particulate matter (PM), sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions. Global shipping represents over 80% of the volume and 70% of the value of goods transported, thus shipping is a major contributor to our global emissions inventory. To control SO_x emissions from marine engines, International Maritime Organization's (IMO) Annex VI regulations include caps on the sulfur content of fuel oil which indirectly also reduces PM emissions. Providing the vessel meets the applicable sulfur limit, heavy fuel oil (HFO) is allowed by IMO if alternative technology is used to limit SO_x emissions to a fuel equivalent 0.1% sulfur (S). Ultra-low sulfur residual fuel oil (ULSFO) is available in lieu of high cost low sulfur distillate Marine Gas Oil (MGO). To minimize PM and NOx emissions further, the California Air Resources Board (CARB) requires OGV to use distillate fuels within 24 nautical miles of California coastline. The CARB fuel rule, thus, prevents OGV from operating with low sulfur residual fuels and high sulfur fuels combined with scrubbers.

Objectives: The objective of this work is to study the in-use emissions from a modern OGV while switching from a California approved distillate low sulfur fuel to a commercially available IMO approved ultra-low sulfur residual fuel. In this study a ULSFO fuel (0.089% sulfur) was compared to a low sulfur compliant MGO fuel (0.038% sulfur). This report presents an evaluation of the emissions comparison between these two fuels. The evaluation was performed on a slow speed diesel main engine (ME), a medium speed auxiliary engine (AE), and an auxiliary boiler housed in a 13,000 TEU container vessel.

Methods: The test methods utilized ISO 8178 E3 and D2 steady state test cycles to determine the emissions rate of gaseous and particulate pollutants for the ME and the AE, respectively. The auxiliary boiler was evaluated at 60% of maximum capacity. The emissions measured were regulated gaseous, $PM_{2.5}$ mass emissions, and PM composition which included elemental carbon PM, organic carbon PM, and sulfate PM. Additional speciated toxics, aldehydes and ketones, and trace metals were analyzed for the auxiliary boiler. Other methods and practices, such as dry to wet correction and NO_x humidity correction, followed ISO and CFR recommendations.

Results gaseous: The brake specific fuel consumption and carbon dioxide emissions were in good agreement with other large marine engine results suggesting the tests were performed well and were representative of a properly operated vessel. The estimated ISO weighted NO_x emissions were at the certification limit for the ME and below the certification limit for the AE. The emissions of the ME at slow speed maneuvering were 27.4 g/kWhr and 16.9 g/kWhr at cruise speed with a weighted emission of 21.29 g/kWhr for the MGO fuel, see Table ES-1. The ULSFO fuel showed higher NO_x emissions than the MGO fuel for the ME, AE and auxiliary boiler, but the differences were not statistically significant except for the auxiliary boiler.

Results PM: The weighted ME $PM_{2.5}$ for the MGO fuel were 0.219 g/kWhr and 0.295 g/kWhr for the ULSFO fuel, suggesting the ULSFO fuel was 35% higher $PM_{2.5}$ emissions than the MGO fuel, see Table ES-1 and Table ES-2. A paired t-test suggest the mean difference between the fuels were statistically significant. The higher ULSFO $PM_{2.5}$ emissions appears to be a result of higher organic carbon PM and elemental carbon PM. The AE and auxiliary boiler $PM_{2.5}$ emissions also varied between the sources where the ULSFO fuel was higher by 55% for the AE and 48%

lower for the auxiliary boiler, but these differences were not statistically significant based on a paired t-test. The organic carbon PM for the ULSFO fuel was higher by 90% compared to the MGO fuel and was statistical significant according to the t-test. The equivalent black carbon emissions (eBC) were low for all the sources and ranged from 0.4 mg/kWhr to 3 mg/kWhr to 0.02 g/kg-fuel for the ME, AE, and auxiliary boiler, respectively.

Table ES-1 Average weighted emissions for selected species (g/kWhr or g/kg-fuel)

Source	Fuel	NOx	PM2.5	PM_EC	PM_OC	PM_S	eBC
ME	MGO	21.29 ± 0.34	**0.219 ± 0.019**	**0.011 ± 0.001**	**0.186 ± 0.016**	0.002 ± 0.000	**0.0037 ± 0.0004**
ME	ULSFO	22.25 ± 0.19	**0.295 ± 0.007**	**0.015 ± 0.000**	**0.251 ± 0.006**	0.009 ± 0.000	**0.0047 ± 0.0004**
AE	MGO	8.31 ± 0.09	**0.137 ± 0.003**	**0.078 ± 0.002**	**0.060 ± 0.003**	0.002 ± 0.000	**0.088 ± 0.003**
AE	ULSFO	8.56 ± 0.04	**0.213 ± 0.021**	**0.051 ± 0.012**	**0.114 ± 0.016**	0.004 ± 0.000	**0.066 ± 0.002**
Boiler	MGO	1.68 ± 0.00	**0.055 ± 0.000**	**0.0002 ± 0.00000**	**0.035 ± 0.011**	0.000 ± 0.000	**0.0004 ± 0.00002**
Boiler	ULSFO	2.28 ± 0.08	**0.029 ± 0.000**	**0.0004 ± 0.00002**	**0.016 ± 0.000**	0.000 ± 0.000	**0.0001 ± 0.00003**

[1] PM2.5 is the PM gravimetric mass measurement (<2.5 µm), PM EC and PM OC are the elemental and organic carbon PM results using the thermal optical NIOSH method, eBC is the photoacoustic equivalent black carbon measurement. S PM is sulfur PM from the ion-chromatography method. The ME and AE emissions are in units of g/kWhr and the auxiliary boiler emissions are in units of g/kg-fuel. Uncertainties are represented by a single standard deviation with a sample of n=3.

Table ES-2 Percent change from baseline MGO fuel (positive implies increased)

Source	NOx	PM2.5	PM_EC	PM_OC	eBC
ME	5%	35%	35%	35%	26%
AE	3%	55%	-34%	90%	-25%
Boiler	36%	-48%	97%	-55%	-69%

[1] Blue percent differences are statistically significant mean differences using the student t-test.

Auxiliary boiler toxics: The auxiliary boiler aldehydes and ketones emissions were below detection limits except for formaldehyde, acetaldehyde, and acetone. Formaldehyde emissions were higher for ULSFO compared to MGO. The formaldehyde emissions ranged from 3.85 mg/kg-fuel for the ULSFO to 0.688 mg/kg-fuel for the MGO fuel. The acetaldehyde emissions ranged from 0.929 mg/kg-fuel for the ULSFO fuel to 0.439 mg/kg-fuel for the MGO fuel. The mean differencces between the MGO and ULSFO fuel was only statisticaly significant for the formaldehyde emissions.

The metal emissions were low and near the detection limits except for nine metals. These nine metals were higher for the ULSFO fuel compared to the MGO fuel except for Chlorine and Nickle.

Speciated hydrocarbons (C2 – C12) were collected in SUMMA canisters. Due to laboratory communication errors, these results were not available for this report.

Summary: Utilizing a low sulfur residual fuel oil increases the vessels overall PM, toxics, and NO_x emission in comparison to a low sulfur California approved distillate fuel. The emissions impact during transit were higher for PM emissions, but for at-berth operation NOx and toxic emissions were higher. Although there is a global benefit for the use of low sulfur residual fuels, there use near ports will increase local emissions compared to distillate fuels.

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) transported showing the impact this industry has on the environment. The major pollutants in ship exhaust are particulate matter with an aerodynamic diameter less than 2.5 µm ($PM_{2.5}$), sulfur oxides (SO_x), and nitrogen oxides (NO_x) (Dalsøren et al 2009, Endresen et al 2007, and Endresen et al 2005). NO_x emissions cause photochemical smog and marine engines are one of the highest emitters of 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 has been linked with increased mortality in coastal regions, with an estimated 60,000 deaths from cardiopulmonary and lung cancer per annum attributed to $PM_{2.5}$ emissions from ship exhaust (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 emit mostly EC and OC PM fractions where the split depends on the fuel quality (Johnson et al 2015).

To control SO_x emissions from marine engines, the IMO MARPOL Annex VI regulations include caps on the sulfur content of fuel oil in emission control areas (ECA) and in global waters, see Figure 1-1 and Figure 1-2. The regulation indirectly reduces PM emissions although the IMO does not have any explicit PM emission limits. Providing the vessel meets the applicable sulfur limit, HFO is allowed even with the ECA fuel sulfur rule 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. Recently, residual ultra-low sulfur fuel oils (ULSFO) have become available that meet the 0.1% sulfur limit, but their total PM and gaseous emissions are not well understood. The exhaust emissions from these new ULSFO fuels are of interest to the California Air Resources Board (CARB).

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 has 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 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.

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. This study is designed to quantify the in-use emissions from a modern Tier 2 container vessel (13,000 TEU) operating on two low sulfur fuels; a residual fuel oil ULSFO and a low sulfur distillate MGO fuel meeting the CARB fuel rule[1].

A container vessel was selected for this study since they represent a large consumer of fuel, frequently visit US ports, and represent a large fraction of the global OGV 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). The 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. It should also be pointed out that container vessels have engines that are about five times larger than bulk carriers and tankers so their impact on the emissions inventory may be grater even thought their calls are less.

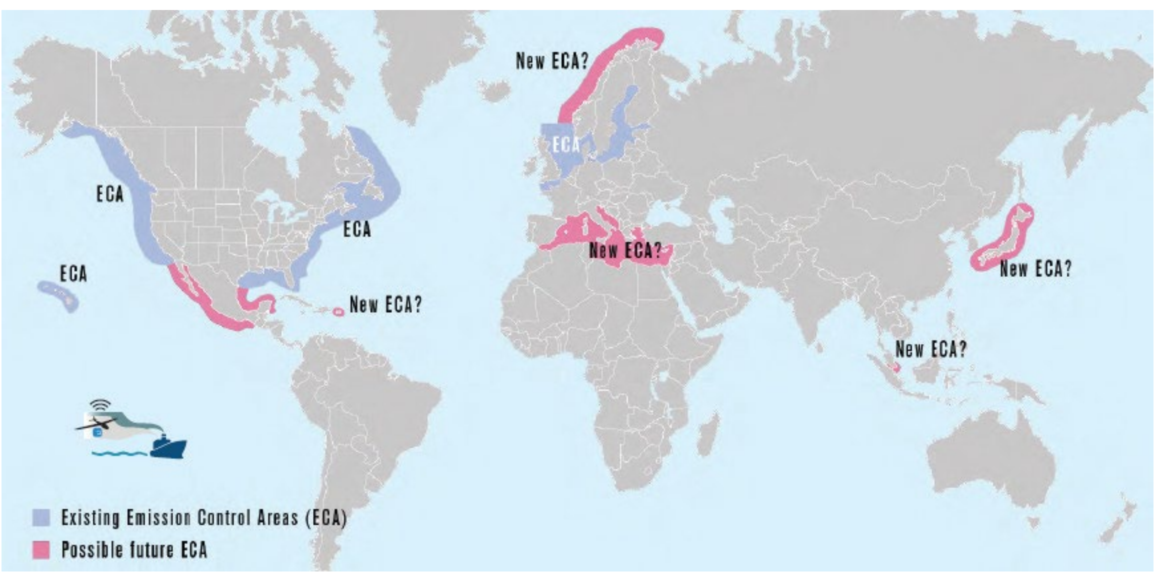


Figure 1-1 Emission control areas (adapted from CLS 2015)

[1] https://www.arb.ca.gov/ports/marinevess/documents/fuelogv13.pdf

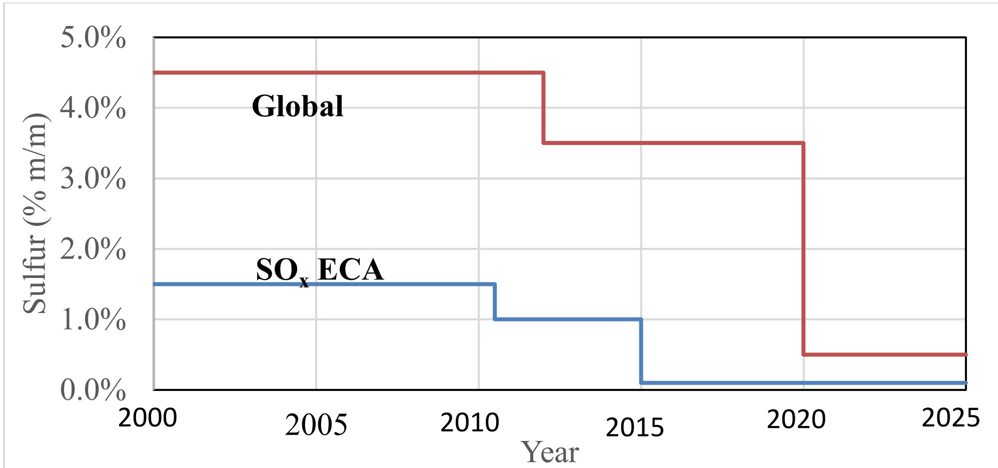


Figure 1-2 Global and ECA fuel sulfur limits

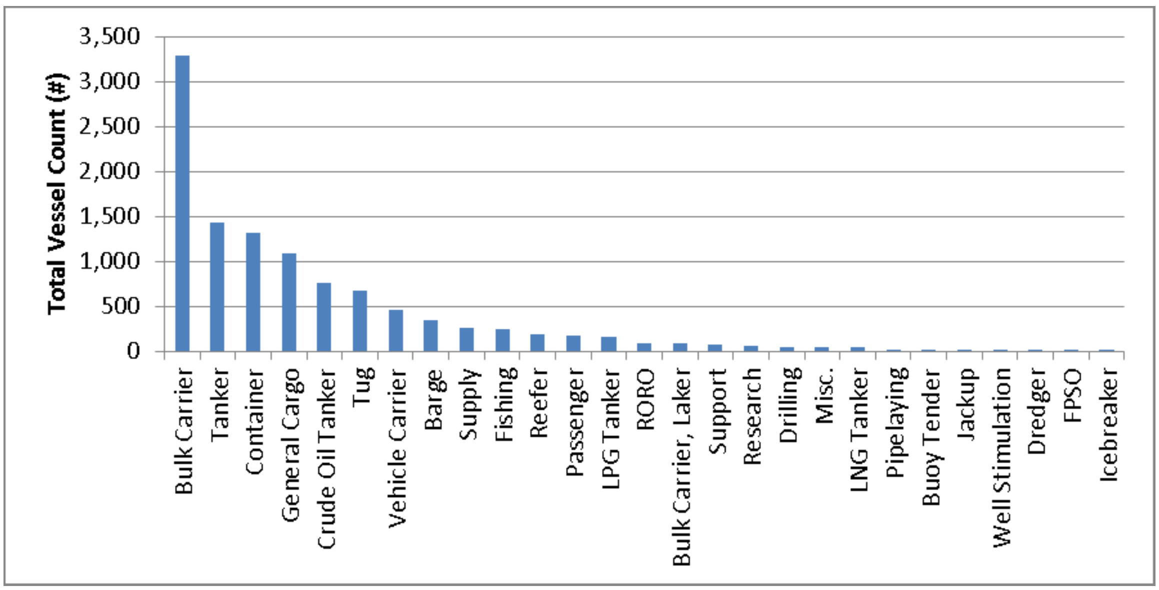


Figure 1-3 Ship inventory count by vessel category (ERG 2015)

1.2 Objective

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

While there are many available technologies to focus on that have been successful in reducing criteria pollutants such as PM, SO_x and NO_x, 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.

In addition to helping to bring awareness to new propitious technologies, as part of the "Sunset Review" for the California Ocean-Going Vessel Fuel Regulation (OGV Fuel Rule[2]) it was determined that there is a need for additional testing of scrubbers and low sulfur non-distillate fuels, tanker auxiliary boilers and auxiliary boilers, as well as alternative fuels such as LNG, which are allowed under the federal ECA regulation, but not directly under the California regulation.

The purpose of this testing is to understand the in-use emissions from a modern Tier 2 ocean going vessel operating on ULSFO and MGO. 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), and a method for equivalent black carbon (eBC). Additional speciated toxic sampling was performed on the auxiliary boiler.

[2] https://www.arb.ca.gov/ports/marinevess/documents/fuelogv13.pdf

2 Approach

This section outlines the in-use emissions testing approach for the modern Tier 2 engine. 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 engines, auxiliary boiler, vessel, engine condition, and fuel are described in this section.

2.1.1 Vessel details

The tested article is a modern container vessel (class DNV + 1A1 Container Carrier) with a deadweight tonnage of 141,550 tons and a net tonnage of 140,979 tons, and an overall length of 350 m and a breadth of 48.2 m, see Table 2-1. The manufacturer of the vessel is Hyundai Samho Heavy Industries, South Korea. The vessel's keel was laid in December 2011 and was delivered in July 2012 for service, see Appendix D. The vessels service speed is 18 knots and is equipped with one main engine (ME), five diesel auxiliary engines (AE) and one auxiliary boiler.

Table 2-1 Tier 2 test vessel specifications

MY	*Class*	*TEUs*	*Draught*	*Length*	*Breadth*	*Service Speed*
2012	DNV-1A1	13,082	15.5	350	48.2	18.0
ULSFO m^3	***MGO Capc. m^3***	***Ballast Water***	***Fresh Water***	***ME***	***AE***	***Aux Boiler***
1,583	425.5	36,600	501	1	5	1

[1] MY is the delivery model year of the vessel, ME is the main engine, and AE is the auxiliary diesel engine/generator. ULSFO is the ultra-low sulfur fuel oil, MGO is marine gas oil. There are also two other fuel tanks on this vessel, they are a heavy fuel oil tank (8,380 m^3) and a diesel oil tank (121 m^3).

2.1.2 Combustion sources

Engines: The ME is a Tier 2 12-cylinder Hyundai MAN-B&W AA4214 72.24 MW SSD 2-stroke engine with a total displacement of 21,723 l (1,810 l/cylinder). The ME turbo systems are equipped with an electronic engine control system model ME-C-ECS ver 1109.1.25. The AEs are Tier 2 HiMSEN BA3707-1 2.87 MW medium speed diesel (MSD) 4-stroke engines with a displacement of 193 l over 6-cylinders (32 l/cylinder). The AE represents around 10% of the total exhaust flow compared to the ME, thus the ME represents the most significant impact on the emissions from the vessel, see Table 2-2. The vessel ME shop-trial was performed in March 2012 from 25% to 110% engine load and showed a brake specific fuel consumption (BSFC) of 171.4 g/kWhr and the AE shop trial was performed in July 2011 from 10% to 100% load with a slightly higher BSFC (shop trial utilized a DMA fuel with a lower heating value was 42.26 MG/kg), see Appendix E.

Auxiliary boiler: The auxiliary boiler tested is a standard auxiliary boiler manufactured by KangRim Heavy Industries Company Ltd. in South Korea. It is a vertical auxiliary boiler with a pressure jet system (RP-500M), with a maximum fuel rate heating capacity of 408 kg/hr utilizing a HFO fuel (287.8 kg/hr utilizing MGO fuel), see Figure 2-1 and additional details in Appendix E. The Chief provided a measured fuel consumption for the auxiliary boiler, this was recorded, but was later found to be a constant value and was not representative of the fuel consumption from the auxiliary boiler, see discussion in Appendix E. Since there was no measured fuel consumption available, load was determined by the physical notch percentages setting which varied from 40% to 60% of the maximum rating for the auxiliary boiler. According to the Chief, 40% is used less frequently and 60% is very common and typically the highest auxiliary boiler load utilized. Further investigation on auxiliary boiler operation from discussions with the vessel management firm and the auxiliary boiler manufacturer, auxiliary boiler operators is as follows:

- **Auxiliary boiler = auto Modulation = auto**, the fuel rate will increase steadily until the auxiliary boiler pressure is reaching (the final set pressure). At this point the auxiliary boiler will shut off. The process will cycle. Normal usage at-berth, slow steaming (VSR), and normal steaming. This mode was used during this testing for 60%.
- **Auxiliary boiler = auto Modulation = manual**, then the auxiliary boiler will fire at the fixed fuel rate which is set by the user. Once the auxiliary boiler pressure reaches the set pressure then the auxiliary boiler will switch off. During issues with auto or to run excess steam.
- **Auxiliary boiler = manual Modulation = manual**, then the auxiliary boiler will fire at the fixed fuel rate however auxiliary boiler will not switch off when the set pressure is reached. The excess steam produced will start to dump once the steam pressure exceeds the dump valve set pressure. Used where there are issues with auto mode. Not performed often. This mode was utilized for the 40% load point.

During this testing, the auxiliary boiler was found in the Auto/Auto mode for the 60% load. The fuel oil flow in the auxiliary boiler is relatively constant in Auto/Auto mode while the auxiliary boiler produces the highest steam rate for the fuel heating, galley, and cabin space heating. To perform the low load condition (40% load) the crew put the auxiliary boiler in Auto/Manual mode. The 40% load point created visible smoke that is not normally observed while container vessel are loading and unloading containers at-berth. Discussions with a large market share auxiliary boiler manufacturer suggest the 40% load was not a reasonable load point due to the visible smoke. A better way to reach low steam loads would be to run at 60% fuel rate, but cycle the auxiliary boiler on and off to achieve a lower steam rate. As such, the 60% load was considered a representative load point and the 40% load point was considered not representative and the emissions data was removed from this report.

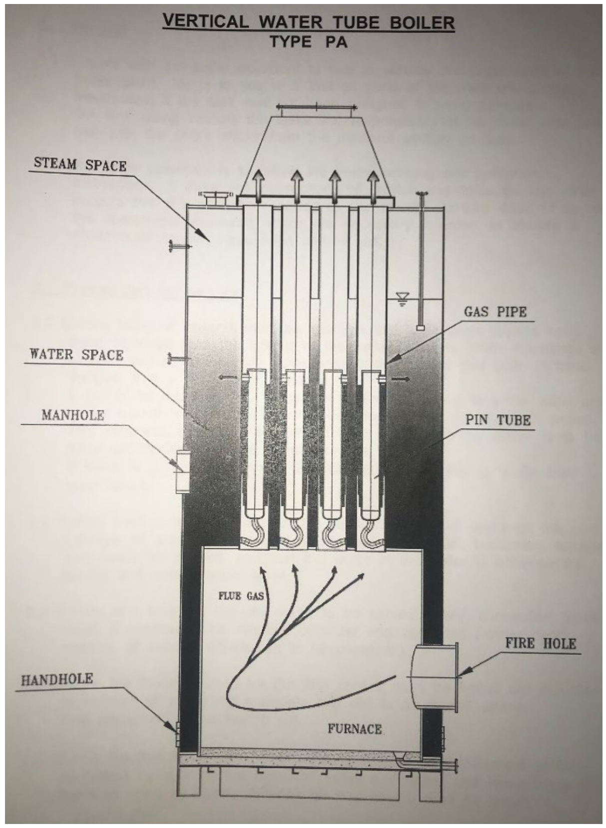


Figure 2-1 Schematic figure of the auxiliary boiler tested

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

Source	*Mfg.*	*Model*	*Rating kW*	*Exhaust Fraction[3]*
ME	MAN-B&W	AA4214	72,2400	91%
AE5	HiMSEN	BA3707-1	2,870	5%
Boiler	KangRim	RP-500M	408 [2]	4%

[1] Data for the ME and AE are based on the documentation on the ship including the shop trial, NOx technical code, and the ship particular reports.
[2] Auxiliary boiler max rating is 408 kg/hr HFO fuel consumption rating (not a power rating). MGO fuel rate is
[3] The exhaust fractions provide an estimate of the fractions of exhaust each source contributes to a total emission from the vessel based on estimates (typical vessel speed ~ 44% ME MCR, AE ~50% MCR, and the auxiliary boiler at 60%). Fractions will vary while at the port or under different vessel speeds and generator needs.

PM emissions are known to vary with the condition and age of diesel engines. OGVs accumulate some of the highest engine hours where PM emissions may be significantly impacted by the status of the engine age and maintenance. After an overhaul some 2-stroke engines utilize increased lubrication during the running-in period where it is expected PM emissions will be elevated. During testing the ME accumulated hours were around 17,000 hr and around 4,000 for the AE tested. Typical ME recommended cylinder overhaul interval is 20,000 hrs where an overhaul was not recently performed and not needed.

The AEs showed similar records where the tested engine (AE5) was not in need of an overhaul and was in good working order. If an engine overhaul is performed for the AE, 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 AE maintenance records at the time of testing suggest the PM emissions from the vessel should be representative of a properly operating OGV. In addition, the auxiliary boiler was in good working order and its emissions are representative of properly maintained auxiliary boilers.

2.1.3 Test fuels

A standard low sulfur MGO fuel and a commercially available ULSFO fuel were used. An exemption was provided by CARB to allow the ME, AE and auxiliary boiler to be operated in Regulated California Waters (a zone approximately 24 nautical miles seaward of the California baseline) on the ULSFO fuel instead of compliant low sulfur MGO fuel required by the California Fuel Rule[3]. The ULSFO had a fuel sulfur level of 0.089% and the MGO fuel had a level of 0.038%, see Table 2-3. The ULSFO also showed a higher viscosity, density, and residual carbon content compared to the MGO fuel. The carbon residual ash was 0.5 for the ULSFO fuel and 0.08% for the MGO fuel. The heating value of the ULSFO fuel was reported as having a heating value 2.5% lower than the MGO fuel and this was incorporated in fuel consumption differences between the ME, AE and auxiliary boiler results. The shop trial ME and AE were performed with a fuel rated at a LHV of 42.26 MJ/kg, see report copy Appendix E.

Table 2-3 Fuel properties for the MGO and ULSFO fuels tested

Tests	Method	Units	ULSFO	MGO [1]
API@60	ASTM D4052		34.24	36.65
SPgr@60			853.7	841.5
Density@15		kg/m3	853.2	841.0
Viscosity@40	ASTM D445	cSt	20.96	3.474
Cetane Index	D4737B			
Carbon Resid.	ASTM D524	mass %	0.5	0.08
Sulfur	ASTM D2622	ppm	893.4	384.4
CCAI	calc.	n/a	719.1	752.4

[1] MGO fuel sulfur was analyzed using ASTM D5453 due to expected low sulfur concentration (< 0.01 %). Sulfur level was higher than expected for MGO, but the selected method is still accurate at the levels measured. CCAI is a calculated value, see details in Appendix E.

2.2 Sampling approach

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

2.2.1 Sample locations

The sampling approach was similar for the ME, AE, and auxiliary boiler emission sources where additional toxic samples were collected for the auxiliary boiler. The sampling locations are 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

[3] https://www.arb.ca.gov/ports/marinevess/documents/fuelogv13.pdf

ME sample was performed just before the waste heat economizer, see Figure 2-2. The AE was sampled in a straight section two decks above the engine turbo exit and one deck below the ME sample, see Figure 2-3. The auxiliary boiler was sample four feet above the heat exchanger in an existing thermopile on the same deck as the AE sampling, see Figure 2-4.

Sampling around an ME economizer is 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 maintain economizer efficiency and performance, ships employ a periodic (at best daily) cleaning process of the heat exchanger surfaces. During cleaning, large amounts of PM (>20%) can be expected to be released that, if sampled, would overestimate the PM emissions factors of the ship. During this testing the Economizer was cleaned during berth in Long Beach prior to testing and was allowed to stabilize for three hours before UCR collected its samples during the voyage from Long Beach to Oakland.

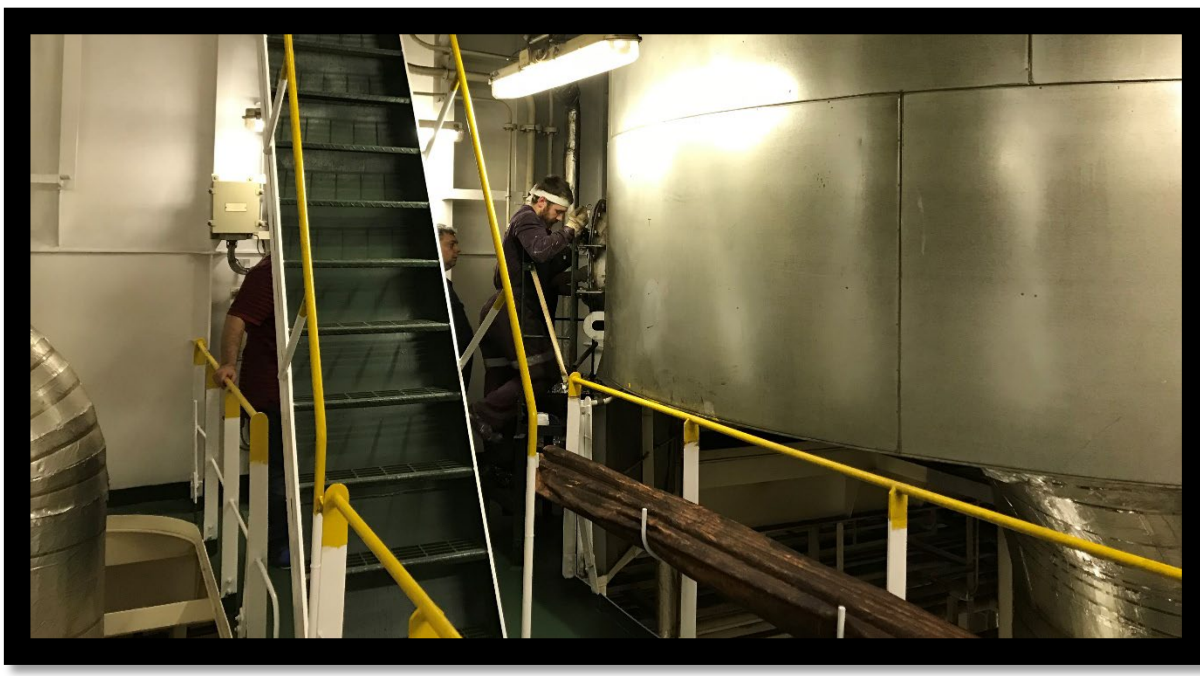


Figure 2-2 Setup on the ME, before the economizer (two decks above the ME)

2.2.2 Toxic sampling

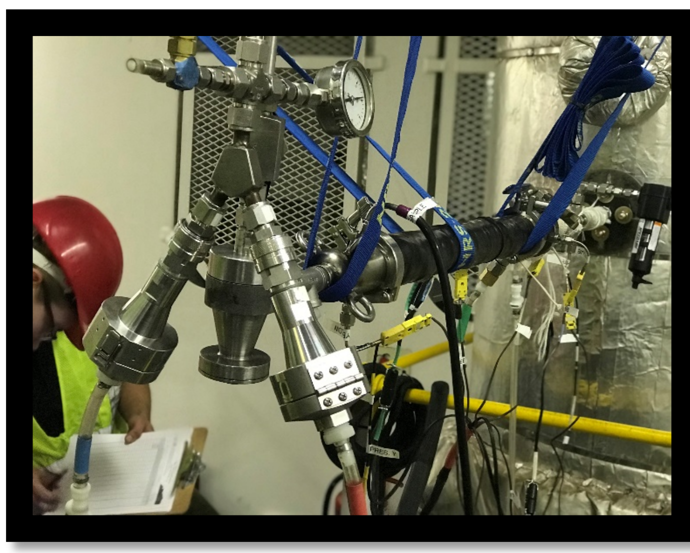
CARB utilizes speciation estimates from auxiliary boiler emissions that are used in the emission inventory and air quality models. These models are lacking toxic data from marine auxiliary boilers. As such, additional toxic samples were measured for the auxiliary boiler tests. These included including aldehydes and ketones, speciated hydrocarbons, and metals.

Aldehydes and ketones: The aldehydes and ketones were sampled onto 2,4-dinitrophenylhydrazine (DNPH) cartridges and analyzed off site at Environmental Analytical Services Inc, see Figure 2-4 for setup. 17 species were analyzed following EPA method TO-11A

Modified HPLC (high performance liquid chromatography). As part of this method several quality control checks are performed which include species spikes, blanks, and controlled duplicates. All quality checks passed at the presented aldehydes and ketone data is representative of valid analytical methods.

Speciated hydrocarbons: Speciated hydrocarbons were measured using $C_2 – C_{12}$ by GC/MS/FID analytical methods. The analytical methods were performed offline using an outside laboratory (Atmospheric Analysis and Consulting Inc. AAC in Ventura CA.). The speciated hydrocarbons include Ethylene to n-Dodecane and are represented by 56 selected species. The analytical methods are in accordance with AAC's ISO/IEC 17025:2005 and NELAP quality assurance plan. Samplers were collected in stainless steel evacuated SUMMA canisters provided by AAC, see Figure 2-4.

Metals: The metal analysis was performed on the Teflon PM samples using X-Ray Fluorescence (XRF) from an offline analytical method utilizing the same Teflon filters used to determine the $PM_{2.5}$ mass. The filters were first weighed then sent out for XRF analysis. The method offers analysis of elements (Na through Pb) represented by 38 elements. XRF is an EPA approved, non-destructive analytical method (IO-3.3) wherein a filter is bombarded with X-ray energy. The subsequent excitement of electrons can be measured when the electrons fall back to their valence state, releasing energy in the process. Each element has a "fingerprint" of energy discharges which are measured to determine the quantity of each element.



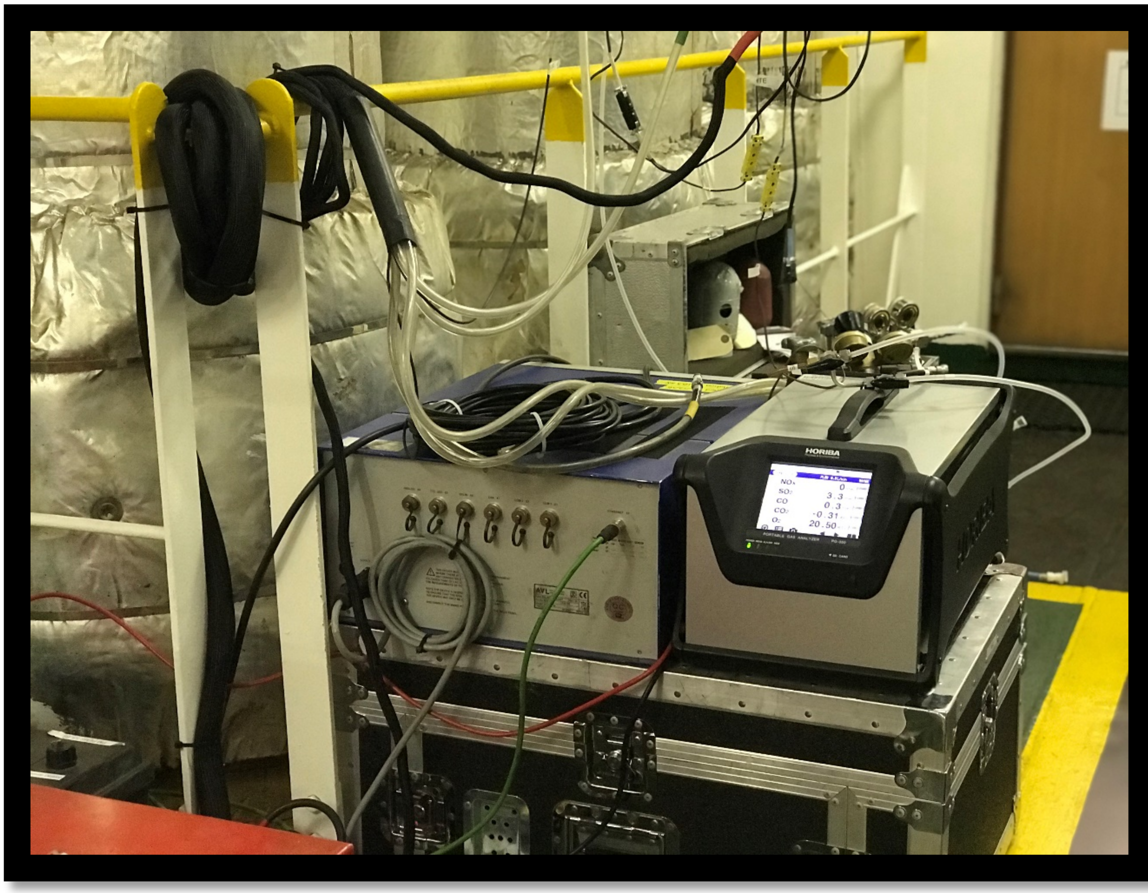


Figure 2-3 Setup on the AE (two deck above the AE)

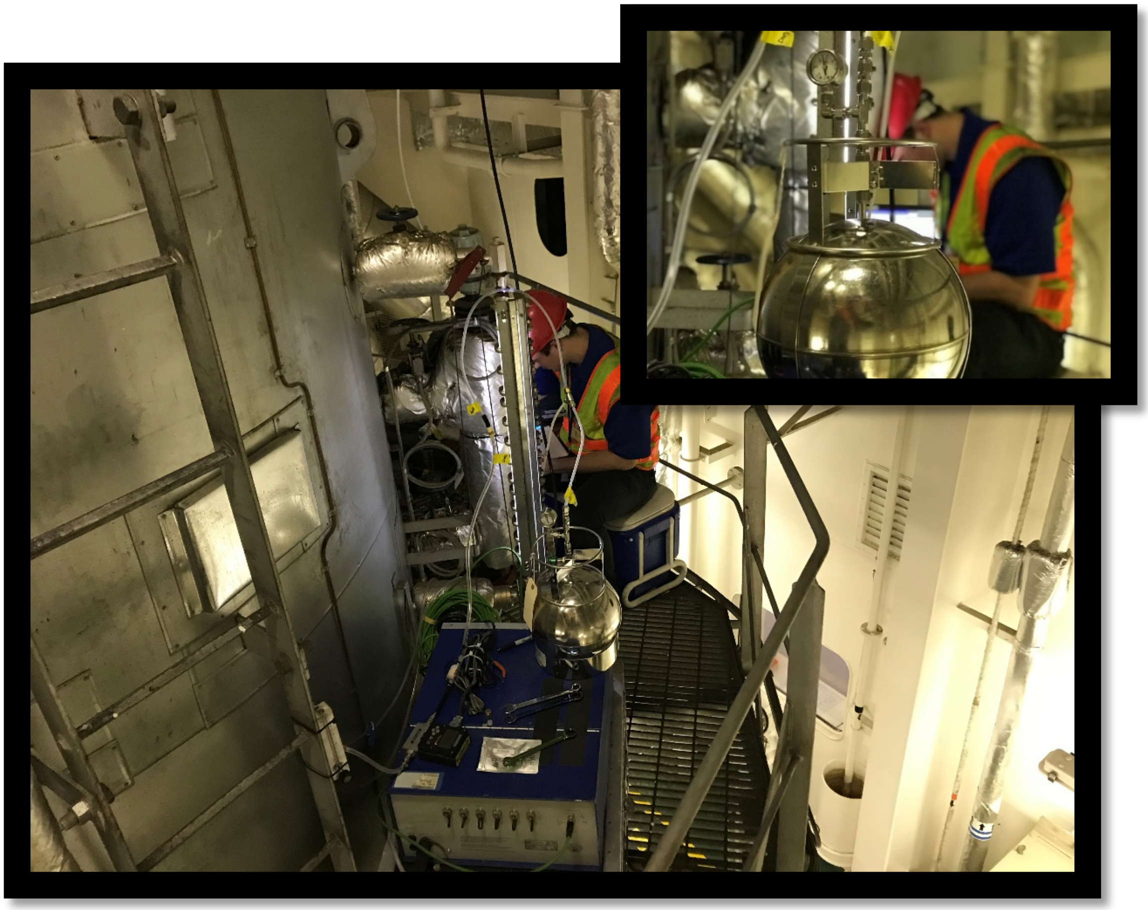


Figure 2-4 Auxiliary boiler setup: probe removed for sampling, SUMMA canister detail

2.2.3 Test matrix

The test matrix subsection covers typical engine certification cycles, proposed test cycles for on-sea and in-use testing, and the impact these load points may have on the analysis.

Engine certification: The ME is directly connected to the propeller where vessel speed is follows the propeller curve. Direct drive engines are certified per the ISO 8178-4 E3 marine test cycle, see Table 2-4 for typical certification test points. Constant speed AEs follow the ISO-8178-4 D2 test cycle, see Table 2-5 for typical certification load points. The maximum achievable ME and AE load are less than 100% and depend on several factors including constraints by navigational details, 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 43% MCR and 63% MCR for the AE as per the Chief Engineer. For additional information on engine test cycles see Appendix C. Emission estimates at higher loads were calculated and are explained in Section 2.3.4.

Table 2-4 Test cycle for ME variable speed (direct drive) engines

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 5th mode at around 10% load and 50% speed. The vessel did operate in areas that utilize VSR, thus, the 10% point is recommended.

Table 2-5 Test cycle for constant-speed auxiliary 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 at-berth. Table 2-6 shows typical ME, AE, and auxiliary boiler operation for the vessel under these different conditions based on discussions with the Chief. While at sea, the ME typically operates at 45% load and two AEs are operated for ship services, hotel, and maneuvering power (typically at loads from 30% to 50% loads and depends on the vessel's needs). During port maneuvers, the ME power is reduced to 10% load while the AEs increase in load and two are operated at higher loads, but still below 60% where a third engine will come on to keep loads at 60% and lower. While at-berth (loading and unloading goods), two AEs are used at around 40% where the other three are reserved for backup and the ME is at zero load (AEs are at 0% if there is shore power). Most of the vessel operation is based on at-sea conditions, estimated to be 95% of the vessel operation, while approximately 1% (or less) is representative of maneuvering, and entry and 4% is representative of at-berth.

Table 2-6 Expected vessel ME, AE, and auxiliary boiler operation modes

Activity	% Load MCR			Auxiliary boiler
	ME	AE4,5	AE1,2,3,	
At Sea	45%	30-60%	backup	60%/Off
Port maneuver	10%	30-60%	backup	60%
At-berth	0%	30-60%	backup	60%

[1] There are 5 AE engines, one ME and one auxiliary boiler.

The matrix of test points and their sequence is provided in Table 2-7. This matrix includes testing the ME at a 9% to 45% load and the AE from 25% to 65%. The auxiliary boiler was operated at two load estimates of 40% and 60%, in Appendix E for more details. Based on discussions after the testing, it was discovered the 40% auxiliary boiler operation is not a representative load for normal operation therefor this data is not presented in the main body of the report. Efforts were made in consulting with the Master and Chief to target loads as close as possible to those in Table 2-5.

The auxiliary boiler is operated at 60% load until the steam pressure is reached then the auxiliary boiler shuts off. The turning on and off of the auxiliary boiler is what is used to meet different loads and is called the duty cycle of the auxiliary boiler and the duty cycle will depend on the actual steam needs. During a port call the auxiliary boiler operates at a normal duty cycle, during normal steaming the auxiliary boiler is typically off where the ME can provide the hot water needs. During slow steaming (vessel speed reduction, VSR), the low exhaust temperature results in the auxiliary boiler being turned on where the duty cycle is lower than when at a port. More research is needed to quantify activity measurements of auxiliary boilers to understand their real duty cycle and emissions impact.

Sequence of events: Due to the fuel switch on three sources there were seven days of testing needed to complete this work. Table 2-7 shows the sequence of events used to complete the testing on each source. The test setup moved between different sampling locations which occurred only once per fuel combination. Overall, it took two to three days for each combustion source to complete the work (one day for initial setup and then testing for two more days), with each setup move taking approximately 6 to 8 hours, so moves were minimized. UCR started testing the AE first on MGO fuel (typical port entry fuel), then fuel switch after approval forms were in hand. UCR tested the auxiliary boiler next followed by the ME. In each case the MGO fuel was tested first as listed in the table. During testing the ME loads were similar for each of the test repeats so the data is representative of valid and comparable data between the fuels.

Table 2-7 Test plan sequence

Day	Location	Special Notes	Source	Fuel	Mode	Load %
1	Dock [1]	-	AE	MGO	2	50-
1	Dock [1]	-	AE	MGO	1	65
1	Dock [1]	-	AE	MGO	3	25
2	Dock [1]	-	AE	ULSFO	2	50
2	Dock [1]	-	AE	ULSFO	1	65
2	Dock [1]	-	AE	ULSFO	3	25
3	Dock [1]	-	boiler	MGO	1	60
3	Dock [1]	-	boiler	MGO	2	40
5	Dock [1]	-	boiler	ULSFO	2	40
5	Dock [1]	-	boiler	ULSFO	1	60
6	at-sea [2]	-	ME	MGO	3	13
6	at-sea [2]	-	ME	MGO	4	9
6	at-sea [2]	-	ME	MGO	2	32
6	at-sea [2]	-	ME	MGO	1	45
7	at-sea [2]	-	ME	ULSFO	2	32
7	at-sea [2]	-	ME	ULSFO	1	45
7	at-sea [2]	-	ME	ULSFO	3	13
7	at-sea [2]	-	ME	ULSFO	4	9

[1] Testing of the pre-scrubber AE occurred in Long Beach, CA [2] Testing of the main engine occurred at-sea between Long Beach and Oakland where the MGO was tested first followed by the ULSFO. There were 10, 10, and 3 hours between the AE, Auxiliary boiler, and ME MGO test and the first ULSFO test to allow for a complete fuel switch respectively. There was no testing on Day 4.

Dilution ratio: Previous ship testing has utilized high dilution ratios (~20:1) 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 and varying dilution ratio with-in these DR conditions. The testing performed in this project was at the targeted 6:1 following the EPA recommendations as specified in Appendix A. Higher dilution ratios (up to 15:1) were utilized for the high PM conditions of the auxiliary boiler where filter weights were 30 times higher than the ME and AE filter weights.

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). This was possible on the ME and AE tests, but due to strict time constraints on the auxiliary boiler this guide was not followed, but emissions were stable regardless.
- 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). For the auxiliary boiler tests the filter weights exceeded 2000 µg even with short sampling times of 6 minutes and high dilution.
- 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. BSFC was not available on this vessel, thus shop trial BSFC was utilized
- 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 (proposed load points to meet EPA desires), 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 was measured with a Horiba PG-350. Nitrogen Oxides (NO_x) utilize a heated chemiluminescence detector (HCLD), carbon monoxide (CO) and sulfur dioxide (SO_2) utilize non-dispersive infrared absorption (NDIR) with cross flow modulation, and oxygen (O_2) utilize a zirconium oxide sensor, 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 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.

Gaseous concentrations were measured directly from the raw exhaust. Dry-to-wet correction were performed using calculated water concentration from the exhaust. Intake air humidity was measured in order to correct for humidity effects on NO_x emissions as per ISO and CFR.

PM2.5: UCR's PM measurements use a partial flow dilution system that was developed based on the ISO 8178-1 protocol, 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 47 mm 2um pore Teflon filters (Whatman Teflo) weighed offline with UCR's UPX2 Mettler Toledo micro balance in a temperature, humidity and particle-controlled environment. The microbalance is operated following the weighing procedures of the Code of Federal Regulations (CFR). Before and after collection, the filters are conditioned for a minimum of 24 hours in an environmentally controlled room (RH = 40%, T = 25 C) and weighed daily until two consecutive weight measurements were within 3µg.

PM Composition: The project measured PM composition which comprises 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 NIOSH method and the sulfate PM was analyzed using a ion-chromatography method during off-site analysis. The sulfate PM presented in this report (denoted as PM_S) is hydrated sulfate particulate matter in the form $H_2SO_4*6.656H_2O$ where the hydration occurs at temperature of 20 °C and 45% RH as per 40 CFR Part 1065. The PM composition filters were sampled from UCR dilution tunnel.

Equivalent black carbon (eBC). Bond et al (2013) provided a definition of BC measurement methods as they relate to characterizing climate impacts. The photoacoustic measurement method is considered to be an equivalent BC method (denoted as eBC), the NIOSH thermal optical method is an apparent elemental carbon measure of BC (denoted as EC), single particle soot photometers such as the laser-induced incandescence measure the refractory nature of BC (denoted as rBC), and particle soot absorption photometers such as the Aethalometer and MAAP instruments measure the equivalent BC (denoted as eBC). The instrument utilized for BC measurements in this study was UCR's in-house photoacoustic real-time analyzer (AVL MSS-483) which represents the eBC measurement method as defined by Bond and is utilized here for consistency. The photoacoustic measurement method is a reliable and robust measurement for quantifying marine BC where the PM fractions vary significantly and have been shown to impact the EC measurement method (Bond et al 2013 and Johnson et al 2016). The photoacoustic measurement was sampled from the same dilution tunnel used for the gravimetric and NIOSH filters, see Figure 2-5 with a dilution ratio of ~6:1 for the AE and ME and up to 15:1 for the auxiliary boiler, see details in Appendix F.

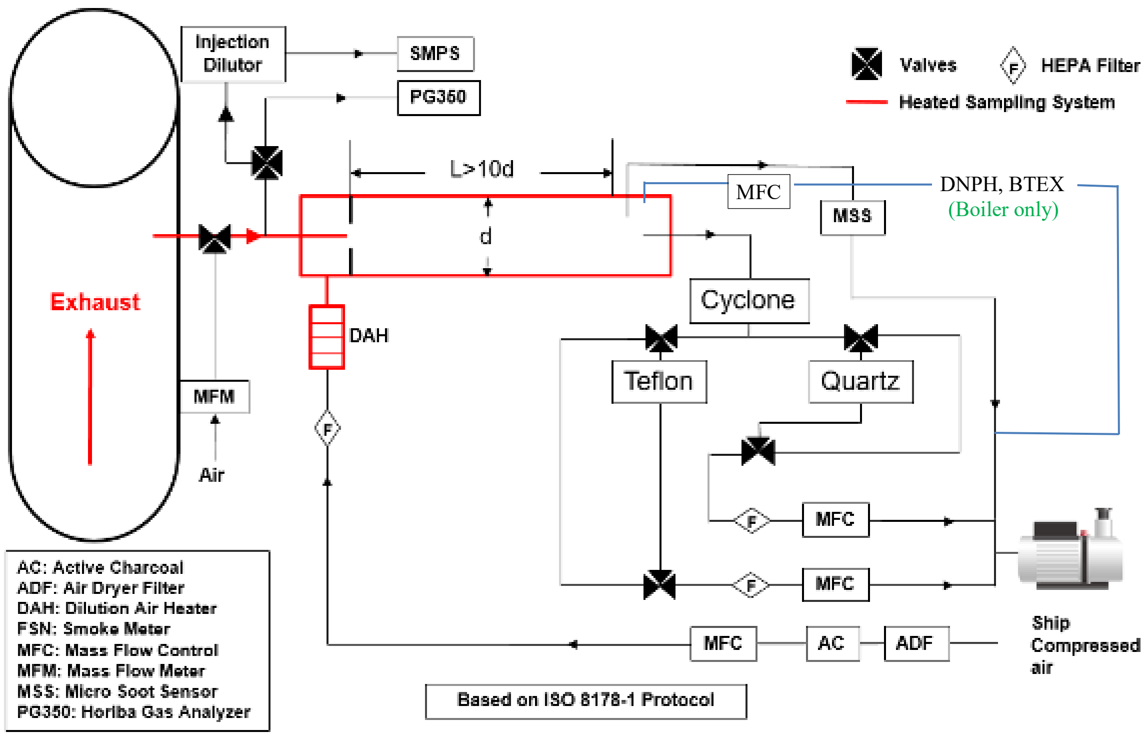


Figure 2-5 Schematic of the dilution sampling system

[1] DNPH aldehyde and ketone sample, BTEX speciated HCs (C2-C12) samples, SMPS particle size distribution.

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 Toxics

The toxic samples were collected off of the dilution tunnel ten diameters from the mixing point and flow was controlled with a mass flow controller for the DNPH and a critical flow orifice for the BTEX sample. In addition to the sample analysis, quality control checks were run and are provided in the Appendix B. The BTEX samplers had issues so there is no data reported for these samples.

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 shop trial vessel fuel consumption for the ME and AE). Generalized auxiliary boiler fuel consumption was utilized from reported values.

3. Air and Fuel Measurement Method (not available)
4. Air Pump method (**utilized** and compared to carbon balance for scavenging fractions) AE and ME only. Not the auxiliary boiler.

Direct exhaust flow measurement is complex and requires long straight exhaust stack sections, without bends, which is not typically available on OGVs. Thus, direct measurement has not been a preferred method at UCR. Fuel flow measurement is the next best method for inferred exhaust flow measurements, but was not available on this OGV. When measured fuel flow is not available, then reported BSFC[4] is utilized in conjunction with the carbon balance calculation method. The air pump method, which is based scavenging air temperature, pressure, and RPM, is also typically available on all vessels. For the work presented in this study the exhaust flow was determined by the **Carbon Balance Method** and by the **Air Pump Method** (not for the auxiliary boiler). For specific calculation details see Appendix A and Appendix E for details on exhaust flow values and assumptions.

2.3.4 Engine

Chapter 6 of the NO_x Technical Code "Procedures for demonstrating compliance with NO_x emission limits on board" provides detailed instructions for the required measurements for on-board testing. 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 AE.

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 (shop trial)	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 Engine load

Engine load was recorded in the engine room on a percent basis for each test. The actual load calculated was based on the lower heating value (LHV) of the fuel used during the shop trial and

[4] Shop trial reports were available for the ME and AE engines. The reports include BSFC at each load point from which fuel flow can be estimated. The estimated fuel flow and the carbon balance method is then used for the reporting of exhaust flow. The boiler also had reported fuel flow at different loads which was utilized for the boiler emissions.

the measured LHV for the ULSFO and MGO fuel. The difference between these fuels is 2%. See Appendix E for specific details on the LHV.

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 Factors

Since the actual loads for the ME and AE could not be performed at each of the certified ISO load points (see Table 2-4 and Table 2-5) estimates were utilized to achieve the 10%, 75% and 100% load points emission factors. These estimates are needed in order to calculate an equivalent in-use ME and AE emission factor and then compare this with the NO_x standard. Table 2-10 and Table 2-11 show the estimated NO_x emissions for the AE and Table 2-12 and Table 2-13 are the estimated NO_x emissions for the ME. Figure 2-6 and Figure 2-7 show the NO_x emissions curves estimates between the fuels for the AE and ME respectively. The curves were created using past emission trends as a function of engine load in combination with measured emissions for a ME and AE engine. The resulting AE NO_x emissions were 30% below the certification value and the resulting ME NOx emissions were just at the certification values and within the tolerances of in-use testing (±20%, 40 CFR Part 1065). In summary, the ME and AE in-use emissions are at or below their certified IMO requirements and thus, the results of this study are representative of an engine meeting the Tier II NO_x regulations.

Table 2-10: Measured and estimated NO_x both fuels: AE (g/kWhr)

Load%	MGO	note	Load%	ULSFO	note
10.0%	10.20	est	10.0%	10.00	est
25.9%	8.97	meas	28%	8.72	meas
53.5%	8.34	meas	54%	8.54	meas
63.0%	8.08	meas	64%	8.38	meas
75%	8.08	est	75%	8.30	est
100%	8.25	est	100%	8.45	est

[1] meas denotes measured and est denotes estimated.

Table 2-11: Calculated NO_x for ISO certified load points: AE (g/kWhr)

% MCR	estMGO	estULSFO	Wt factor	wt MGO	wt ULSFO
10%	10.17	9.95	0.1	1.02	1.00
25%	9.10	8.97	0.3	2.73	2.69
50%	8.25	8.37	0.3	2.47	2.51
75%	8.13	8.44	0.25	2.03	2.11
100%	8.24	8.42	0.05	0.41	0.42
			estMeas	**7.6**	**7.7**
		ISO CAT1 stds		**9.8**	**9.8**
Allowance is +20% (thus within spec)				**-22%**	**-21%**

Table 2-12: Measured and estimated NO_x both fuels: ME (g/kWhr)

Load%	MGO	note	Load%	ULSFO	note
8.8%	27.41	meas	9%	28.83	meas
12.0%	25.77	meas	13%	26.59	meas
33.0%	18.65	meas	33%	19.54	meas
44%	16.85	meas	42%	17.69	meas
75%	13.00	est	75%	14.00	est
100%	12.80	est	100%	13.70	est

[1] meas denotes measured and est denotes estimated.

Table 2-13: Calculated NO_x for ISO certified load points: ME (g/kWhr)

% MCR	estMGO	estULSFO	Wt factor	wt MGO	wt USLFO
25%	21.19	21.98	0.15	3.18	3.30
50%	15.49	16.16	0.15	2.32	2.42
75%	13.12	14.09	0.5	6.56	7.04
100%	12.77	13.68	0.2	2.55	2.74
			estMeas	**14.6**	**15.5**
			ISO CAT1 stds	**14.4**	**14.4**
Allowance is +20% (thus within specs)				**1%**	**8%**

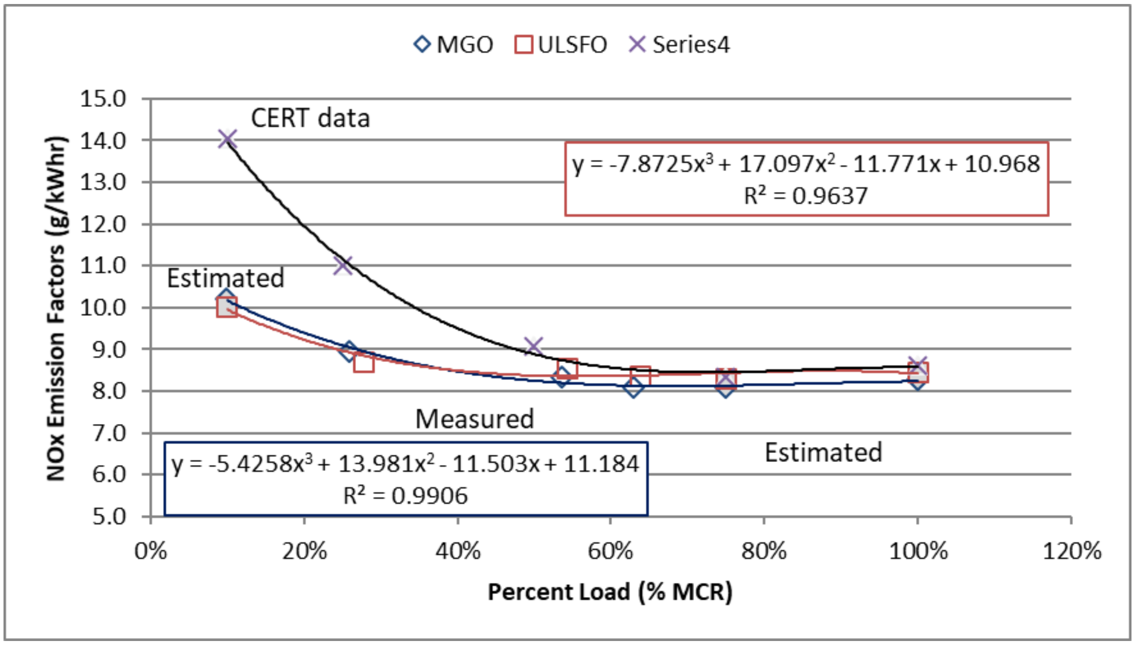


Figure 2-6 Measured and estimated NO_x emissions for the AE MGO and ULSFO tests

[1] CERT data is from the IMO NO_x Technical File for this engine SN AA4214 utilizing DMC bunker fuel from July 11, 2011. The results of this NO_x Technical File are from a parent engine which may be different than the engine tested. The other differences noted are, 1) intake air temperature was 35C for the in-use test and 55 C for the NO_x Technical File, 2) humidity correction was near unity for the in-use test (0.99 to 1.03) and unknown for the NO_x Technical File, 3) the agreement in fuel consumption between the NO_x Technical File and the in-use test as < 1% kg/hr and kg/kWhr. Thus, it is unclear why the current in-use NO_x emission is about 30% lower than the sea-trial data. More investigation is needed to understand the difference.

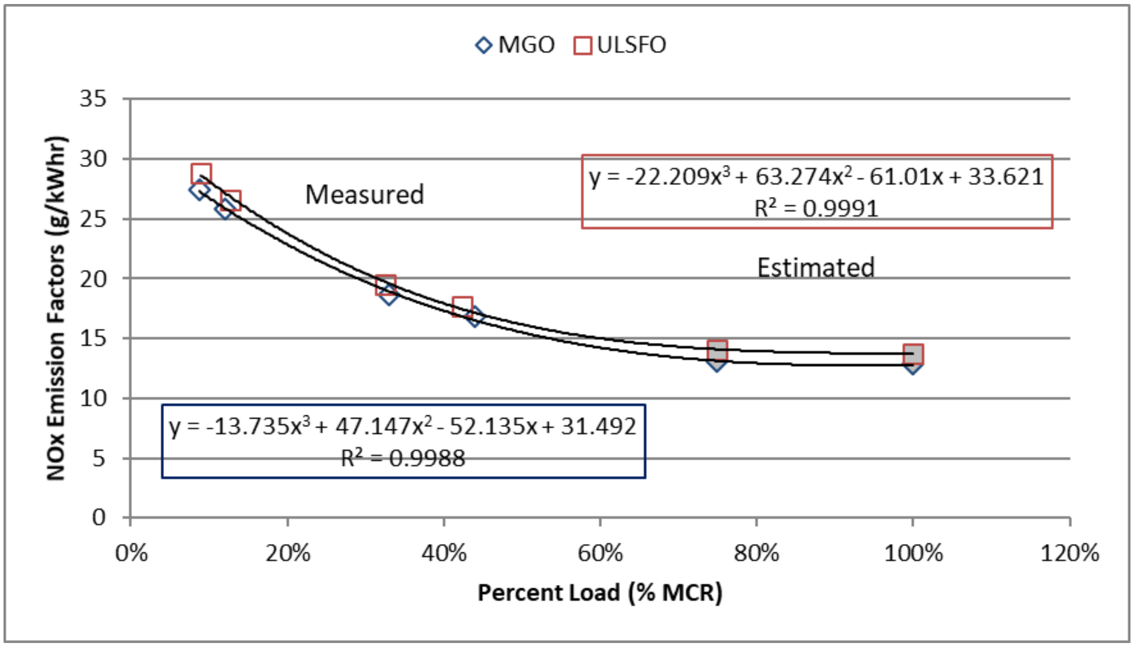


Figure 2-7 Measured and estimated NO_x emissions for the ME MGO and ULSFO tests

3 Results

The results for the Tier 2 ME, AE, and auxiliary boiler are described in this section. The results compare the ULSFO fuel with the MGO fuel for the three emission sources. The sections are divided into gaseous, PM (PM mass and composition), BC, and toxics (auxiliary boiler only). The two last sections present a discussion on the statistical significance and a comparison to previous tests.

3.1 Gaseous

The gaseous emissions include NO_x, CO, CO_2, and SO_2. The SO_2 emissions were both measured and calculated. The measured values were near the detection limit of the SO_2 NDIR system (1-2 ppm) so the calculated values are more representative. As such, it is recommended to use the calculated values over the measured values listed in Appendix F.

NO_x Emissions: The NO_x emissions for the ME and AE are shown in Figure 3-1 and Figure 3-2 in units of g/kWhr, respectively and the auxiliary boiler emissions are shown in Figure 3-3 in units of g/kg-fuel (kg/tonne-fuel). The ME Tier 2 engine NO_x emissions ranged from about 27.4 to 16.85 g/kWhr for the ULSFO fuel over the different load points with the MGO fuel slightly lower for each test point (less by ~ 5%). The NO_x emissions for both fuels declined with increasing engine load which agrees with previous SSD emission results. The ME ISO estimated combined NO_x emissions were calculated to be 15.5 g/kWhr for the ULSFO fuel and 14.6 g/kWhr for the MGO fuel, see Section 2.4.3 for details on the calculation assumptions. The ME NO_x emissions are with-in the expectations of Tier 2 Category 3 marine engines given in-use measurement uncertainties of ~20% in addition to other recommended multipliers for in-use conditions (20% allowance and a 1.5 multiplier is typical, Johnson et al 2009 and Kahn et al 2012). As such, these results are comparable to the certification values for Tier 2 Category 1 marine engines. In general, the ME results show good repeatability at each of the load points, indicating test consistency and proper engine maintenance.

The AE NO_x emissions also showed similar results as the ME results between fuels. The AE NO_x emissions ranged from 8.15 to 7.6 g/kWhr for the MGO fuel. The ULSFO NO_x emissions were slightly higher than MGO NO_x emissions (3%), but the difference was not statistically significant. The brake specific emissions decreased with increasing load and the estimated ISO weighted emissions were less than the Tier 2 standard for this size and category engine.

The auxiliary boiler NO_x emissions (on a g/kg-fuel basis) averaged 1.68 and 2.28 g/kg-fuel for the MGO and ULSFO fuel respectively at the 60% load condition. The ULSFO NO_x emissions were 33% higher than the MGO fuel. The results from a paired t-test suggest this difference is statistically significant, see Section 3.4 below.

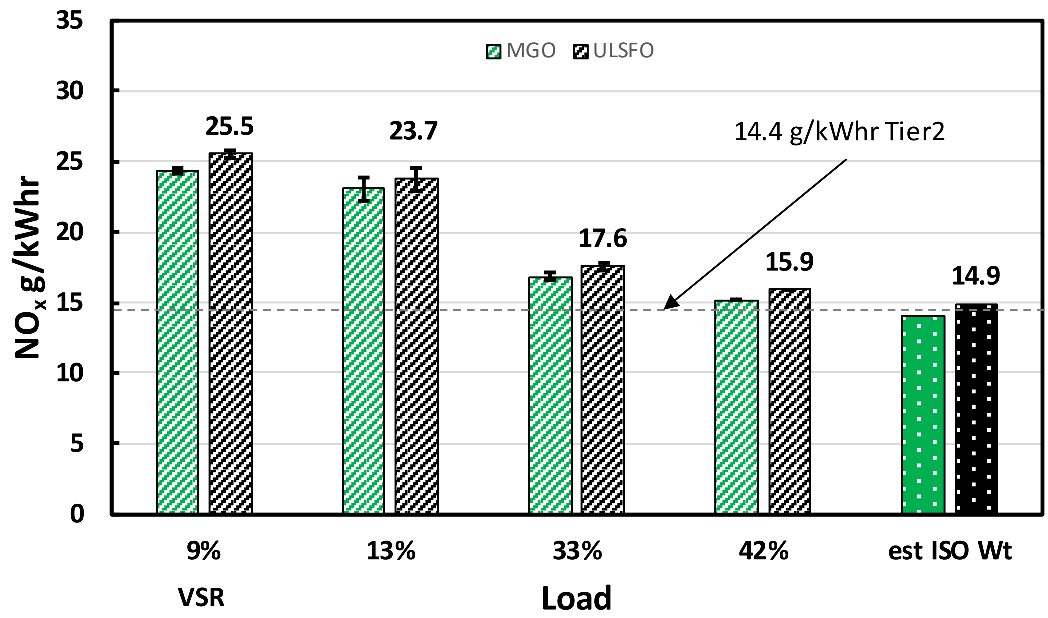


Figure 3-1 NO_x Emissions for the ME g/kWhr

[1] est ISO Wt is the estimated ISO weighted emissions factor for this engine type. Since actual loads points could not be matched to the certification test estimates were calculated. Because of this measured emission factors were higher than the estimated ISO weighted values. See Section 2.4.3 for additional clarifications and details.

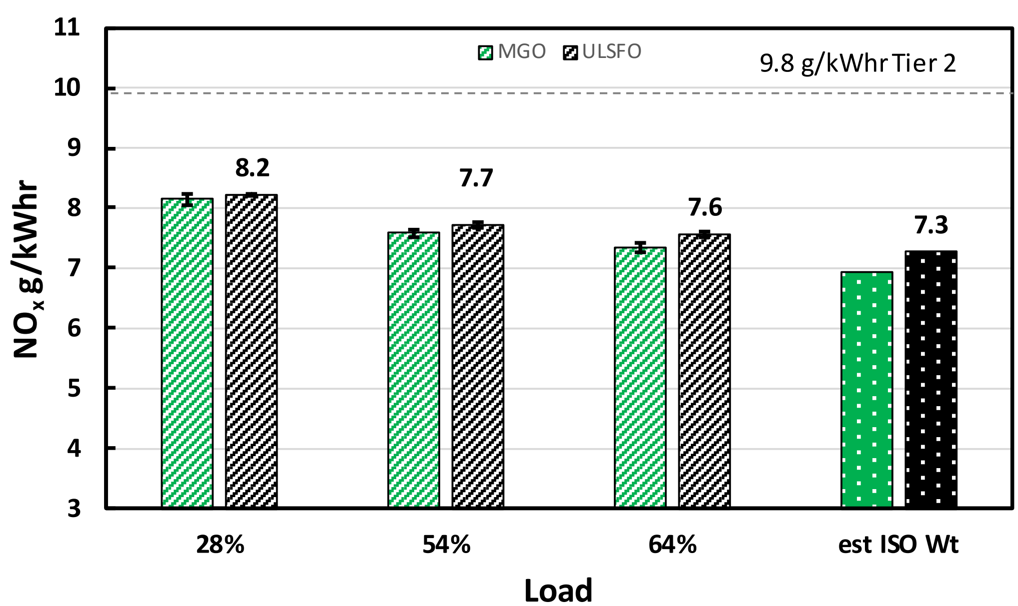


Figure 3-2 NO_x Emissions for the AE in g/kWhr

[1] est ISO Wt is the estimated ISO weighted emissions factor for this engine type. Since actual loads points could not be matched to the certification test estimates were calculated. See Section 2.4.3 for details. Differences between the Tier 2 CERT for this engine and the reported values are discussed in Section 2.4.3.

[2] It is unclear why the NOx Technical File results are about 30% higher than the in-use test. More investigation is needed to understand. See discussion Section 2.4.3

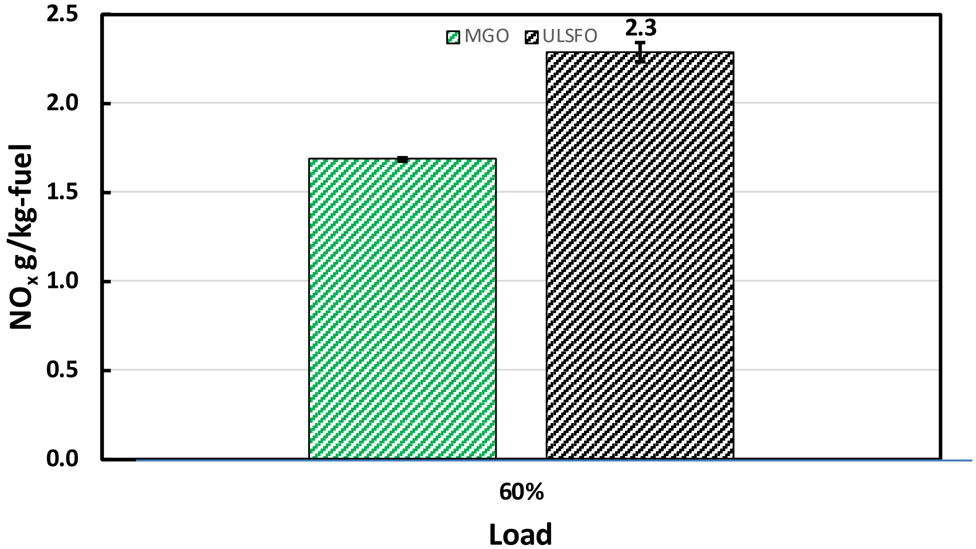


Figure 3-3 NO_x Emissions for the auxiliary boiler g/kg-fuel

CO Emissions: The CO emissions results for the two fuels and three sources are shown in Figure 3-4, Figure 3-5, and Figure 3-5 for the ME, AE and Auxiliary boiler respectively. CO emissions were relatively constant as a function of load for the ME and highest at light load for the AE and Auxiliary boiler. The engine emissions varied from 0.21 g/kWhr for the ME to 2.43 g/kWhr for the AE. The auxiliary boiler emissions were 0.1 g/kg-fuel for the 60% load. For the ME the CO emissions were lower for the MGO fuel compared to the USLFO fuel. The AE and auxiliary boiler sources showed slightly higher emissions on MGO fuel as compared to the ULSFO fuel for the higher load points, but slightly lower emissions on the light load tests.

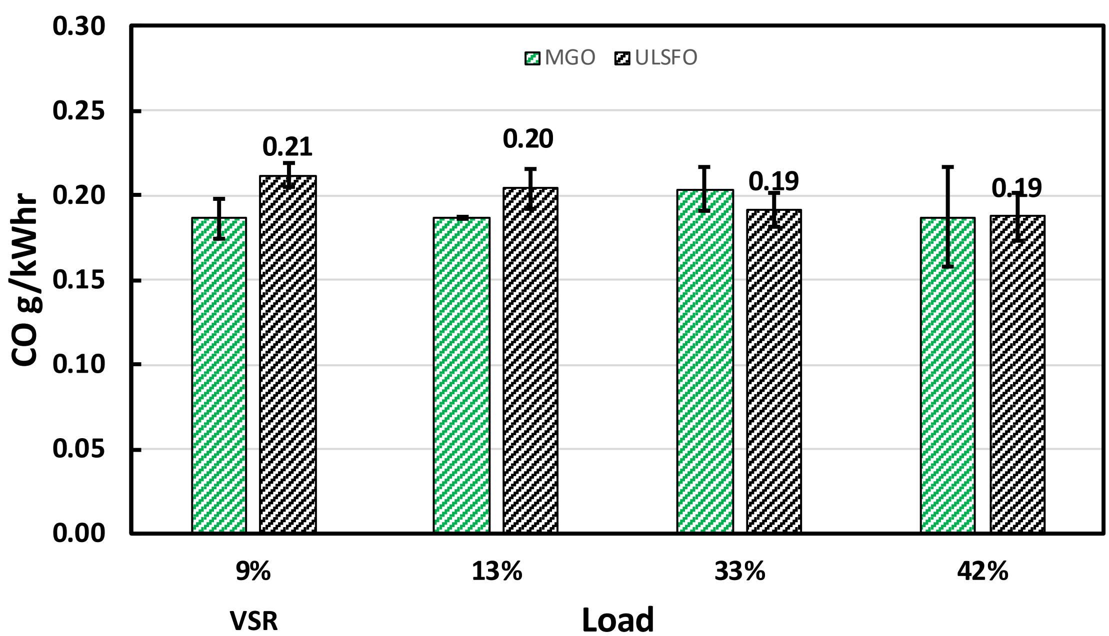


Figure 3-4 CO Emissions for the ME g/kWhr

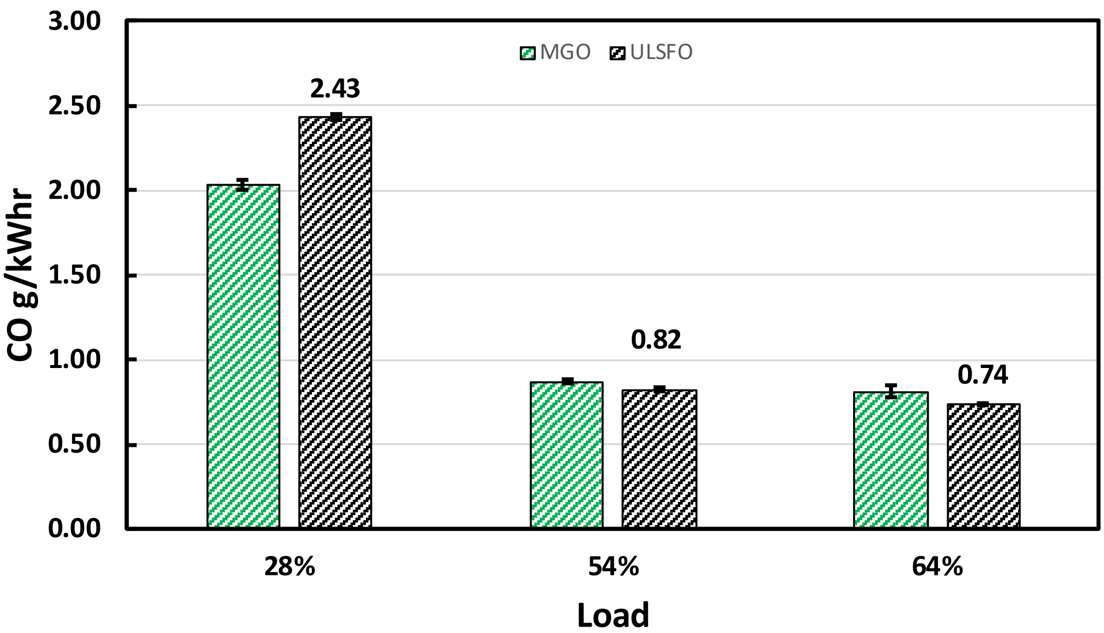


Figure 3-5 CO Emissions for the AE g/kWhr

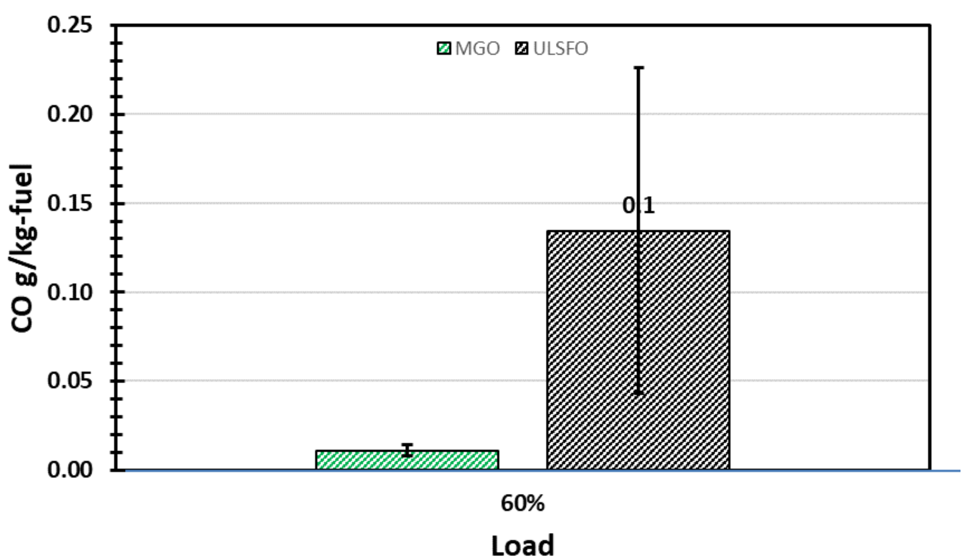


Figure 3-6 CO Emissions for the auxiliary boiler g/kg-fuel

CO_2 Emissions: The brake specific CO_2 ($bsCO_2$) emission results for the two fuels and three sources are shown in Figure 3-7 and Figure 3-8 for the ME and AE, respectively. The ME $bsCO_2$ emissions decreased with increasing load for the ME and AE sources. The ME $bsCO_2$ emissions ranged from 656 g/kWhr to 597 g/kWhr and the AE $bsCO_2$ emissions ranged from 787 to 650 g/kWhr. The $bsCO_2$ emissions are comparable to those for other ME and AE engine tested at-sea where there is a decreasing trend of $bsCO_2$ emissions as load increases. The AE had a higher bsCO_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 results show good repeatability at each of the load points, indicating testing consistency. The ULSFO fuel showed slightly higher CO_2 emissions for the ME and AE engines which is expected since the ULSFO lower heating value (LHV) is about 2% lower than the MGO fuel. The CO_2 auxiliary boiler emissions were a constant value of CO_2 of around 3170 g/kg-fuel.

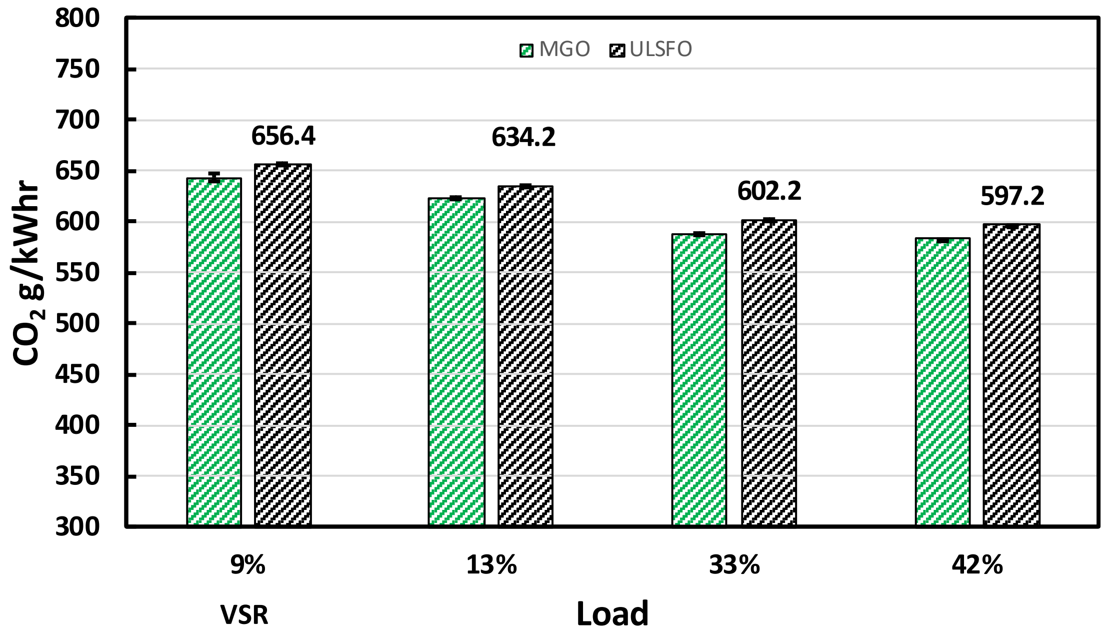


Figure 3-7 CO_2 Emissions for the ME in g/kWhr

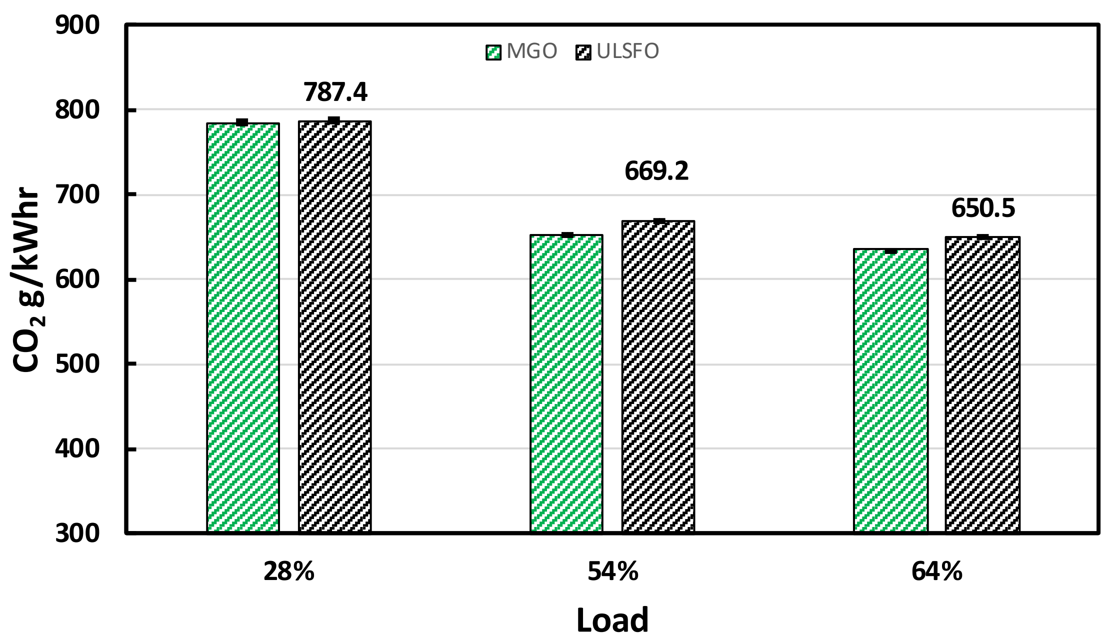


Figure 3-8 CO_2 Emissions for the AE in g/kWhr

SO_2: The SO_2 emission results are provided in Appendix F (starting at Table F-08) where the ULSFO showed higher SO_2 emissions compared the MGO fuel due to its slightly higher fuel sulfur level (0.089% vs 0.038% respectively). The tables show the measured and calculated SO_2 emissions, where the calculated values are more representative of the actual emissions because SO_2 concentrations for the MGO fuel should be around 4 ppm and for the ULSFO it should be around 9 ppm, but there is no noticeable response between the fuels and the SO2 concentration remained at 1-2 ppm for the full testing program, see Figure F-25. More investigation is needed in the Cross-Flow Modulation Non-Dispersive Infrared Absorption measurement method used for SO_2 emissions.

3.2 PM

The PM emissions are organized by PM mass, PM composition (EC, OC, Sulfate), and equivalent BC (eBC), see Section 2.3 for more details on sampling methodology.

PM Mass: The $PM_{2.5}$ mass emissions for the ME, AE, and auxiliary boiler for both fuels are shown in Figure 3-9, Figure 3-10 in units of g/kWhr and in Figure 3-11 in units of g/kg-fuel, respectively. The ME $PM_{2.5}$ emissions were higher for the ULSFO fuel (35%) compared to the MGO fuel and ranged from about 0.35 to 0.26 g/kWhr for the ULSFO fuel and from 0.22 to 0.20 g/kWhr for the MGO fuel. A similar trend was found for the AE where the ULSFO fuel was higher (55%) than the MGO fuel and the PM emissions decreased with increasing load. A discussion on the statistical significance of these differences is provided in Section 3.4 below.

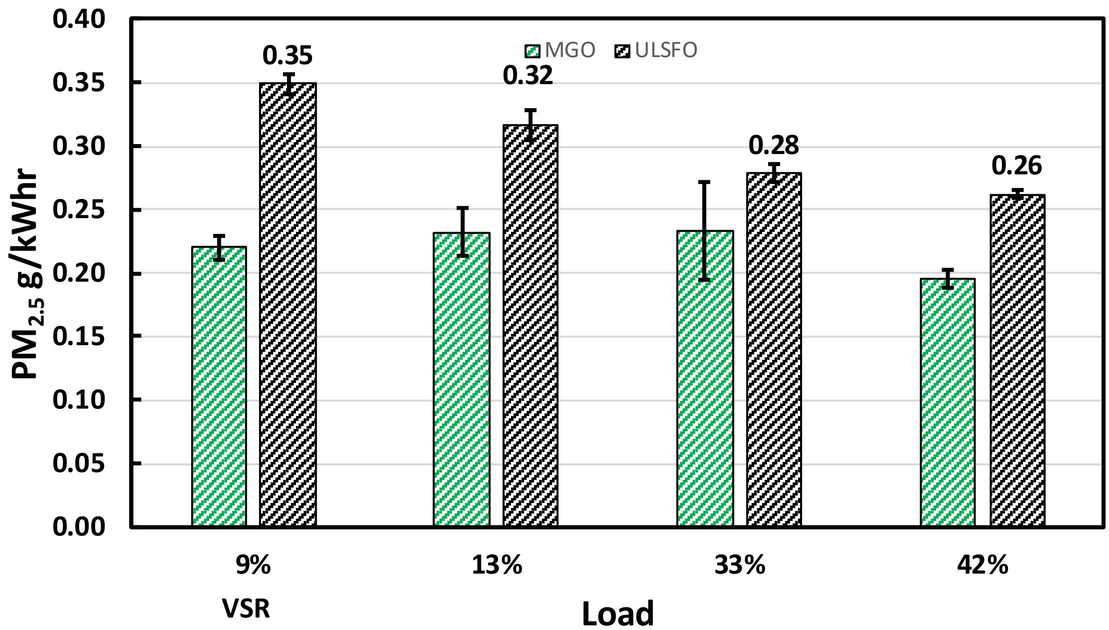


Figure 3-9 $PM_{2.5}$ Emissions for the ME in g/kWhr

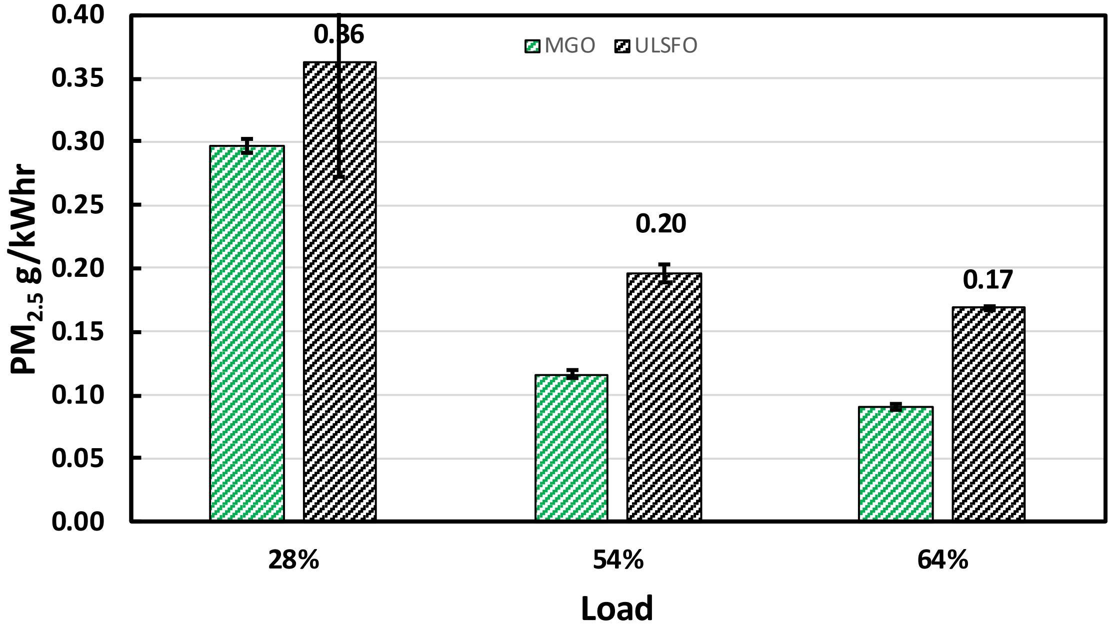


Figure 3-10 PM2.5 Emissions for the AE in g/kWhr

The auxiliary boiler $PM_{2.5}$ emissions showed a slightly different trend where the ULSFO fuel showed lower emissions compared to the MGO fuel, see Figure 3-11. The $PM_{2.5}$ emissions were 55 mg/kg-fuel for the MGO fuel and 29 mg/kg-fuel for the ULSFO fuel. The $PM_{2.5}$ emissions for MGO fuel was about 49% higher than the PM emissions for the ULSFO fuel. The results from a paired t-test suggest this difference is not statistically significant at the 95% confidence, see Section 3.4 below.

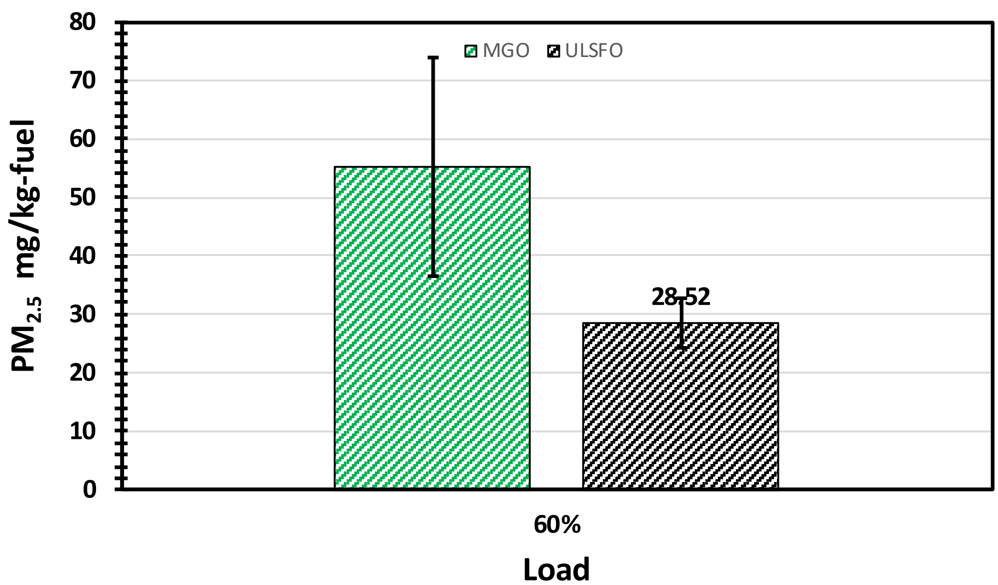


Figure 3-11 PM2.5 Emissions for the auxiliary boiler in mg/kg-fuel

PM composition: The PM composition for both fuels is compared for the three emission sources in Figure 3-12, Figure 3-13 (units of g/kWhr), and Figure 3-14 (g/kg-fuel) for the ME, AE, and auxiliary boiler respectively. The ME PM emissions are predominantly composed of OC (92%), with a smaller contribution from EC (5-6%), and a small contribution from S (2-3%). The ULSFO fuel showed a higher total PM emission compared to the MGO fuel where the increase in total PM resulted from an increase in organic PM emissions. The student t-test suggest the mean differences between ULSFO and MGO in OC PM emissions are statistically significant, see Section 3.4.

The AE PM emissions showed a decrease in elemental carbon PM, but an increase in organic carbon PM fraction between the ULSFO and MGO fuel. The student t-test suggest the mean differences between the fuels are statistically significant for the organic carbon but not for the elemental carbon, see Section 3.4. The AE PM emissions are predominantly composed of EC and OC (50% ea.) with a small contribution from S (1-2%) for the MGO fuel.

Elemental carbon (or combustion soot) is typically a product of combustion efficiency and organic carbon is typically a product of fuel quality. It is interesting that for the ME most of the PM for both fuels emitted mostly (>90%) organic carbon where the elemental carbon was at a similar level of around 0.01 g/kWhr. For the AE, however, the ULSFO showed lower elemental carbon compared to the MGO fuel at an emission level of 0.2 g/kWhr (this is 20 times higher than that of the ME).

The auxiliary boiler PM composition showed a decrease in OC PM for the MGO fuel compared to the ULSFO fuel. The OC_PM represented more than 90% of the total PM composition where for the MGO fuel the EC was less than 0.5% and for the ULSFO the fraction was larger at 1.5% of the total PM. The student t-test suggest the mean differences between ULSFO and MGO are not statistically significant, see Section 3.4. The auxiliary boiler PM emissions are predominantly composed of EC (77%), OC (21%), with a small contribution from S (1-2%) for both fuels.

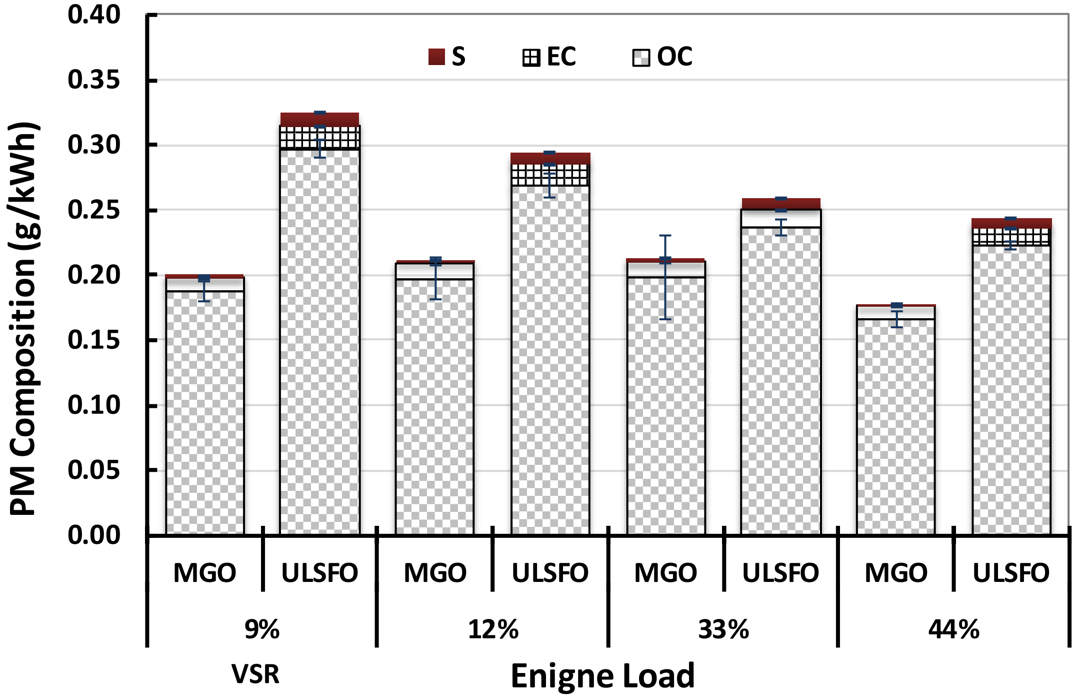


Figure 3-12 PM composition Emissions for the ME in g/kWhr\

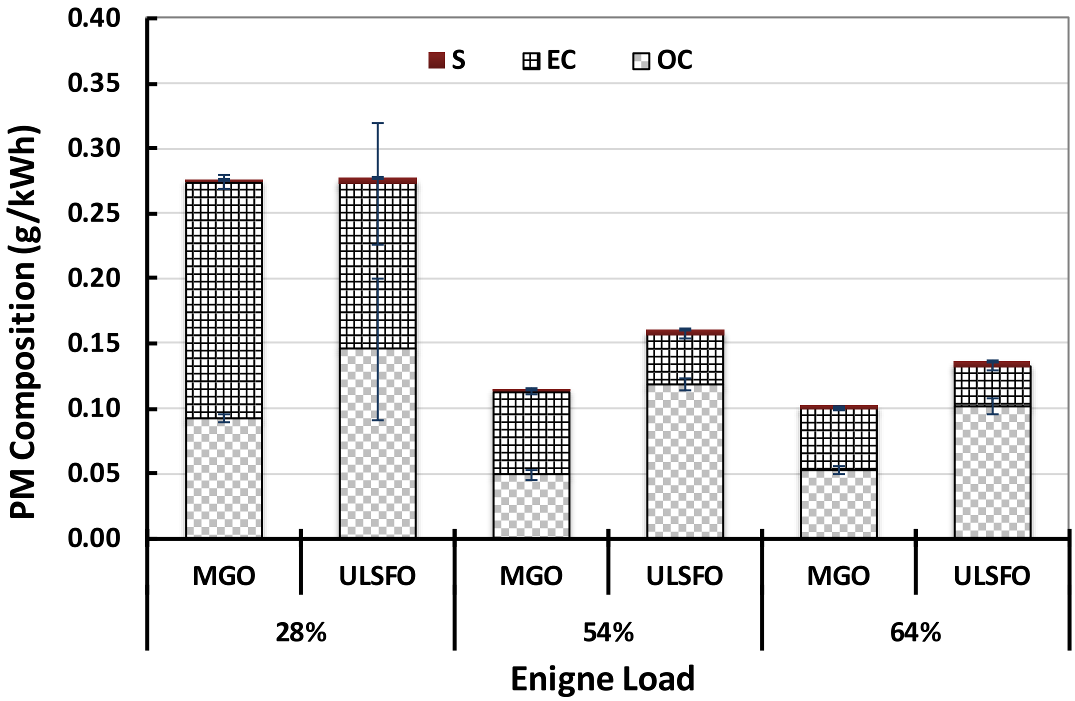


Figure 3-13 PM composition Emissions for the AE in g/kWhr

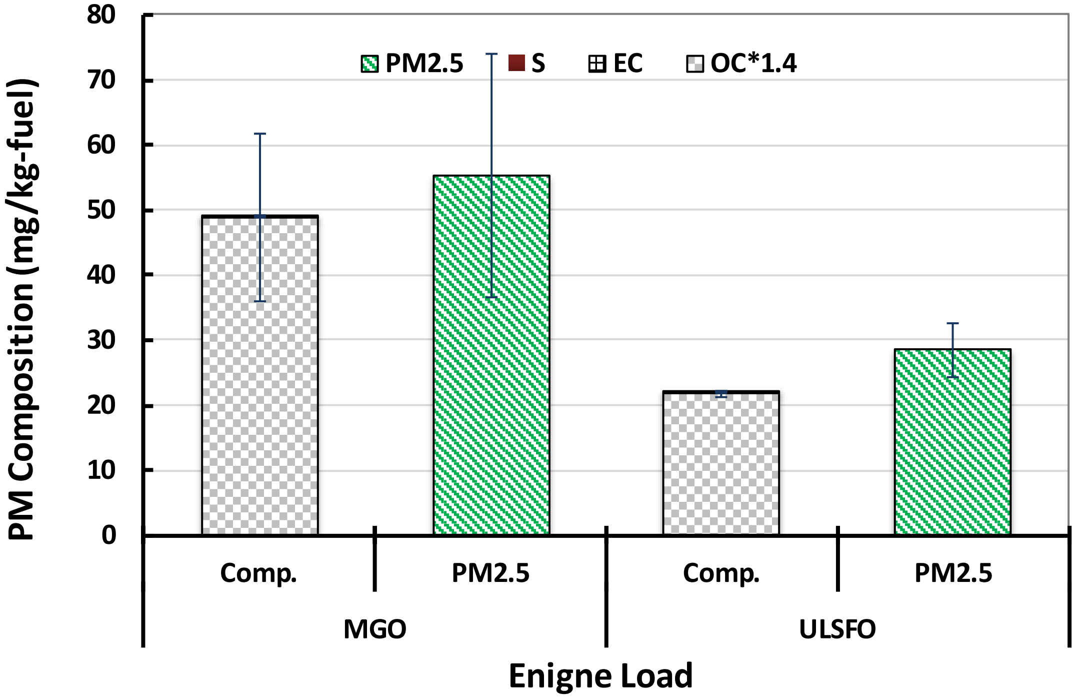


Figure 3-14 PM composition emissions for the auxiliary boiler in mg/kg-fuel

Black Carbon: The equivalent black carbon (eBC) emissions for both fuels is compared for the three emission sources in Figure 3-15 and Figure 3-16 (units of g/kWhr), and Figure 3-17 (g/kg-fuel) for the ME, AE, and auxiliary boiler respectively. Since BC emissions are referenced to their fuel specific emissions, two additional figures were prepared to show for the ME and AE engines on a g/kg-fuel basis, see Figure 3-18 and Figure 3-19. The ME eBC emissions were highest for both fuels at the 13% load point and lowest for the high load (on a g/kWhr and g/kg-fuel basis). The ME eBC emissions ranged from 0.0078 g/kWhr to 0.0015 g/kWhr and for the AE it ranged from 0.19 g/kWhr to 0.031 g/kWhr. The medium speed diesel (MSD) AE eBC emissions were highest at light load and lowest at high load and were about 20x higher compared to the SSD ME. The 20x higher eBC emissions for MSDs compared to SSD is common and has been reported by UCR during previous studies (Johnson et al 2016). The ULSFO showed higher (26%) ME and auxiliary boiler eBC emissions, but lower (26%) eBC emissions for the AE when compared to the MGO fuel. A discussion on the statistical significance of these differences is provided in Section 3.4 below.

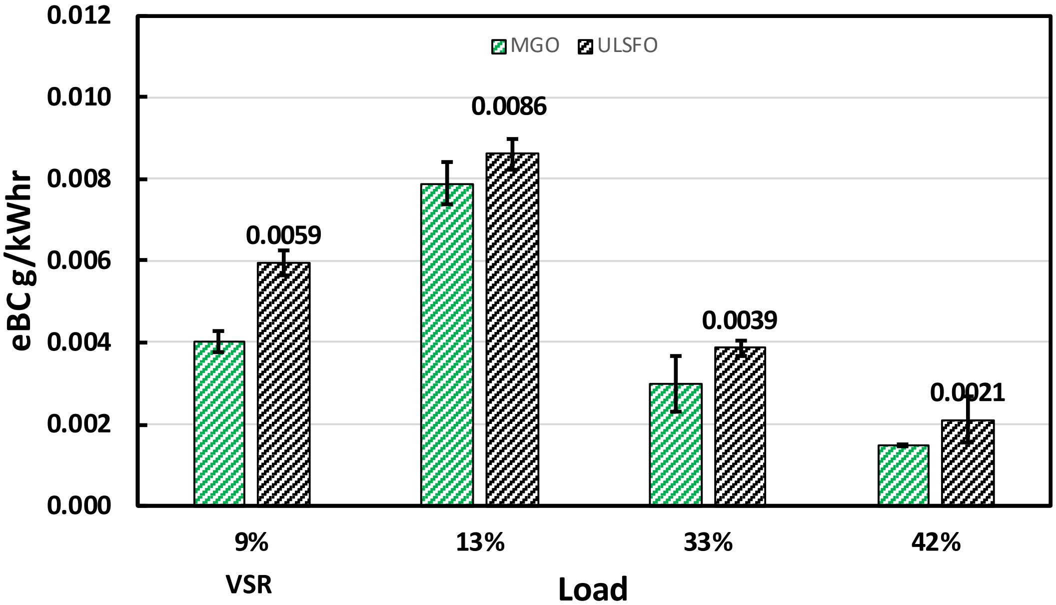


Figure 3-15 BC Emissions for the ME in g/kWhr

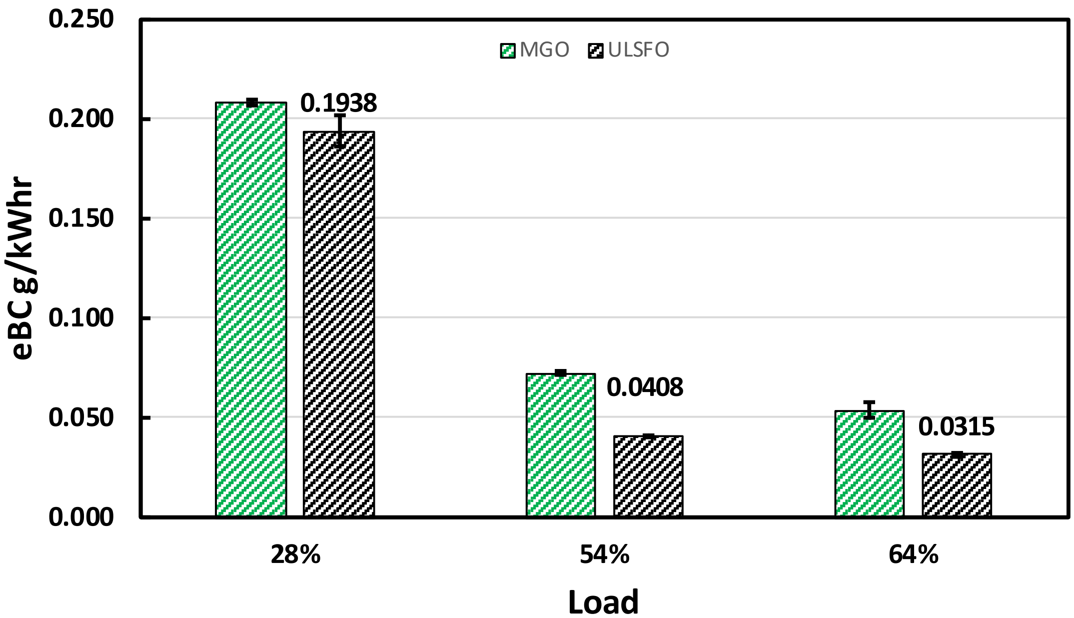


Figure 3-16 BC Emissions for the AE in g/kWhr

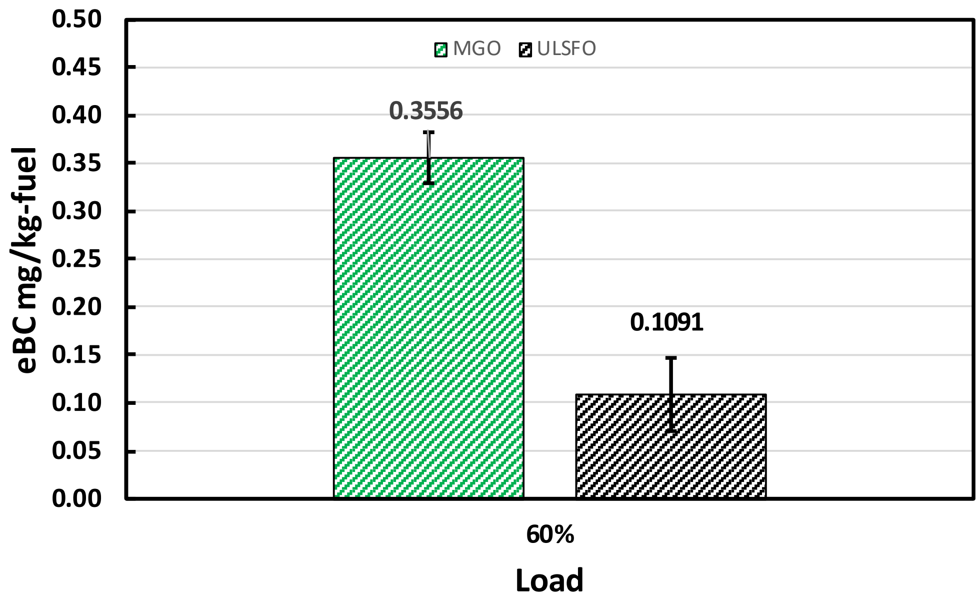


Figure 3-17 BC emissions for the auxiliary boiler in mg/kg-fuel

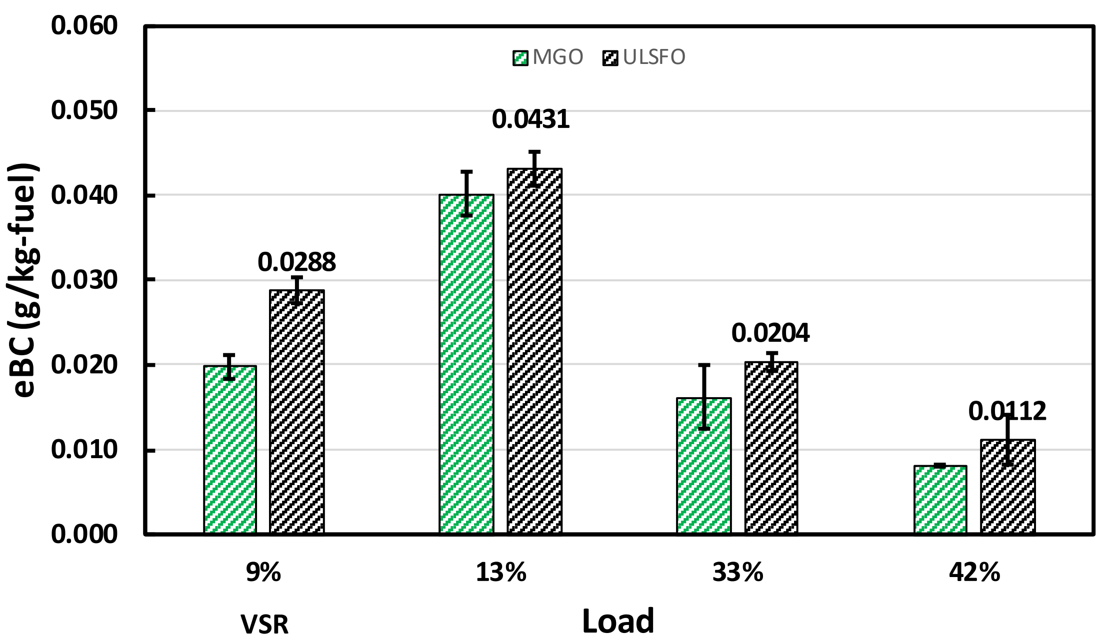


Figure 3-18 BC fuel specific emissions for the ME in g/kg-fuel

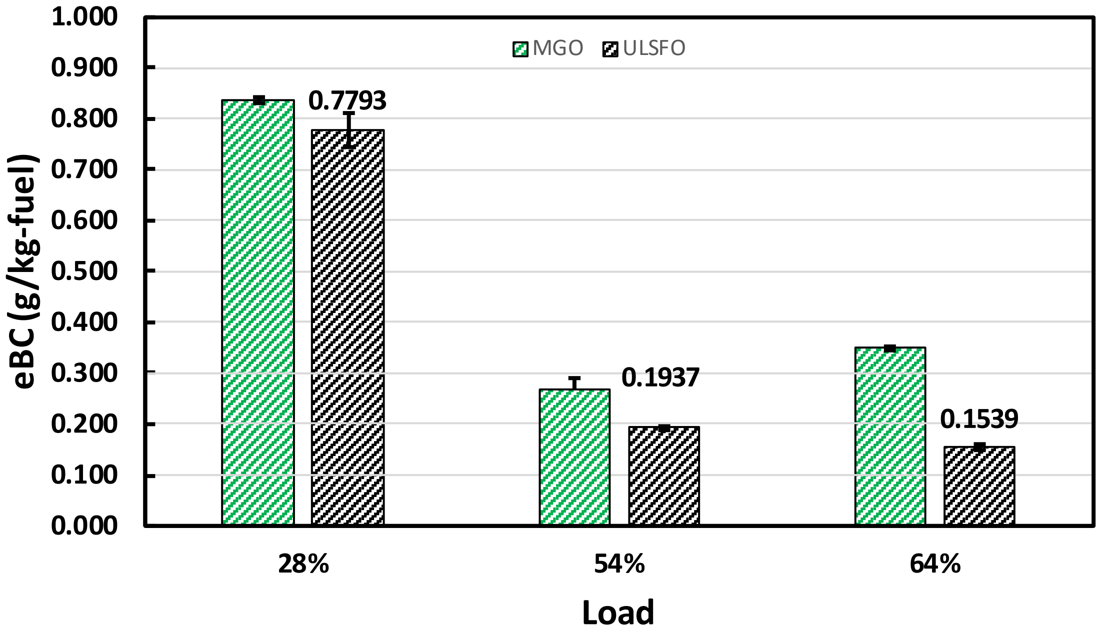


Figure 3-19 BC fuel specific emissions for the AE in g/kg-fuel

3.3 Toxics

Toxics measurements were collected for the auxiliary boiler tests including aldehydes and ketones, speciated hydrocarbons, and metals.

Aldehydes and ketones: The aldehydes and ketones are presented in Figure 3-20 and Figure 3-1 for selected species that showed some measured value (formaldehyde, acetaldehyde and acetone). The other species showed no measurement amount and were below the method detection limit. Formaldehyde emissions were higher for ULSFO compared to MGO. Both acetaldehyde and acetone were lower for the MGO fuel when compared to the ULSFO fuel. The formaldehyde emissions ranged from 3.855 mg/kg-fuel for the ULSFO to 0.688 mg/kg-fuel for the MGO fuel. The acetaldehyde emissions ranged from 0.929 mg/kg-fuel for the ULSFO fuel to 0.439 mg/kg-fuel for the MGO fuel.

Table 3-1 Average aldehydes and ketone emissions by fuel by test load (mg/kg-fuel).

Fuel	Load %	Formaldehyde			Acetaldehyde			Acetone		
MGO	60.0%	0.688	±	0.069	0.439	±	0.080	0.426	±	0.183
ULSFO	69.0%	3.855	±	0.463	0.929	±	0.178	1.113	±	0.603

[1] Statistical student t-test suggest fuel mean differences are statistically significant for formaldehyde, but not acetaldehyde and acetone, See Section 3.4 for details.

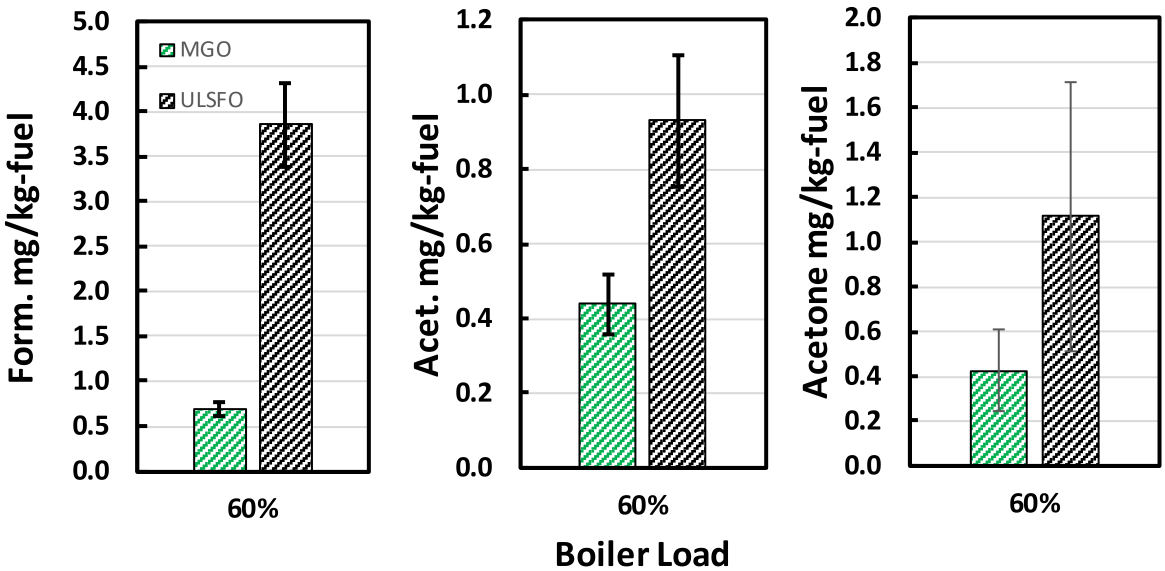


Figure 3-20 BC fuel specific toxic emissions for the auxiliary boiler in mg/kg-fuel

[1] selected toxics 1) form. formaldehyde, 2) acet. acetaldehyde and 3) acetone emissions.

BTEX speciated hydrocarbons: The speciated hydrocarbons are not available due to issues with the samples and their off-site analysis. A discussion of this is in the Appendix F.

Metals: The metals for the auxiliary boiler results are shown in Table 3-4 and Table 3-3 for the auxiliary boiler on the MGO and ULSFO fuel. The MGO fuel showed a statistically lower metals emission result for selected metals that ranged from a factor of 58 for Nickle (Ni) to 28% for Magnesium (Mg). Only chlorine (Cl) was lower for the ULSFO compared to the MGO fuel. The mean difference statistical significance test (two tailed, not paired, equal variance), showed a p-value less than 0.05 for Mg, Al, P, Cl, V, Fe, and Ni suggesting these mean differences are statistically significant. The full list of metal results can be found in Appendix F.

Table 3-2 Average selected metals by fuel by test load (mg/kg-fuel).

Fuel	Load %	Mg			AL			Si			P		
MGO	60.0%	0.17	±	0.01	0.02	±	0.02	0.18	±	0.05	0.14	±	0.00
ULSFO	69.0%	0.26	±	0.01	0.28	±	0.04	0.40	±	0.03	0.41	±	0.05
factor change		0.51			16.83			1.27			1.84		

Table 3-3 Average selected metals by fuel by test load (mg/kg-fuel).

Fuel	Load %	S			Cl			V			FE			NI		
MGO	60.0%	3.65	±	0.34	0.03	±	0.01	0.16	±	0.02	0.21	±	0.02	0.01	±	0.01
ULSFO	69.0%	8.78	±	1.52	0.00	±	0.00	2.49	±	0.49	0.79	±	0.15	1.05	±	0.19
factor change		1.40			-1.00			14.66			2.85			68.9		

[1] The statistical t-tests p-values for Mg, Al, P, Cl, V, Fe, and Ni were all below 0.05 suggesting these mean differences were statistically significant

3.4 Statistics

The gaseous and PM emissions are compared in this section to consider the statistical significance for the mean differences presented between the fuels tested (i.e. whether or not the percent differences are statistically significant). The emissions factors for the ME, AE, and auxiliary boiler were simplified with a weighting function that is representative of expected in-use operation, see Table 3-4 for weighting factors used and discussion in Section 2.2.3 for operational background. The results of the averaged weighted emissions for each source organized by emission source and by fuel is presented in Table 3-5. A student t-test was used to test for statistical significance between the means of each of the fuels tested and each of the sources. The t-test results are shown in Table 3-7.

ME: The NO_x emission differences between the MGO and ULSFO fuel were slightly lower (3%), but this difference was found to not be statistically significant. The weighted ME $PM_{2.5}$ emissions ranged from 0.219 g/kWhr for the MGO fuel to 0.295 g/kWhr for the ULSFO fuel which is a mean difference of 35%, see Table 3-7. The results of the t-test suggest the ME $PM_{2.5}$, PM_EC, and PM_OC are statistically significant mean differences.

AE: The NO_x emission differences between the MGO and ULSFO fuel were slightly lower (5%), but this difference was found to not be statistically significant. The AE $PM_{2.5}$ emissions were higher for the ULSFO fuel (by 55%) compared to the MGO fuel. The AE emissions showed statistically higher organic carbon PM emissions (90%) for the ULSFO compared to the MGO fuel, but not for total PM and elemental carbon emissions ($PM_{2.5}$, PM_EC), see Table 3-6. Note, there was a shift in PM composition from high OC to high EC for the ULSFO fuel in comparison to the MGO which showed a lower OC and higher EC PM emissions. This shift in lower OC and higher EC caused the denominator basis to be reduced from 0.137 g/kWHr (total $PM_{2.5}$) to 0.060 g/kWHr for OC, thus magnifying the percent difference (the percent difference in comparison to total PM would only be 39% which is more in line with the other comparisons). In addition, the PM_OC difference did not impact the total PM mass significantly since eBC increased for the MGO compared to the ULSFO thus affecting the total $PM_{2.5}$ comparison, as demonstrated by the high p-value from the student t-test analysis on $PM_{2.5}$.

Auxiliary boiler: The auxiliary boiler NO_x emissions for the ULSFO fuel were 36% higher than the MGO fuel and these results showed statistically significant mean differences. The auxiliary boiler $PM_{2.5}$ emissions were lower (48%) for the ULSFO fuel compared to the MGO fuel, but the difference was not statistically significant, see Table 3-6.

In summary, the ULSFO fuel showed a statistically significant increase in PM and PM composition for the ME, but not for the AE. However, these differences are small in comparison to high sulfur fuels as is discussed in the Section 3.5.

Table 3-4 Weighting functions used for each of the emission sources

ME		AE		Boiler	
Load	Weight	Load	Weight	Load	Weight
8.8%	0.20	25.9%	0.20	-	-
12.0%	0.20	53.5%	0.20	60.0%	0.90
33.0%	0.30	63.0%	0.60	-	-
44.0%	0.30	-	-	-	-

[1] The ME weighting is relatively flat where the higher weightings are used for typical open water speeds (33 to 44%), the 8.8% is representative of VSR which is common along the CA coastline and the 12% load is representative of entering and exiting the ports. The AE's operate at the higher loads of 61% and 52% so 80% of the weighting is used for these loads with 20% being used for the light load. The auxiliary boiler is mostly operated at the higher 60% load at the ports and sometimes at 40%.

Table 3-5 Average weighted emissions for selected species (g/kWhr and g/kg-fuel)

Source	Fuel	NOx	PM2.5	PM_EC	PM_OC	PM_S	eBC
ME	MGO	21.29 ± 0.34	**0.219 ± 0.019**	**0.011 ± 0.001**	**0.186 ± 0.016**	0.002 ± 0.000	**0.004 ± 0.000**
ME	ULSFO	22.25 ± 0.19	**0.295 ± 0.007**	**0.015 ± 0.000**	**0.251 ± 0.006**	0.009 ± 0.000	**0.005 ± 0.000**
AE	MGO	8.31 ± 0.09	**0.137 ± 0.003**	**0.078 ± 0.002**	**0.060 ± 0.003**	0.002 ± 0.000	**0.088 ± 0.003**
AE	ULSFO	8.56 ± 0.04	**0.213 ± 0.021**	**0.051 ± 0.012**	**0.114 ± 0.016**	0.004 ± 0.000	**0.066 ± 0.002**
Boiler	MGO	1.68 ± 0.00	**0.040 ± 0.000**	**0.0002 ± 0.00000**	**0.035 ± 0.011**	0.000 ± 0.000	**0.0004 ± 0.00002**
Boiler	ULSFO	2.28 ± 0.08	**0.029 ± 0.000**	**0.0004 ± 0.00002**	**0.016 ± 0.000**	0.000 ± 0.000	**0.0001 ± 0.00003**

[1] PM2.5 is the PM gravimetric mass measurement (<2.5 µm), PM EC and PM OC are the elemental and organic carbon PM results using the thermal optical NIOSH method, eBC is the photoacoustic equivalent black carbon measurement. S PM is hydrated sulfate PM ($H_2SO_4*6.656H_2O$) from the ion-chromatography method. The ME and AE emissions are in units of g/kWhr and the auxiliary boiler emissions are in units of g/kg-fuel. Uncertainties are represented by a single standard deviation with a sample of n=3.

Table 3-6 Percent change from baseline MGO fuel (positive implies increased)

Source	NOx	PM2.5	PM_EC	PM_OC	eBC
ME	5%	35%	35%	35%	26%
AE	3%	55%	-34%	90%	-25%
Boiler	36%	-48%	97%	-55%	-69%

[1] Black text was shown not to be statistically significant and blue text was statistically significant, see table below.

Table 3-7 Statistical t-test p-value for selected species

Source	Load %	NOx	CO	CO2	PM2.5	PM_EC	PM_OC	eBC
ME	0.982	0.806	0.314	0.544	0.009	0.009	0.009	0.616
AE	0.948	0.135	0.904	0.909	0.464	0.569	0.044	0.767
Boiler	1.000	0.000	0.080	-	0.080	0.006	0.170	0.001

[1] Samples for EC, OC, and S PM had n=2. The student t-test (non-paired, two tailed, equal variance) shows the statistical significance between means on two data sets. The t-test was performed on these selected species between the MGO fuel and the ULSFO fuel. P-values less than 0.05 suggest statistical different means, p-values greater than 0.05 suggest the means are not statistically significant at the 95% confidence level.

Toxics: The t-test results show a p-value higher than 0.05 (0.1 to 0.3) for all species except for formaldehyde which resulted in a p-value of 0.012. The p-value less than 0.05 for formaldehyde suggests the mean differences for formaldehyde was statistically different between the fuels. The mean difference for acetaldehyde and acetone between the fuels was not statistically significant.

Metals: The statistical t-tests p-values for Mg, Al, P, Cl, V, Fe, and Ni were all below 0.05 suggesting these mean differences were statistically significant, see Appendix F.

3.5 Comparisons

The current study is compared with a previous study where a similar Tier 2 ME and AE engine were operated on high sulfur HFO fuel (2.5% S). This vessel was equipped with a scrubber so it met the requirements for sulfur limits where the results presented are from the pre-scrubber exhaust sample (Johnson et al, 2018). Figure 3-21 shows the $PM_{2.5}$ emissions at three different fuel sulfur levels for both a 4-stroke and a 2-stroke engine (note x-axis is on a log scale to show the difference at small sulfur concentration). The $PM_{2.5}$ emissions from the ME (orange) and the

AE (blue) increased linearly with increasing fuel sulfur. A regression line shows the correlation to sulfur is very good ($R^2 > 0.85$) for both the ME and AE where at around 0.1% fuel sulfur there is a relatively constant offset of the $PM_{2.5}$ emissions. This is where the sulfur fraction of the PM starts to play a minor role in the total PM fraction. At 0.1% fuel sulfur, the contribution of sulfate PM to the total PM is less than 5%. At this point the OC dominates the PM with the next biggest fraction being EC followed by sulfate and metals. The range of emissions at each sulfur level are the different load points tested, where the lower emission points are the higher loads and the higher emission points are the lower loads. The figure shows that there is a benefit for ULSFO and MGO fuels over high sulfur fuels where MGO has a slightly better benefit (lower PM emissions) for the ME, but not for the AE.

Figure 3-22 shows the eBC emissions for the same three fuel sulfur levels and engines. Figure 3-23 is the same data in Figure 3-22, but with the y-axis also on a log scale to visualize the results at the lower eBC emission levels. The eBC emissions for the ME and AE do not show the same clear trend as total PM. The eBC emissions for the AE appear to slightly decrease in BC emissions with increasing sulfur. The AE eBC emissions showed a much larger difference between light and heavy loads (as seen by the spread in data at each load), see Figure 3-22. This suggests light load AE operation (25%) are not recommended if BC emission are desired to be minimized. The ME eBC emission trend is hard to see with Figure 3-22, but can be visualized with Figure 3-23 where the ME shows a slight trend of increasing eBC emissions with higher sulfur level. The BC emission from the ME did not show a significantly high eBC emissions at light load like the AE suggesting the ME is not as sensitive to load variability like the AE.

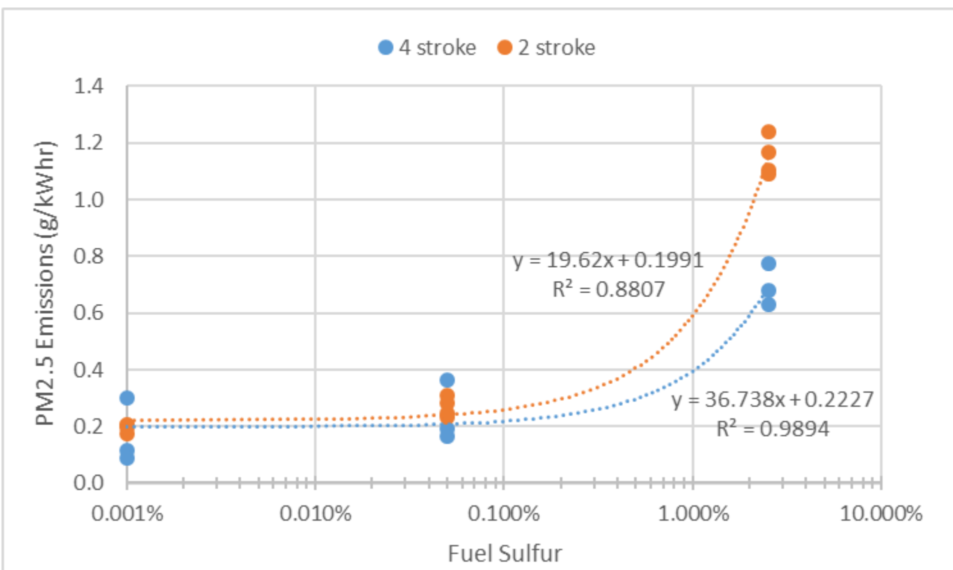


Figure 3-21 PM2.5 emissions by % load, fuel, and engine type (g/kWhr)

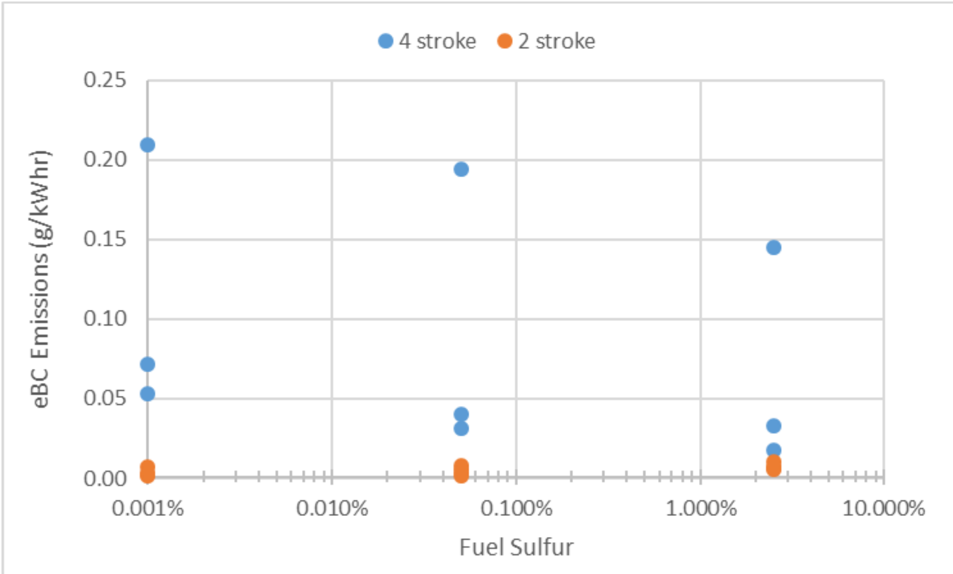


Figure 3-22 eBC (PM_EC) emissions by % load, fuel, and engine type (g/kWhr): linear, log
[1] Engine model year, size and fuel were different for each column of points where only fuel sulfur level is plotted on the x-axis for this discussion.

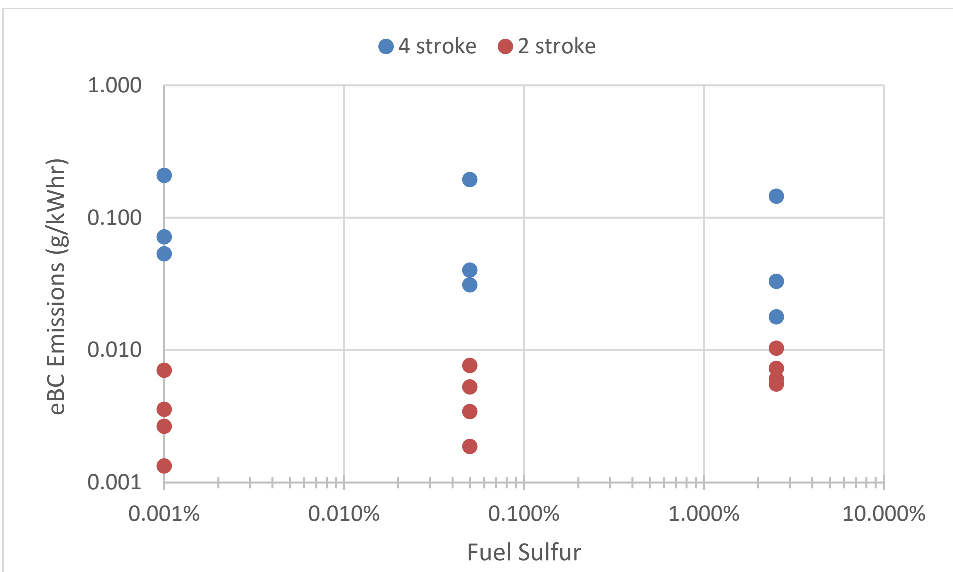


Figure 3-23 eBC (PM_EC) emissions by % load, fuel, and engine type (g/kWhr): log, log
[1] Engine model year, size and fuel were different for each column of points where only fuel sulfur level is plotted on the x-axis for this discussion.

Summary

Emissions measurements were made on a modern Tier 2 large ocean-going container vessel (13,000 TEU) on two fuels, a low sulfur MGO fuel and a new low sulfur residual fuel (ULSFO). Testing occurred at the port of Long Beach for the AE and auxiliary boiler and the ME was tested from Long Beach to Oakland. The ME testing utilized four load points from 45% load (maximum recommended by the Chief) and VSR load (9%), the AE testing followed the D2 test cycle with a maximum recommended by the Chief of 65%, and the auxiliary boiler testing utilized two loads that were typical for its usage. Emissions were measured following ISO and CFR methods for gaseous, and PM (total mass, elemental, and organic carbon species, sulfated PM). Auxiliary boiler sampling also include toxics to help CARB update its auxiliary boiler emissions inventory. Dilution ratios and filter temperatures, as specified in 1065, were met during this testing.

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

- The emissions were stable for all days suggesting the results for this testing are representative of a properly operating OGV.
- The ME CO_2 emissions ranged from 656 g/kWhr to 597 g/kWhr and the AE CO_2 emissions ranged from 787 to 650 g/kWhr for the MGO fuel. The CO_2 emissions are comparable for the ULSFO fuel and to those for other ME and AE engine tested at-sea.
- The ME Tier 2 engine NO_x emissions ranged from about 27.4 to 16.85 g/kWhr for the MGO fuel with the ULSFO fuel slightly higher for each test point (more by ~ 5%). The AE NO_x emissions ranged from 8.15 to 7.6 g/kWhr for the MGO fuel. The ULSFO NO_x emissions were slightly higher than MGO NO_x emissions (3%), but the difference were not statistically significant. The auxiliary boiler MGO NO_x emissions were lower than the LSHFO fuel and the differences was statistically significant.
- The ME $PM_{2.5}$ emissions were statistically higher for the ULSFO fuel (35%) compared to the MGO fuel. The emissions ranged from about 0.35 to 0.26 g/kWhr for the ULSFO fuel and from 0.22 to 0.20 g/kWhr for the MGO fuel.
- The AE $PM_{2.5}$ emissions were also higher for the ULSFO fuels by 54%, but lower for the auxiliary boiler by 49% compared to the MGO fuel. The AE and auxiliary boiler PM differences were not statistically significant according to a student t-test.
- The ME and AE organic carbon PM emissions for the ULSFO fuel were higher (35% and 90%, and statistically significant) than the MGO fuel and ranged from 0.20 to 0.17 g/kWhr for the ME and 0.092 to 0.053 g/kWHr for the AE. The ME organic carbon emissions represented 92% of the total PM fraction and the AE organic carbon only represented 25%. Although the AE organic carbon PM emissions were statistically higher, their total fraction was only 25% of the total PM so this difference is small compared to the total PM emissions. The auxiliary boiler emissions also showed higher amounts of organic carbon PM compared to the ULSFO fuel, but the differences were not statistically significant.
- The ME eBC emissions ranged from 0.0078 g/kWhr to 0.0015 g/kWhr and 0.19 g/kWhr to 0.031 g/kWhr for the AE (ULSFO fuel). The MSD AE eBC emissions where highest at light load and lowest at high load and were about 20x higher compared to the SSD ME.
- Auxiliary boiler emissions
  - The auxiliary boiler NO_x emissions ranged from 1.68 to 2.28 g/kg-fuel for the MGO and ULSFO. The PM emissions ranged from 0.029 to 0.055 g/kg-fuel for both fuels.

   - The formaldehyde emissions ranged from 3.86 mg/kg-fuel (ULSFO fuel) to 0.688 mg/kg-fuel for the MGO fuel. The mean differences for Formaldehyde was statistically different between the fuels, but not for acetaldehyde and acetone based on a two tailed t-test.
   - The speciated HCs were collected in SUMMA canisters, but due to laboratory communication issues, these results are not available for this report.
   - The metal emisison for the MGO fuel showed a statistically lower emission for selected metals that ranged from a factor of 58 for Nickle (Ni) to 28% for Magnesium (Mg). Only chlorine (Cl) was lower for the ULSFO compared to the MGO fuel.
- The results of the student t statistical significance test suggest none of the measured mean differences were statistically significant except for the ME $PM_{2.5}$ emissions where the ULSFO fuel $PM_{2.5}$ emissions were 35% higher than the MGO fuel and the ME and AE organic carbon PM emissions.

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Appendix A – Sample Collection Methods

ISO 8178-1[5] and ISO 8178-2[6] 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[7], 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.

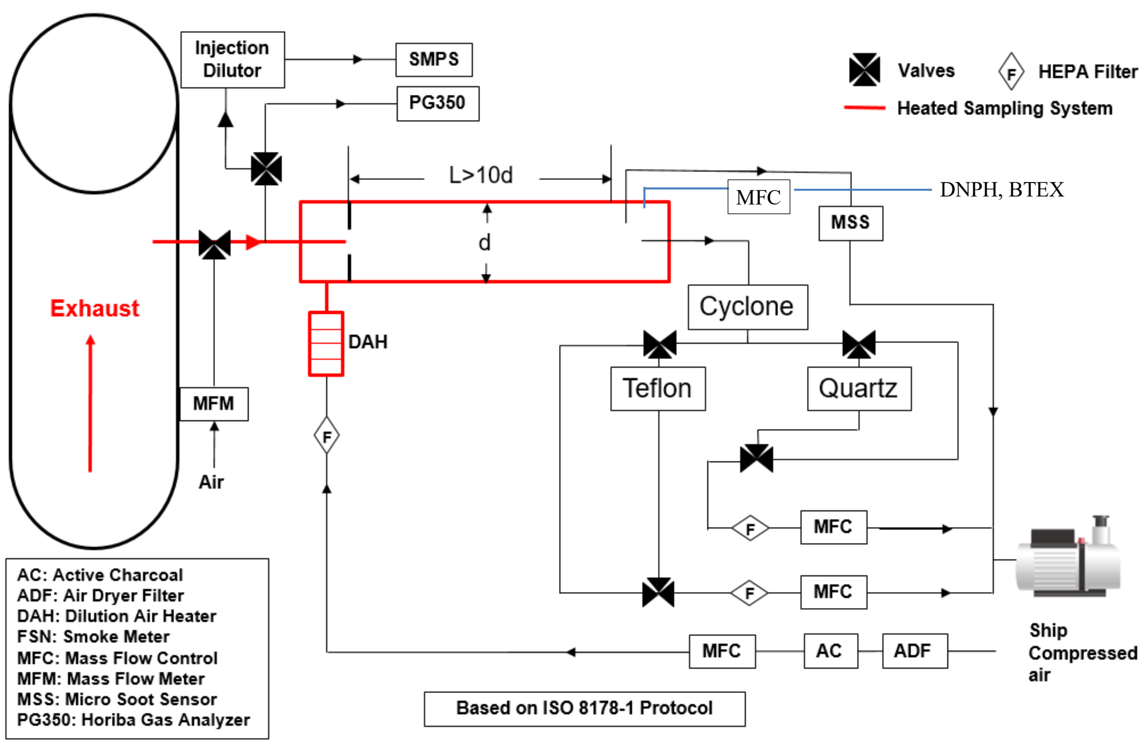


Figure A-1 Regulated and non-regulated emissions sampling system

[5] 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

[6] 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

[7] 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-1. 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.

In 2015 UCR upgraded its dilution tunnel to include dilution air heating and sample heating. These upgrades are implemented on all testing systems, but due to heat in the exhaust, they do not impact the sampling system for non-scrubber tests. 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 above the saturation point of the supersaturated exhaust. 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.

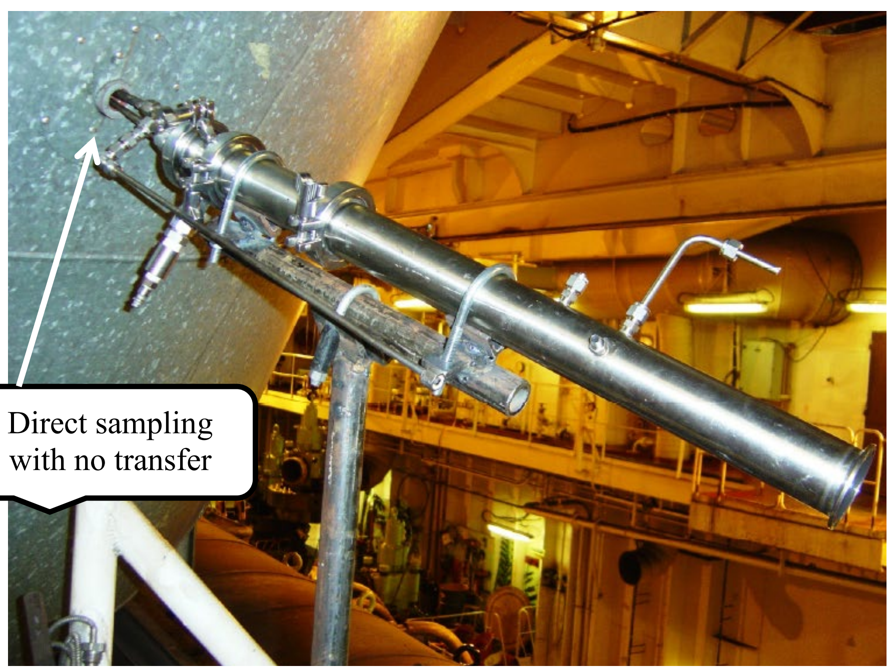


Figure A-2 measurement layout on an engine exhaust stack

UCR implemented active dilution air and sample heating for scrubber equipped vessels. 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. Since this testing did not involve a scrubber, the heater was turned off due to high exhaust temperatures.

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; • Equal to/greater than probe diameter & < 25 mm diameter; • 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; • 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 used by UCR. For SO_2, ISO/CFR recommends that the concentration of SO_2 is calculated based on the fact that 97.75% of the fuel sulfur is converted to SO_2 (40 CFR Part 1065). UCR agrees with this recommendation and the enclosed SO2 reported emissions are calculated from fuel sulfur levels.

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 dioxide;
- Heated chemiluminescent detector (HCLD) or equivalent for measurement of nitrogen oxides;
- Paramagnetic detector (PMD) or equivalent for measurement of oxygen.
- Cross-Flow Modulation Non-Dispersive Infrared Absorption Method for sulfur dioxide and carbon monoxide

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-250 portable multi-gas analyzer. The PG-250 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-250 was tested and verified under the U.S. EPA ETV program.

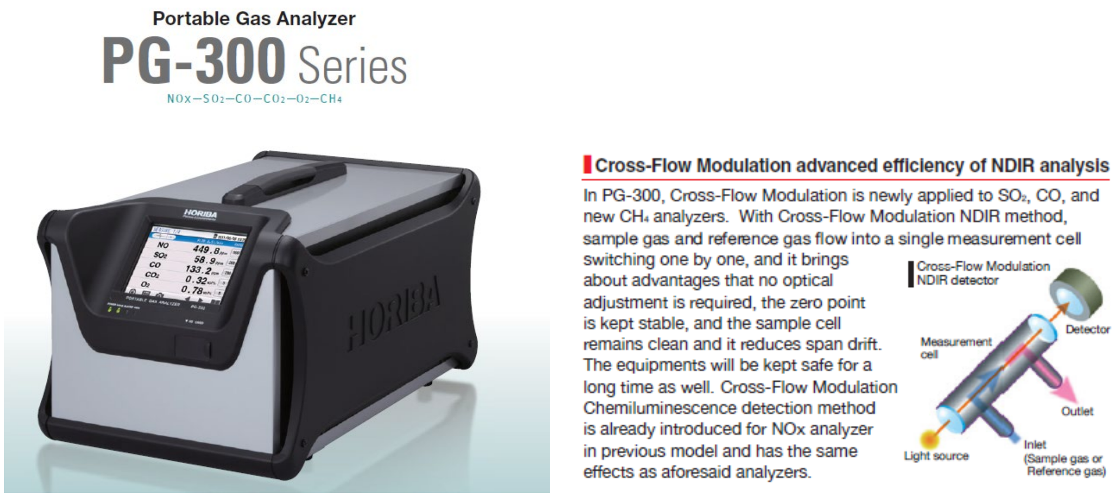


Figure A-4 Gas analyzer setup with measurement cell description

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.

Table A-3 Quality Specifications for the Horiba PG-350

Repeatability	±0.5% F.S. (NO_x: </= 100ppm range CO: </= 1,000ppm range) ±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-4b 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 ug 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. 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-5 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.

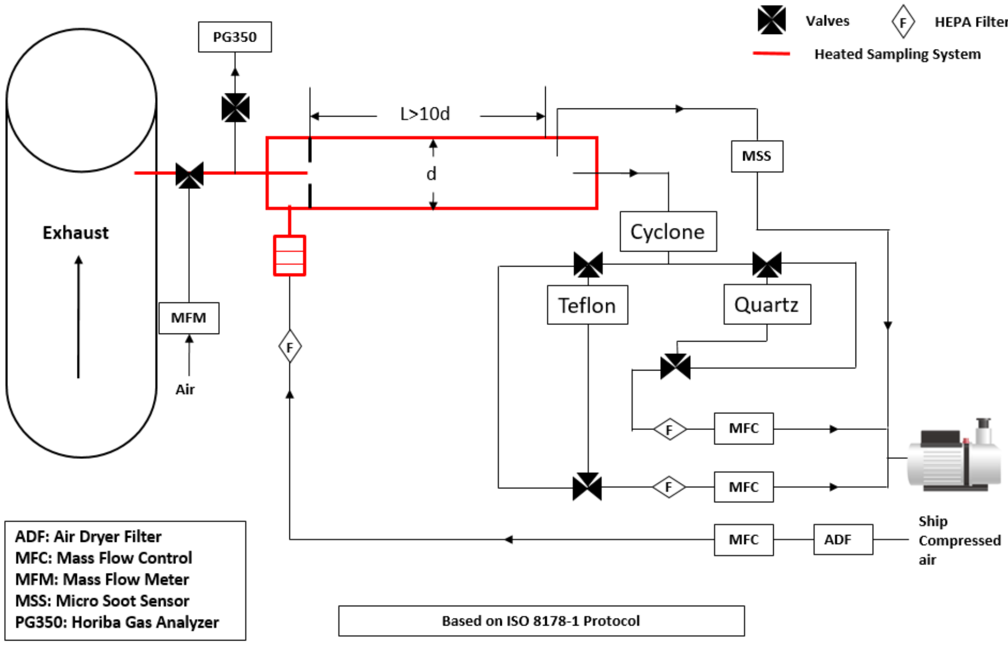


Figure A-5 Regulated emission sampling system

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 an example of 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**

Chas Manning (CMM)
Analyst: **Chas Manning**

Nelson Ma
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 8178-4[8] is to provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. ISO 8178-4 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.

Table C-1 Definitions Used Throughout ISO 8178-4

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. 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 8178-4 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.

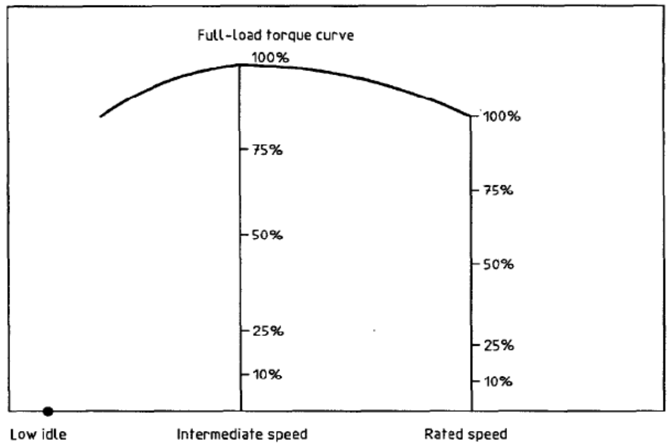


Figure C-1 Torque as a Function of Engine Speed

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.

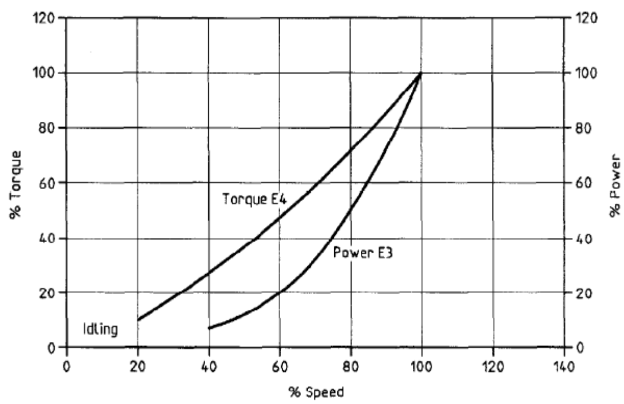


Figure C-2 Examples of Power Scales

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. 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 2. Manufacturer or supplier	Reference fuel, if one is defined Commercial fuel if no reference fuel is defined
Acceptance test	1. Manufacturer or supplier 2. Customer or inspector	Commercial fuel as specified by the manufacturer[1)]
Research/development	One or more of: 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 –Test Details and Data Records

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

1: Engine Maintenance Records

These records were collected only once during vessel testing to document the status of the ME and both AEs 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.

Class	*DNV+1A1 CONTAINER CARRIER*	Class ship ID Number	*114*
Class Notation	*DG-P, E0, BWM-E(s), BIS, TMON, NAUTICUS*		
Builder	*HYUINDAI SAMHO HEAVY INDUSTRIES*	Hull No.	*S459*
Date of Keel Laid	*29/12/2011*	Date of Build	*07/06/2012*
Last Docking Date	*N/A*	Next Docking Due Date	*2019*
Suez Canal ID No.		Panama Canal ID No.	*N/A*

Characteristics					
L.O.A	*366.53*	L.B.P.	*350*	Registered Length	*350.08*
Breadth	*48.2*	Moulded Depth	*29.85*	Max Height above BL	*68.5*
Light Ship	*43167*	International GRT	*140.979*	International NRT	*59.132*
Suez Canal Gross /Net Tonnage	*145.798,48*	Panama Canal Gross/Net Tonnage	*N/A*	Fresh Water Allowance	*306*
TPC Summer Draft	*151.10*	Scantling Draught / Deadweight	*15.50/141.550*	Design draught / Deadweight	*14.50/126.629*
Tropical FW Draught	*N/A*	Tropical FW Freeboard	*N/A*	Tropical FW Deadweight	*N/A*
Fresh Water Draught	*15.829*	Fresh Water Freeboard	*4.653*	Fresh Water Deadweight	*157550*
Tropical Draught	*N/A*	Tropical Freeboard	*N/A*	Tropical Deadweight	*N/A*
Summer Draught	*15.523*	Summer Freeboard	*4.959*	Summer Deadweight	*141550*
Winter Draught	*N/A*	Winter Freeboard	*N/A*	Winter Deadweight	*N/A*

Propulsion / Machinery / Maneuvering			
Main Engine No. / Maker / Type	*HYUNDAI-B&W 12K98ME-C7*	Main Engine MCR/RPM and NCR/RPM	*(MCR): 72240 kW x 104 RPM (NCR): 65016 KW X 100.4 RPM*
M/E Grade of Fuel Used	*HSFO/ LSFO/ HSDO/ LSDO*		*ABOUT 115MT (SPEED = 18 KNOTS)*
Aux./ Engines No. / Maker / Type	*HYUNDAI-HiMSEN 6H32/40 – 5x2870 kW , AC 6.6 KV, 60 Hz*	Aux./ Engines Rated Power (KW) and R.P.M.	*5x2870 kW*
A/E Grade of Fuel Used	*HSFO/ LSFO/ HSDO/ LSDO*		*ABOUT 12 MT*
Bow Thrusters No. / Maker / Model / Power	*MODEL : KAWASAKI KT-255B5 2 x 1800=3600 kW / 4894 BHP*	Stern Thrusters No./ Maker / Model / Power	*N/A*
Propeller Type / Diameter / Pitch	*6 Blades, Solid Type / 8.800 mtrs*	Rudder Type	*SEMO-BALANCED STREAM LINE*
Trial Max Speed	*About 24,70 Knots*	Service Speed	*About 18 knots*
Minimum Maneuvering Speed / R.P.M.	*About 7.00 Knots / 30 RPM*	Maximum Maneuvering Speed / R.P.M.	*About 17.50 Knots / 72RPM*

Load Ability /Gargo Gear					
Container Nominal Capacity (TEUS)	*13082*	Max. 20'(40') Deck/Hold Container Capacity	*6774 (150) / 5678 (165)*	Max. 40'(20) Deck/Hold Container Capacity	*3512 (50) / 2968 (72)*
Max. 40'HC under Deck w/out loosing tier	*349*	Max. 40'HC on Deck w/out loosing tier	*NIL*	Max. 45' on Deck	*1660*
Homogeneous intake of TEU's of 14mt	*9174*	Max. Reefer Capacity Deck/Hold (Voltage)	*800 / NIL (440 V)*	Number of Holds / Hatches	*10/21*
Number & Type of Hatch Covers	*83/PONTOON*	Hatch Cover weights	*38.9 (MAX)*	Stackweight on Deck 20'/40'	*90/140 MT*
Stackweight in Hold 20'/40'	*24MT/UNIT / 30.5 MT/UNIT*	Cargo Cranes No/Type	*NIL*	Cargo Cranes Load/Outreach	*N/A*

Tanks Capacity					
Number of B.W. tanks / 100% tank Capacity (m3)	*26/36089.8 MT*	Number of Fuel Oil tanks / 90% tank Capacity	*5/8380.518 MT*	Number of Diesel Oil tanks / 90% tank Capacity	*1/121.89 MT*
Number of ULSFO tanks / 90% tank Capacity (m3)	*3/1587.315 MT*	Number of LSDO tanks / 90% tank Capacity (m3)	*3/425.5727 MT*	Number of F.W. tanks / 100% tank Capacity (m3)	*2/501.8 MT*
Number of L.O. tanks / 100% tank Capacity (m3)	*9/655.1 MT*	Number of Sludge Tanks / 100% tank Capacity (m3)	*2/62.6 MT*	Number of Bilge tanks / (100% tank Capacity	*2/ 227.4 MT*

Figure D-1 Selected 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 0.0893 % for the ULSFO fuel and 0.0382 % for the MGO fuel (fuel sample FS19001 and FS19002 respectively, see Figure D-1). The heating value utilized for the ULSFO fuel was 42.99 MJ/kg and for the MGO it was 44.0 MJ/kg. A vessel bunker report, from June 2018, listed the ULSFO sulfur at 0.05%, see Table D2, suggesting the fuel sulfur level does vary a bit between refueling (0.05% 2018 analysis and 0.089% in the UCR 2019 analysis).

Table D-1 ULSFO and MGO fuel analysis measured results (performed by SwRI)

Method	ODDB 47323 FS19001	ODDB 47324 FS19002
ASTM D2622, Sulfur Run 1, ppm Run 2, ppm Average, ppm	 901.07 908.72 893.42	Not Requested
ASTM D4052 API At 60F Specific Gravity at 60F Density at 15C, g/ml	 34.24 0.8537 0.8532	 36.65 0.8415 0.8410
ASTM D445 Viscosity at 40C, cSt	20.966	3.474
ASTM D524 Carbon Residue, mass %	0.50	0.08
ASTM D5453 Sulfur, ppm	Not Requested	383.41

Table D-2 Fuel bunker report provided by the vessel during a previous Bunker visit in June 2018

Sample Number	SNG1822600		
Bunker Port	Vostochnyy		
Bunker Date	04-Jun-2018		
Quantity per C.Eng.	500 MT		
Product Type	ULSFO		
Fuel Usage	Not Stated		
Sampling Point	Ship Manifold	Source Of Data	B.D.N.
Sampling Date	04-Jun-2018	Density @ 15°C	851.0 kg/m³
Sampling Method	Continuous Drip	Viscosity @ 50°C	17.1 mm²/s
Seal Data	1580313 (VPS, Intact)	Sulfur	0.051 % m/m
Related Seals	1580314, 1580315	Volume @ 52.6°C	589.345 m³
Marpol Seal	1580316	Quantity	500.000 MT

Test Results

	Unit	Test Results	RMD80	Test Method
Density @ 15°C	kg/m³	851.4	975.0	ISO 12185
Viscosity @ 50°C	mm²/s	16.60	80.00	ASTM D7042
Water	% V/V	0.03	0.50	ASTM D6304-C
Micro Carbon Residue	% m/m	0.30	14.00	ISO 10370
Total Sediment Potential[2]	% m/m	0.08	0.10	ISO 10307-2
Ash	% m/m	< 0.01	0.07	LP 1001
Vanadium	mg/kg	< 1	150	IP 501
Sodium	mg/kg	< 1	100	IP 501
Calcium	mg/kg	< 1	30	IP 501
Zinc	mg/kg	< 1	15	IP 501
Phosphorus	mg/kg	< 1	15	IP 501
Pour Point	°C	18	30	ISO 3016
Flash Point	°C	> 70.0	60.0	ISO 2719-B
CCAI (Ignition Quality)[1]	-	757	860	ISO 8217
Aluminium + Silicon	mg/kg	< 2	40	
Acid Number	mg KOH/g	< 0.1	2.5	ASTM D664
Sulfur	% m/m	0.040		ISO 8754
Aluminium	mg/kg	1		IP 501
Silicon	mg/kg	< 1		IP 501
Iron	mg/kg	1		IP 501
Nickel	mg/kg	1		IP 501
Magnesium	mg/kg	< 1		LP 1101
Potassium	mg/kg	< 1		LP 1101
Net Specific Energy[1]	MJ/kg	42.99		ISO 8217

[1] Calculated value; [2] Retested parameters

3. Engine Screen Shot

UCR collects engine data from the control room using a data collection system that relies on photographs. Engine load for the ME, AE, and auxiliary boiler were collected from photographs of these systems for specific information on engine load, fuel consumption, temperatures, pressures and other relevant information. Each load test point captured up to four photo-screen shots to quantify stability of readings. Loads during testing were stable and this approach was reasonable and reliable. These pictures include a time reference to track alignment of the data in addition to hand logs, 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. Examples of the photographs are provided in Figure D-2 through Figure D-6. Figure D7 and 8 show details of the aux boiler tested.

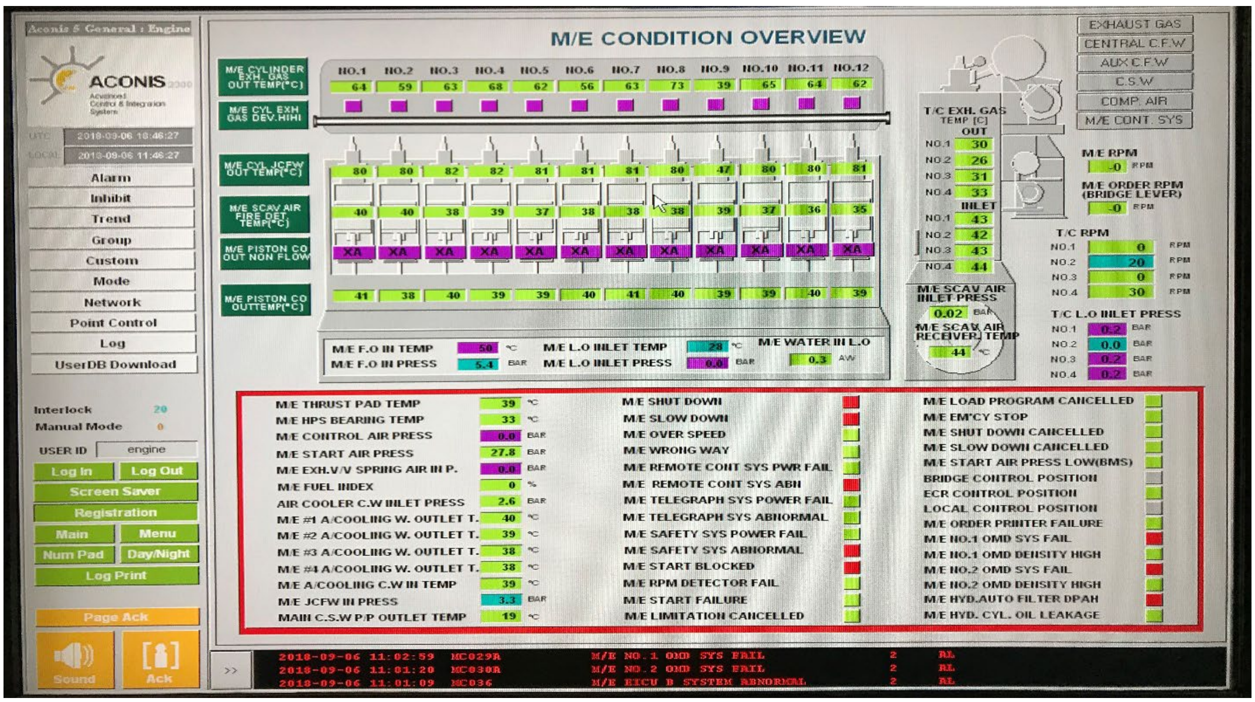


Figure D-2 ME example of data photo utilized (data not from actual voyage): part 1

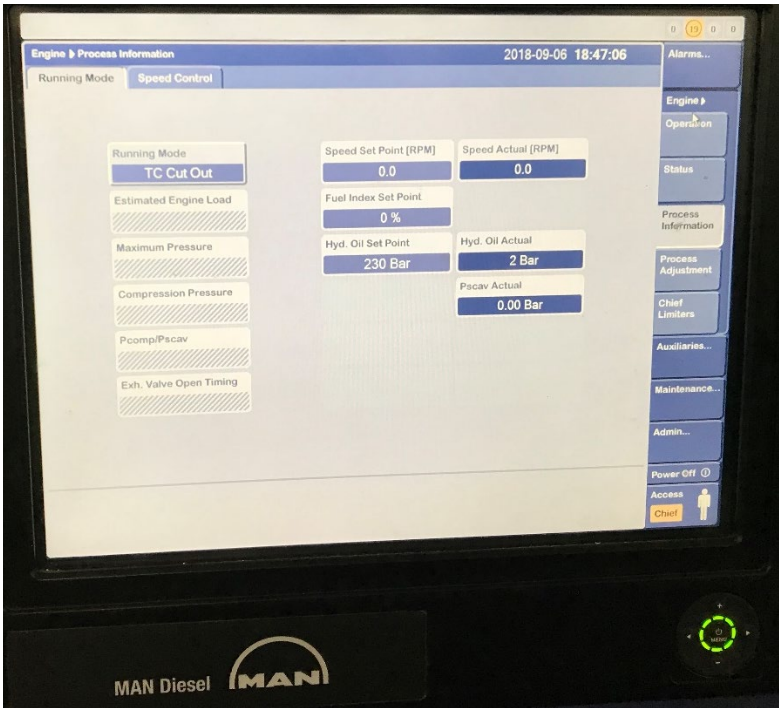


Figure D-3 ME example of data photo utilized (data not from actual voyage): part 2

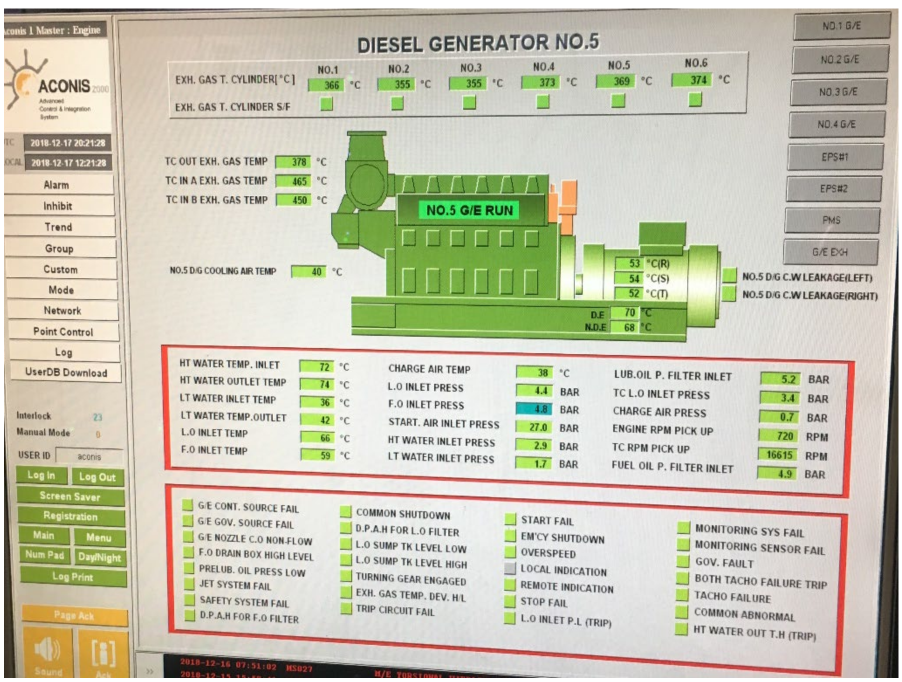


Figure D-4 AE example of data photo utilized: part 1

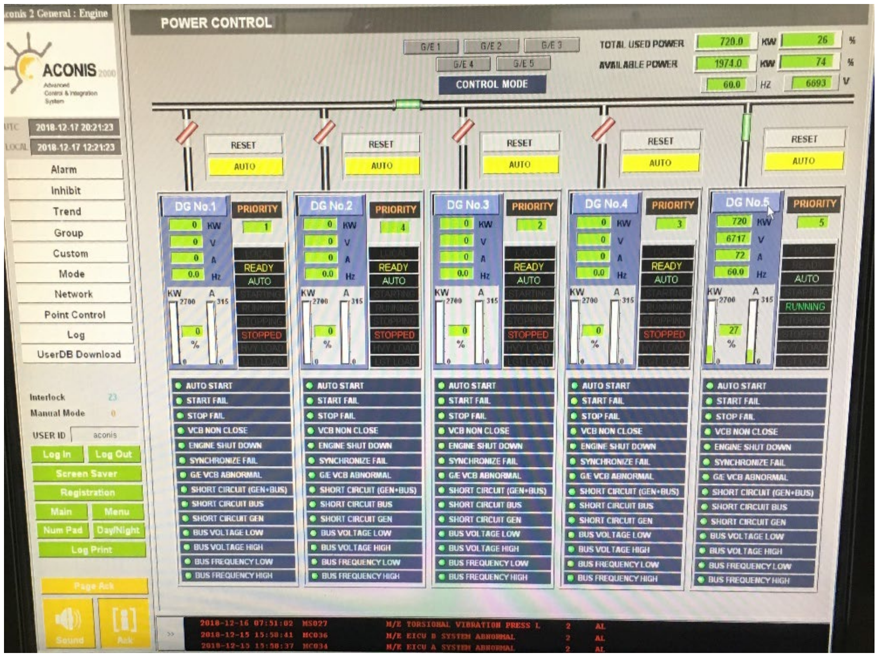
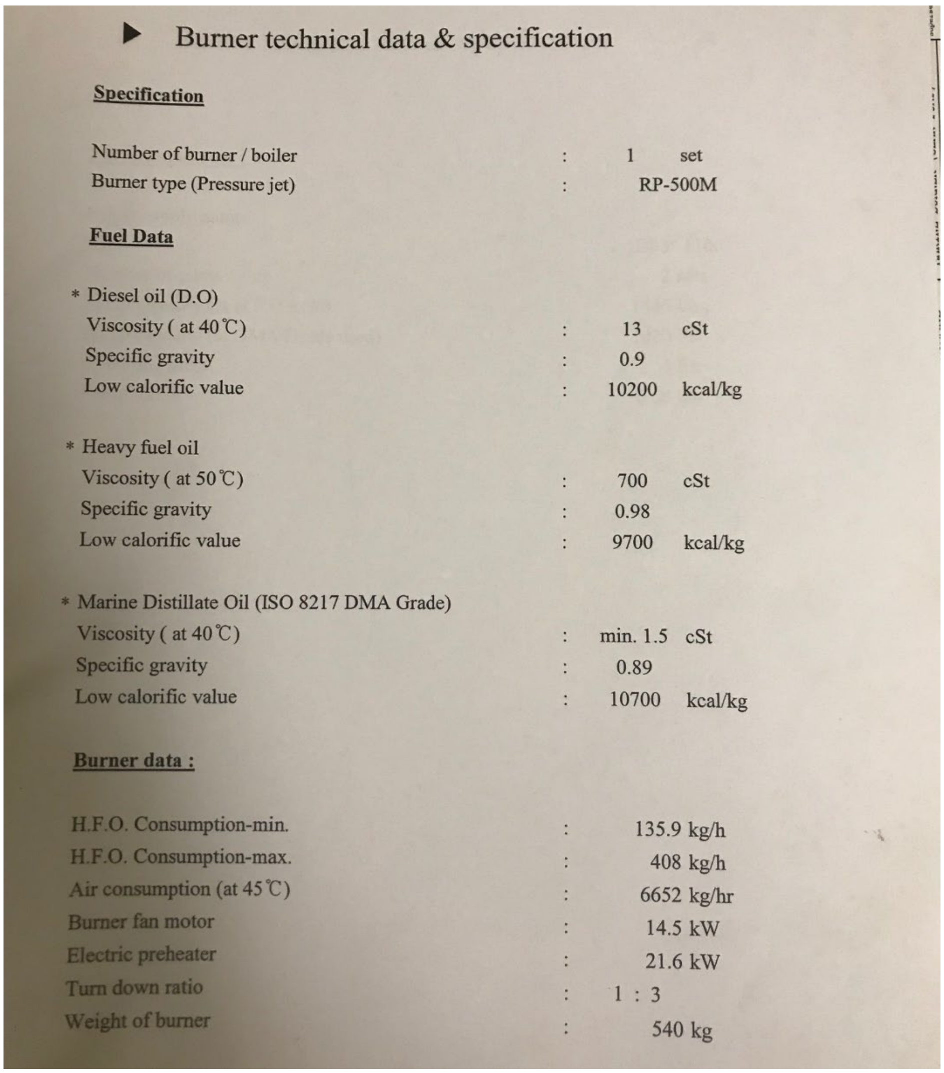


Figure D-5 AE example of data photo utilized: part 2

Figure D-6 Example of engine room data entry. Picture is taken, then data is entered into our excel spreadsheets.



▶ Burner technical data & specification

Specification

Number of burner / boiler	:	1 set
Burner type (Pressure jet)	:	RP-500M

Fuel Data

* Diesel oil (D.O)		
Viscosity (at 40℃)	:	13 cSt
Specific gravity	:	0.9
Low calorific value	:	10200 kcal/kg
* Heavy fuel oil		
Viscosity (at 50℃)	:	700 cSt
Specific gravity	:	0.98
Low calorific value	:	9700 kcal/kg
* Marine Distillate Oil (ISO 8217 DMA Grade)		
Viscosity (at 40℃)	:	min. 1.5 cSt
Specific gravity	:	0.89
Low calorific value	:	10700 kcal/kg

Burner data :

H.F.O. Consumption-min.	:	135.9 kg/h
H.F.O. Consumption-max.	:	408 kg/h
Air consumption (at 45℃)	:	6652 kg/hr
Burner fan motor	:	14.5 kW
Electric preheater	:	21.6 kW
Turn down ratio	:	1 : 3
Weight of burner	:	540 kg

Figure D-7 Auxiliary boiler specificaions from the manual.

▶ Burner technical data & specification

F.O. Equipments :

H.F.O supply pump	
Type	: DS3 -1100
Number of pump / ship	: 2 sets
Pump capacity (at H.F.O used)	: 1446 l/h
Pump capacity (at DMA Grade used)	: 1020 l/h
Operating press.	: 4 bar
Pump motor	: 0.66 kw

Figure D-8 Auxiliary boiler specificaions from the manual (cont.).

Appendix E –Engine Power, Auxiliary boiler Load, and Exhaust Flow

This appendix present the engine related results utilized for the mass and brake-specific emission values. These results rely on the data collected from the engine control room for actual load, shop 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 ME percent load for each mode are presented in Table E-1, the AE loads and calculated exhaust flow are listed in Table E-2, and the auxiliary boiler specific manufacturer specifications are listed in Figure E-1. The shop trial information is listed in Figure E-2 through E-6.

Some systems refer to effective power which 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 brake fuel flow from the shop trial reported fuel flow since other measures were not available.

Figure E-7 shows the AE shop trial measured exhaust flow compared against the estimated exhaust flow utilized in this report. The shop trial exhaust flow is about 1.33 times higher than the exhaust flow estimated as part of this project. It is unclear why there is a difference, but it is reported here to make a note of the difference. If the AE shop trial exhaust flow value is utilized, the NOx emissions match the certified value. In general, the higher exhaust flow would not change the A/B comparison of this work. More investigation is recommended to understand this difference.

Table E-01 Summary of ME power, exhaust flow, and test conditions

Date	Project Name	Fuel	ATS	Location	Test Mode	Start Time	Load			Fuel Rate Meas.	cor. Factor	cor. Fuel Rate	Sample Duration	DR	Exh Temp	Filter Temp	Stack Pres	Carb. Bal. Exh Flow I		Speed Density Exh Flow II		Exh Fllow Utilized I
mm/dd/yyyy	name					hh:mm:ss	% MCR	MW	% NCR	kg/hr	n/a	kg/hr	min	n/a	C	C	mbar	(scfm)	(m3/hr)	(scfm)	(m3/hr)	m3/hr
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	2_1	11:00:00	9%	6.50	12%	1314	1.00	1,314	30.0	5.1	231.6	44.9	-4.0	41,882	88,743	35,379	74,964	88,743
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	2_2	11:35:00	9%	6.50	12%	1314	1.00	1,314	30.0	5.0	231.6	41.7	-4.0	40,625	86,080	35,165	74,511	86,080
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	2_3	12:10:00	8%	6.02	11%	1228	1.00	1,228	30.0	5.3	229.7	42.5	-3.6	40,344	85,485	34,415	72,920	85,485
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	1_1	9:00:00	12%	8.67	16%	1701	1.00	1,701	30.0	5.2	239.1	44.2	-4.0	42,491	90,032	42,773	90,630	90,032
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	1_2	9:35:00	12%	8.67	16%	1701	1.00	1,701	32.0	5.3	239.1	41.0	-3.7	43,881	92,978	42,625	90,318	92,978
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	1_3	10:12:00	12%	8.67	16%	1701	1.00	1,701	30.0	5.3	239.1	43.5	-3.4	43,407	91,975	42,343	89,720	91,975
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	3_1	17:25:00	32%	23.36	42%	4323	1.00	4,323	30.0	5.2	257.8	42.9	-4.0	75,869	160,756	70,645	149,688	160,756
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	3_2	18:00:00	34%	24.32	44%	4495	1.00	4,495	30.0	5.2	257.5	44.5	-3.9	81,506	172,702	75,320	159,594	172,702
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	3_3	18:35:00	33%	23.84	43%	4409	1.00	4,409	30.0	5.2	257.7	45.7	-3.6	80,160	169,849	74,762	158,412	169,849
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	4_1	19:30:00	44%	31.79	58%	5828	1.00	5,828	30.0	5.2	250.9	44.4	-2.7	109,542	232,106	100,563	213,082	232,106
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	4_2	20:05:00	44%	31.79	58%	5828	1.00	5,828	30.0	5.3	250.9	44.7	-2.4	109,554	232,132	100,463	212,869	232,132
12/20/2018	Tier 2 Modern Engine	MGO	n/a	ME-PostEconomizer	4_3	20:20:00	44%	31.79	58%	5828	1.00	5,828	0.0	0.0	250.9	0.0	0.0	0	0	100463	212869	0
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	8_1	4:40:00	9%	6.50	12%	1344	1.00	1,344	30.0	5.3	231.6	43.5	-4.1	94,339	94,339	36,354	77,030	94,339
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	8_2	5:15:00	9%	6.50	12%	1344	1.00	1,344	30.0	5.3	231.6	41.7	-3.4	105,543	105,543	36,391	77,109	105,543
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	8_3	5:50:00	9%	6.50	12%	1344	1.00	1,344	30.0	5.2	231.6	41.0	-3.8	91,280	91,280	35922	76115	91280
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	7_1	3:20:00	13%	9.39	17%	1873	1.00	1,873	30.0	5.2	241.2	41.2	-4.1	51,344	108,791	45,596	96,611	108,791
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	7_2	3:55:00	13%	9.15	17%	1829	1.00	1,829	30.0	5.2	240.5	43.4	-4.1	49,859	105,646	44,753	94,825	105,646
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	7_3	4:10:00	13%	9.15	17%	1829	1.00	1,829	-	-	-	-	-	-	-	-	-	-
12/20/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	5_1	23:35:00	32%	23.12	42%	4381	1.00	4,381	30.0	5.2	257.9	41.6	-3.4	89,303	189,222	77,901	165,063	189,222
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	5_2	0:10:00	33%	23.60	43%	4469	1.00	4,469	30.0	5.2	257.7	44.7	-3.3	92,164	195,285	78,626	166,599	195,285
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	5_3	0:45:00	33%	23.84	43%	4513	1.00	4,513	30.0	5.2	257.7	43.5	-3.0	92,283	195,537	78,020	165,316	195,537
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	6_1	1:50:00	43%	31.06	56%	5833	1.00	5,833	30.0	5.2	251.8	42.7	-2.2	123,582	261,856	101,913	215,941	261,856
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	6_2	2:25:00	42%	30.34	55%	5701	1.00	5,701	30.0	5.2	252.7	43.1	-2.3	120,986	256,355	102,386	216,943	256,355
12/21/2018	Tier 2 Modern Engine	ULSFO	n/a	ME-PostEconomizer	6_3	2:40:00	42%	30.34	55%	5701	1.00	5,701	-	-	-	-	-	-	-	-	-	-

Table E-02 Summary of AE power, exhaust flow, and test conditions

Date	Project Name	Fuel	ATS	Location	Test	Start Time	Engine Load [1]			Fuel Rate Meas.	cor. Factor	cor. Fuel Rate	Sample Duration	DR	Exh Temp	Filter Temp	Stack Pres	Carb. Bal. Exh Flow I		Speed Density Exh Flow II		Exh Fllow Utilized I
mm/dd/yyyy	name	n/a	n/a	n/a	#	hh:mm:ss	% MCR	MW	% NCR	kg/hr	n/a	kg/hr	min	n/a	C	C	mbar	(scfm)	(m3/hr)	(scfm)	(m3/hr)	m3/hr
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	3_1	15:47:00	26%	0.75	26%	186	1.00	186	6.0	6.4	238.2	40.8	-0.3	2,452	5,195	2,383	5,049	5,195
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	3_2	15:55:00	26%	0.74	26%	184	1.00	184	6.0	6.4	238.5	43.0	-0.3	2,432	5,154	2,377	5,037	5,154
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	3_3	16:03:00	26%	0.74	26%	184	1.00	184	6.0	6.4	238.7	41.5	-0.8	2,433	5,155	2,381	5,046	5,155
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	1_1	14:00:00	53%	1.53	53%	316	1.00	316	15.0	6.4	217.8	43.9	-1.1	4,023	8,524	4,031	8,540	8,524
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	1_2	14:23:00	54%	1.54	54%	318	1.00	318	10.0	6.4	217.6	43.6	-1.0	4,047	8,574	4,076	8,636	8,574
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	1_4	14:59:00	53%	1.53	53%	316	1.00	316	6.0	6.3	217.8	43.1	-1.0	4,013	8,504	4,033	8,545	8,504
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	2_1	15:14:00	63%	1.82	63%	365	1.00	365	6.0	6.3	214.9	43.0	-0.2	4,583	9,710	4,604	9,754	9,710
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	2_2	15:21:00	63%	1.81	63%	362	1.00	362	6.0	6.4	215.0	42.2	-0.3	4,549	9,639	4,621	9,792	9,639
12/15/2018	Tier 2 Modern Engine	MGO	-	AE#5-Stack	2_3	15:28:00	63%	1.79	63%	360	1.00	360	6.0	6.4	215.1	42.6	-0.3	4,514	9,565	4,562	9,666	9,565
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	4_1	12:27:00	27%	0.79	27%	196	1.00	196	6.0	6.3	236.7	42.1	-0.8	2,586	5,480	2,521	5,342	5,480
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	4_2	12:36:00	28%	0.80	28%	198	1.00	198	6.0	6.4	236.3	41.2	-0.8	2,610	5,531	2,521	5,342	5,531
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	4_3	12:43:30	28%	0.80	28%	197	1.00	197	10.0	6.3	236.5	43.4	-0.9	2,591	5,490	2,522	5,345	5,490
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	6_1	14:17:00	54%	1.55	54%	327	1.00	327	6.0	6.3	217.5	42.4	-1.4	4,205	8,911	4,085	8,655	8,911
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	6_2	14:26:00	54%	1.56	54%	328	1.00	328	6.0	6.3	217.3	42.5	-1.3	4,217	8,936	4,078	8,642	8,936
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	6_3	14:36:00	54%	1.55	54%	326	1.00	326	6.0	6.3	217.5	42.3	-1.4	4,197	8,892	4,022	8,522	8,892
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	5_1	13:38:00	65%	1.85	65%	377	1.00	377	6.0	6.4	214.7	42.4	-0.4	4,832	10,239	4,621	9,792	10,239
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	5_2	13:48:00	63%	1.82	63%	372	1.00	372	6.0	6.3	214.9	41.9	-0.5	4,759	10,084	4,611	9,771	10,084
12/17/2018	Tier 2 Modern Engine	ULSFO	-	AE#5-Stack	5_3	13:58:00	63%	1.82	63%	371	1.00	371	6.0	6.3	214.9	41.9	-0.6	4,753	10,071	4,608	9,763	10,071

[1] Engine load includes the alternator efficiency. The alternator efficiency ranged from 97.4% at 100% load to 84.9% at 10% load as reported in the shop trial data.

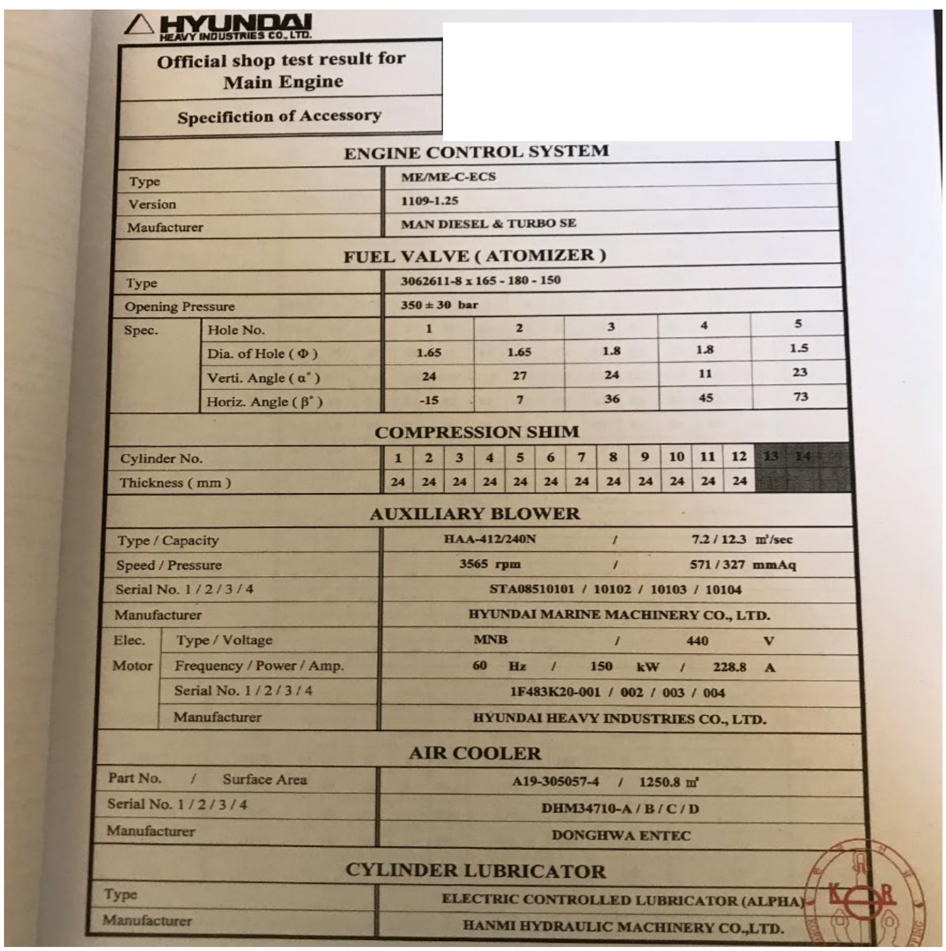
Table E-03 Summary of Auxiliary boiler power, exhaust flow, and test conditions

Date	Project Name	Fuel	ATS	Location	Test	Start Time	Boiler Load			Fuel Rate Meas.	cor. Factor	cor. Fuel Rate	Sample Duration	DR	Exh Temp	Filter Temp	Stack Pres	Carb. Bal. Exh Flow I		Exh Fllow Utilized I
mm/dd/yyyy	name	n/a	n/a	n/a	#	hh:mm:ss	%	g/kJ	Setpt	kg/hr	n/a	kg/hr	min	n/a	C	C	mbar	(scfm)	(m3/hr)	m3/hr
12/18/2018	Tier 2 Modern Engine	MGO	-	Post Boiler	1_1	17:39:00	60%	4.25	Normal	173	1.00	173	15.0	7.1	-	39.5	-1.1	1,546	3,276	3,145
12/18/2018	Tier 2 Modern Engine	MGO	-	Post Boiler	1_2	17:56:00	60%	4.25	Normal	173	1.00	173	22.0	3.1	-	41.3	-1.0	1,571	3,329	3,196
12/18/2018	Tier 2 Modern Engine	MGO	-	Post Boiler	1_4	18:47:00	60%	4.25	Normal	173	1.00	173	26.0	3.0	-	44.2	-1.0	1,570	3,327	3,194
12/19/2018	Tier 2 Modern Engine	ULSFO	-	Post Boiler	4_1	13:10:00	69%	3.70	Normal	150	1.00	150	30.0	4.6	-	41.3	1.7	1,193	2,527	2,464
12/19/2018	Tier 2 Modern Engine	ULSFO	-	Post Boiler	4_2	13:46:00	69%	3.70	Normal	150	1.00	150	30.0	4.6	-	42.6	1.7	1,189	2,520	2,457
12/19/2018	Tier 2 Modern Engine	ULSFO	-	Post Boiler	4_3	14:22:00	69%	3.70	Normal	150	1.00	150	30.0	4.6	-	44.2	2.1	1,189	2,518	2,455

Aux Boiler Specifications				
Max HFO Fuel Usage	408	kg/hr		
Min HFO Fuel Usage	135.9	kg/hr		
LHV HFO	9700	kcal/hr		
LHV HFO	40612	kJ/hr		
HFO Specific Grav.	0.98			
# boilers	1			
Max MGO fuel usage	288	kg/hr		
Type (Pressure Jet)	RP-500M			
Turn down ratio	1:3			
Type (arrangement)	Vertical			
Pump capacity HFO	1446	l/hr		
mfg	KangRim Heavy Industries Co. LTD			
location	China and S. Korea			

Figure E-01 Summary of Auxiliary boiler power, exhaust flow, and test conditions

[1] Measured fuel rate was not correct. The chief said this was the correct measure for auxiliary boiler fuel use, but it was a constant, see Pic. As such, the estimated fuel rate (or load) is based on communication with chief and manufacturer reported values. See appendix D for specifications of the aux boiler.



HYUNDAI HEAVY INDUSTRIES CO., LTD.

Official shop test result for Main Engine

Specifiction of Accessory

ENGINE CONTROL SYSTEM

Type	ME/ME-C-ECS
Version	1109-1.25
Maufacturer	MAN DIESEL & TURBO SE

FUEL VALVE (ATOMIZER)

Type		3062611-8 x 165 - 180 - 150				
Opening Pressure		350 ± 30 bar				
Spec.	Hole No.	1	2	3	4	5
	Dia. of Hole (Φ)	1.65	1.65	1.8	1.8	1.5
	Verti. Angle (α˚)	24	27	24	11	23
	Horiz. Angle (β˚)	-15	7	36	45	73

COMPRESSION SHIM

Cylinder No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Thickness (mm)	24	24	24	24	24	24	24	24	24	24	24	24		

AUXILIARY BLOWER

Type / Capacity		HAA-412/240N / 7.2 / 12.3 m³/sec
Speed / Pressure		3565 rpm / 571 / 327 mmAq
Serial No. 1 / 2 / 3 / 4		STA08510101 / 10102 / 10103 / 10104
Manufacturer		HYUNDAI MARINE MACHINERY CO., LTD.
Elec. Motor	Type / Voltage	MNB / 440 V
	Frequency / Power / Amp.	60 Hz / 150 kW / 228.8 A
	Serial No. 1 / 2 / 3 / 4	1F483K20-001 / 002 / 003 / 004
	Manufacturer	HYUNDAI HEAVY INDUSTRIES CO., LTD.

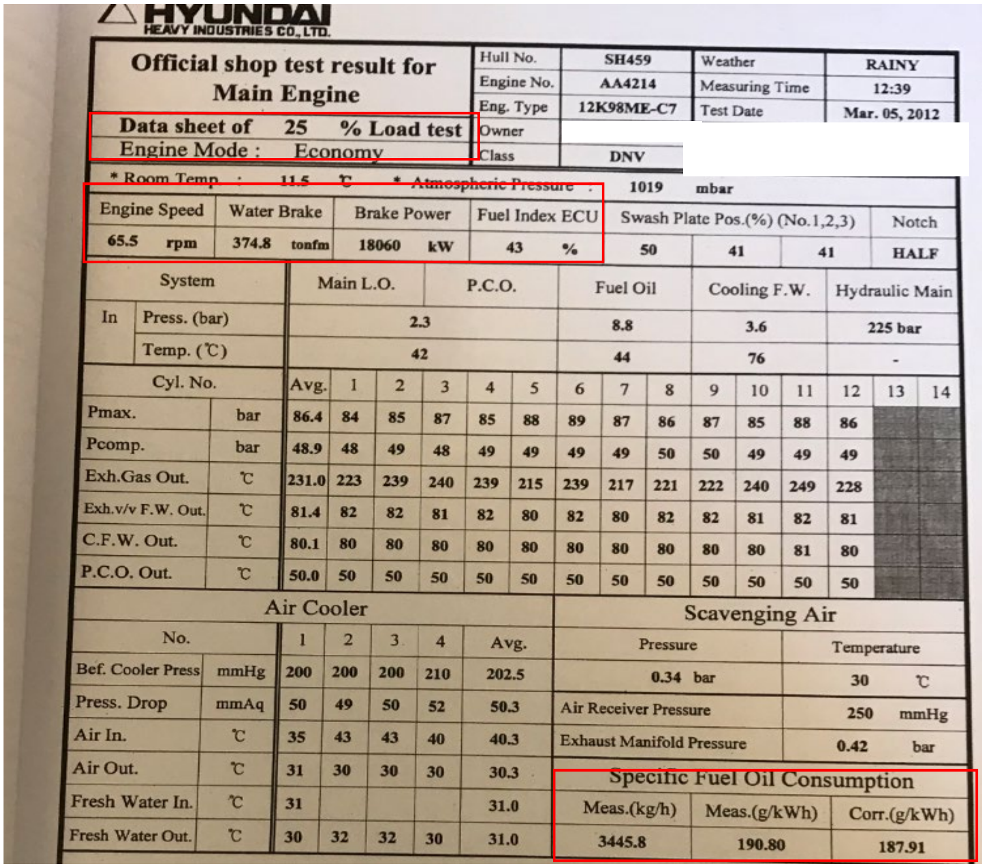
AIR COOLER

Part No. / Surface Area	A19-305057-4 / 1250.8 m²
Serial No. 1 / 2 / 3 / 4	DHM34710-A / B / C / D
Manufacturer	DONGHWA ENTEC

CYLINDER LUBRICATOR

Type	ELECTRIC CONTROLLED LUBRICATOR (ALPHA)
Manufacturer	HANMI HYDRAULIC MACHINERY CO.,LTD.

Figure E-02 Shop trial data sheet for the ME with Engine Control System and Lubrication


HYUNDAI HEAVY INDUSTRIES CO., LTD.

Official shop test result for Main Engine

Data sheet of 25 % Load test
Engine Mode : Economy

Hull No.	SH459	Weather	RAINY
Engine No.	AA4214	Measuring Time	12:39
Eng. Type	12K98ME-C7	Test Date	Mar. 05, 2012
Owner			
Class	DNV		

* Room Temp : 11.5 ℃ * Atmospheric Pressure : 1019 mbar

Engine Speed	Water Brake	Brake Power	Fuel Index ECU	Swash Plate Pos.(%) (No.1,2,3)			Notch
65.5 rpm	374.8 tonfm	18060 kW	43 %	50	41	41	HALF

System		Main L.O.	P.C.O.	Fuel Oil	Cooling F.W.	Hydraulic Main
In	Press. (bar)	2.3		8.8	3.6	225 bar
	Temp. (℃)	42		44	76	-

Cyl. No.		Avg.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pmax.	bar	86.4	84	85	87	85	88	89	87	86	87	85	88	86		
Pcomp.	bar	48.9	48	49	48	49	49	49	49	50	50	49	49	49		
Exh.Gas Out.	℃	231.0	223	239	240	239	215	239	217	221	222	240	249	228		
Exh.v/v F.W. Out.	℃	81.4	82	82	81	82	80	82	80	82	82	81	82	81		
C.F.W. Out.	℃	80.1	80	80	80	80	80	80	80	80	80	80	81	80		
P.C.O. Out.	℃	50.0	50	50	50	50	50	50	50	50	50	50	50	50		

Air Cooler

No.		1	2	3	4	Avg.
Bef. Cooler Press	mmHg	200	200	200	210	202.5
Press. Drop	mmAq	50	49	50	52	50.3
Air In.	℃	35	43	43	40	40.3
Air Out.	℃	31	30	30	30	30.3
Fresh Water In.	℃	31				31.0
Fresh Water Out.	℃	30	32	32	30	31.0

Scavenging Air

Pressure	Temperature
0.34 bar	30 ℃
Air Receiver Pressure	250 mmHg
Exhaust Manifold Pressure	0.42 bar

Specific Fuel Oil Consumption

Meas.(kg/h)	Meas.(g/kWh)	Corr.(g/kWh)
3445.8	190.80	187.91

Figure E-03 Shop trial data sheet for the ME 25% load (ref LHV = 42.36) [9]

[9] Instructions Hyundai-MAN B&W Diesel Engines Operation.

Technical File

I. Ambient & Gaseous Emission Data (For Information)

Parent engine of engine group

[redacted]

Mode	-	1	2	3	4	5
Test No.	-	01	02	03	04	05
Running time	-	09:10-09:30	09:30-09:50	09:50-10:10	10:10-10:30	10:30-10:50
Recorded time	-	09:15-09:27	09:35-09:47	09:55-10:07	10:15-10:27	10:35-10:47
Engine power (actual)	%	100	75	50	25	10
	kW	2870.0	2152.5	1435.0	717.5	287.0
Engine speed (actual)	%	100	100	100	100	100
	rpm	720.0	720.0	720.0	720.0	720.0
Generator power	kW	2795.4	2090.9	1382.8	671.6	243.5
Generator efficiency	%	97.4	97.1	96.4	93.6	84.9
Max. cylinder pressure	bar	198.7	167.7	127.8	84.5	57.5
Mean effective pressure	bar	24.8	18.6	12.4	6.2	2.5
Exhaust gas temp. at T/C outlet	℃	301.0	293.0	315.0	333.0	304.0
Turbocharger speed	rpm	29800	26900	22700	15900	10800
Ambient Data						
Charge air pressure	kg/cm²	3.60	2.70	1.20	0.50	0.10
Barometric pressure	kPa	101.2	101.2	101.2	101.2	101.2
Intake air humidity	%	65.8	65.1	64.4	62.7	61.9
	g/kg	12.08	12.24	12.64	12.53	12.59
Charge air humidity	g/kg	14.82	17.57	26.93	35.86	44.24
Intake air temperature	℃	23.7	24.1	24.8	25.1	25.4
Charge air temperature	℃	47.0	46.0	44.0	42.0	40.0
Intercooled air reference temp.	℃	47.0	46.0	44.0	42.0	40.0
Governor						
Pump index	mm	31.0	23.5	16.0	9.0	5.0
Indicator position	-	7.0	5.5	4.0	2.5	1.5
Fuel						
Uncorrected fuel consumption	kg/h	540.0	415.0	309.0	180.0	105.0
Charge air						
Air flow	kg/h	19222	15925	13298	8775	6373
Exhaust gas						
Exhaust gas flow	kg/h	19762	16340	13607	8955	6478
Gaseous Emissions Data						
CO concentration (Dry)	ppm	63.9	77.4	80.4	125.4	179.1
CO_2 concentration (Dry)	%	6.06	5.61	4.99	4.39	3.51
T.HC concentration (Wet)	ppmC	139.0	157.0	185.5	189.5	180.0
O_2 concentration (Dry)	%	12.58	13.48	14.18	14.98	16.05
NOx concentration (Dry)	ppm	840	720	620	482	398
NOx humidity/temp. corr. factor	-	1.014	1.017	1.024	1.023	1.025
Dry / wet corr. factor exhaust	-	0.944	0.947	0.951	0.955	0.961
NOx mass flow	kg/h	25.18	17.96	13.02	6.69	4.03
NOx specific	g/kWh	8.77	8.34	9.07	9.32	14.03
Test Cycle (D2)	g/kWh	8.90				

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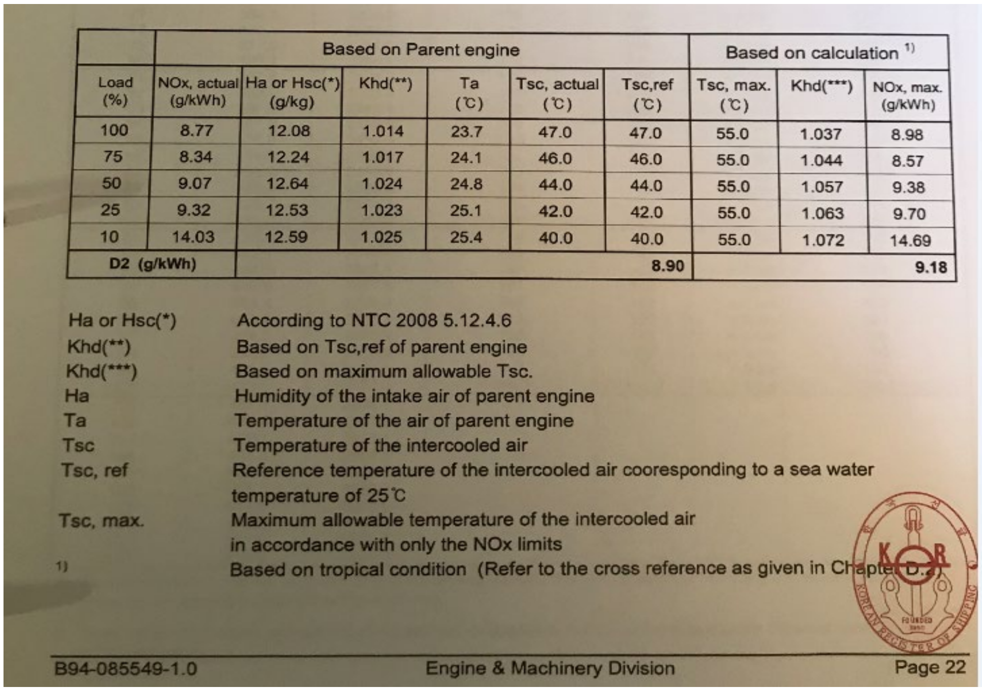
Figure E-04 Shop trial data sheet for the auxiliary engine tested [10]

[10] Instructions Book Volume II Engine B94-085549-1.0 Hyundai Himsen Auxiliary Generator.



Load (%)	Based on Parent engine						Based on calculation 1)		
	NOx, actual (g/kWh)	Ha or Hsc(*) (g/kg)	Khd(**)	Ta (℃)	Tsc, actual (℃)	Tsc,ref (℃)	Tsc, max. (℃)	Khd(***)	NOx, max. (g/kWh)
100	8.77	12.08	1.014	23.7	47.0	47.0	55.0	1.037	8.98
75	8.34	12.24	1.017	24.1	46.0	46.0	55.0	1.044	8.57
50	9.07	12.64	1.024	24.8	44.0	44.0	55.0	1.057	9.38
25	9.32	12.53	1.023	25.1	42.0	42.0	55.0	1.063	9.70
10	14.03	12.59	1.025	25.4	40.0	40.0	55.0	1.072	14.69
D2 (g/kWh)						8.90			9.18

Ha or Hsc(*) According to NTC 2008 5.12.4.6
Khd(**) Based on Tsc,ref of parent engine
Khd(***) Based on maximum allowable Tsc.
Ha Humidity of the intake air of parent engine
Ta Temperature of the air of parent engine
Tsc Temperature of the intercooled air
Tsc, ref Reference temperature of the intercooled air cooresponding to a sea water temperature of 25℃
Tsc, max. Maximum allowable temperature of the intercooled air in accordance with only the NOx limits
1) Based on tropical condition (Refer to the cross reference as given in Chapter D.2)

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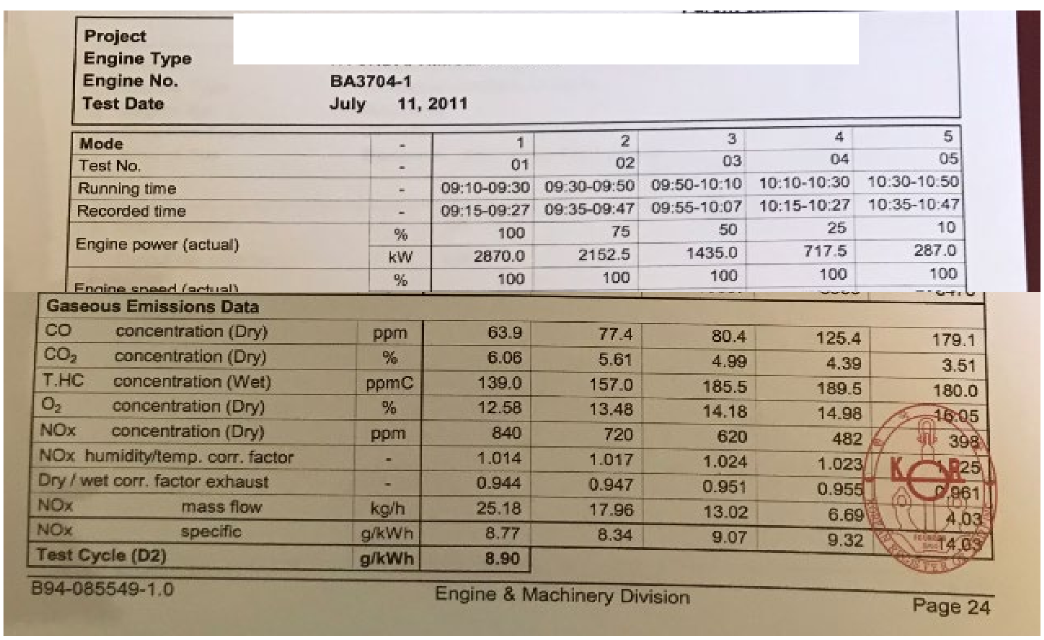
Figure E-05 Shop trial certification values for the tested engine [11]



Project [redacted]
Engine Type [redacted]
Engine No. BA3704-1
Test Date July 11, 2011

Mode	-	1	2	3	4	5
Test No.	-	01	02	03	04	05
Running time	-	09:10-09:30	09:30-09:50	09:50-10:10	10:10-10:30	10:30-10:50
Recorded time	-	09:15-09:27	09:35-09:47	09:55-10:07	10:15-10:27	10:35-10:47
Engine power (actual)	%	100	75	50	25	10
	kW	2870.0	2152.5	1435.0	717.5	287.0
Engine speed (actual)	%	100	100	100	100	100
Gaseous Emissions Data						
CO concentration (Dry)	ppm	63.9	77.4	80.4	125.4	179.1
CO_2 concentration (Dry)	%	6.06	5.61	4.99	4.39	3.51
T.HC concentration (Wet)	ppmC	139.0	157.0	185.5	189.5	180.0
O_2 concentration (Dry)	%	12.58	13.48	14.18	14.98	16.05
NOx concentration (Dry)	ppm	840	720	620	482	398
NOx humidity/temp. corr. factor	-	1.014	1.017	1.024	1.023	1.025
Dry / wet corr. factor exhaust	-	0.944	0.947	0.951	0.955	0.961
NOx mass flow	kg/h	25.18	17.96	13.02	6.69	4.03
NOx specific	g/kWh	8.77	8.34	9.07	9.32	14.03
Test Cycle (D2)	g/kWh	8.90				

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Figure E-06 Shop trial certification concentrations for the tested engine [7]

[11] Instructions Book Volume II Engine B94-085549-1.0 Hyundai Himsen Auxiliary Generator.

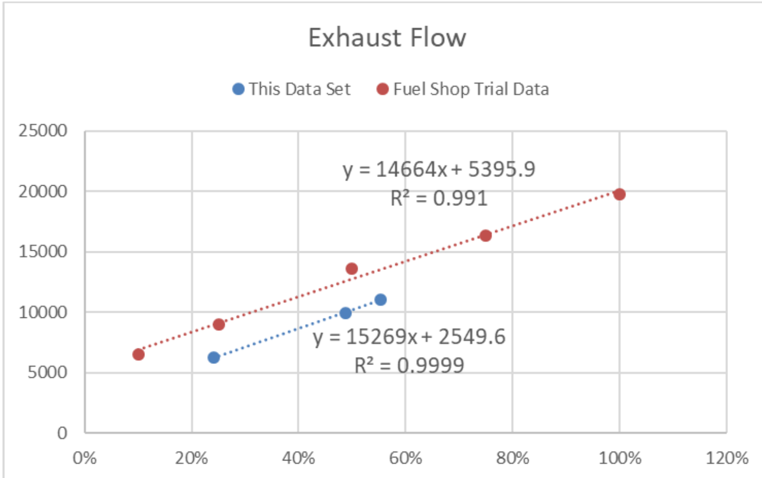

Figure E-06 AE Shop trial exhaust flow compared to this testing (1.33 difference)

[1] If the shop trial fuel rate was used the NOx emissions from the auxiliary engine would be closer to the certification value compared to what is presented in these results. More investigation is needed to understand these differences.

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 for the ME, AE, and auxiliary boiler for gaseous and PM emissions. The auxiliary boiler toxic emissions are also listed below for their selected tests. The EC/OC results were sent to an outside laboratory and were analyzed using the NIOSH thermal optical method. The sulfate ion-chromatography results sent to an outside laboratory.

Table F-01 – Table F-06 shows the average and standard deviation (sigma = 1) data for the triplicate sampled emissions from the ME, AE, and auxiliary boiler. Tables F-07 shows the results from the statistical students t-test with unpaired analysis, two tails, equal variance. Tables F-08 through Table F-17 show all the individual results and conditions of the testing such as dilution ratio, dry to wet correction, and NOx humidity correction factors.

The speciated C2 – C10 hydrocarbon analysis via the SUMMA canisters was collected, but analyzed with an incorrect method and thus the data is not valid for reporting. It was a typo in UCR's chain of custody form that cased the analysis method problem. Changes were made at CE-CERT to prevent the problem on future testing campaigns.

The overall sampling for the main engine, aux engine, and auxiliary boiler went well and the auxiliary boiler emissions were stable for gaseous and PM-soot, see Figure F-24 at the 60% load point. The stability for each test conditions can be seen by the relatively small error bars (1 sigma) in Figures 3-2 through 3-4, see Section 3 Results.

Table F-01 Summary of ME average results for selected species (g/kWhr), n=3

Test	Fuel	Load %	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	eBC	kH
1	MGO	8.8%	27.41	0.19	644	0.0283	3,069	0.220	0.011	0.187	0.002	0.179	0.00400	0.913
2	MGO	12.0%	25.77	0.19	623	0.0262	2,260	0.232	0.012	0.197	0.002	0.186	0.00788	0.971
3	MGO	33.0%	18.65	0.20	588	0.0138	1,306	0.234	0.012	0.199	0.002	0.160	0.00300	0.974
4	MGO	44.0%	16.85	0.19	583	0.0085	1,379	0.196	0.010	0.166	0.002	0.151	0.00150	0.970
5	ULSFO	9.0%	28.83	0.21	656	0.0383	3,301	0.349	0.017	0.297	0.010	0.260	0.00595	0.955
6	ULSFO	12.8%	26.59	0.20	634	0.0258	2,439	0.317	0.016	0.269	0.009	0.246	0.00860	0.961
7	ULSFO	32.6%	19.54	0.19	602	0.0141	1,588	0.278	0.014	0.237	0.008	0.206	0.00386	0.965
8	ULSFO	42.3%	17.69	0.19	597	0.0126	1,648	0.262	0.013	0.223	0.008	0.200	0.00210	0.968

[1] Only two samples (n=2) were possible for MGO Test #2, MGO Test #4, and ULSFO Test #8. EC, OC, and S PM had n=2.

Table F-02 Summary of ME standard deviation (σ=1) results for selected species (g/kWhr), n=3

Test	Fuel	Load %	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	eBC	kH
1	MGO	0.4%	0.29	0.01	3.4	0.0025	123.9	0.009	0.000	0.008	0.000	-	0.00025	0.001
2	MGO	0.0%	0.90	0.00	0.0	0.0027	47.9	0.019	0.001	0.016	0.000	0.005	0.00051	0.002
3	MGO	0.7%	0.31	0.01	0.4	0.0020	35.3	0.038	0.002	0.032	0.000	0.014	0.00068	0.001
4	MGO	0.0%	0.03	0.03	0.0	0.0019	0.6	0.007	0.000	0.006	0.000	0.010	0.00002	0.002
5	ULSFO	0.0%	0.54	0.01	0.2	0.0058	299.3	0.008	0.000	0.007	0.000	0.006	0.00031	0.001
6	ULSFO	0.2%	0.19	0.01	1.0	0.0008	9.8	0.011	0.001	0.009	0.000	0.008	0.00037	0.005
7	ULSFO	0.5%	0.01	0.01	0.3	0.0013	12.3	0.007	0.000	0.006	0.000	0.001	0.00020	0.000
8	ULSFO	0.6%	0.15	0.01	0.3	0.0005	3.2	0.003	0.000	0.003	0.000	0.001	0.00056	0.001

[1] Only two samples (n=2) were possible for MGO Test #2, MGO Test #4, and ULSFO Test #8, EC, OC, and S PM had n=2.

Table F-03 Summary of AE average results for selected species (g/kWhr), n=3

Test	Fuel	Load %	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	eBC	Kh
1	MGO	25.9%	8.97	2.04	784	-0.0034	1,244	0.297	0.182	0.092	0.002	0.274	0.20782	1.013
2	MGO	53.5%	8.34	0.87	653	0.0010	971	0.116	0.064	0.049	0.002	0.113	0.07221	1.008
3	MGO	63.0%	8.08	0.81	635	-0.0014	923	0.090	0.047	0.053	0.002	0.100	0.05385	0.999
4	ULSFO	27.7%	9.10	2.43	787	0.0420	1,230	0.362	0.127	0.145	0.005	0.273	0.19385	1.023
5	ULSFO	54.2%	8.54	0.82	669	0.0082	1,005	0.196	0.038	0.119	0.004	0.157	0.04083	1.028
6	ULSFO	63.7%	8.38	0.74	651	0.0071	967	0.169	0.030	0.102	0.004	0.132	0.03152	1.029

[1] Samples for EC, OC, and S PM had n=2

Table F-04 Summary of AE standard deviation (σ=1) results for selected species (g/kWhr), n=3

Test	Fuel	Load %	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	eBC	Kh
1	MGO	0.2%	0.10	0.03	2.3	0.0015	8.2	0.005	0.005	0.004	0.000	0.002	0.00152	0.000
2	MGO	0.2%	0.07	0.01	0.6	0.0022	1.5	0.003	0.002	0.004	0.000	0.006	0.00087	0.007
3	MGO	0.5%	0.09	0.03	0.8	0.0005	1.7	0.002	0.001	0.003	0.000	0.003	0.00413	0.000
4	ULSFO	0.2%	0.03	0.01	1.8	0.0033	6.0	0.090	0.047	0.054	0.000	0.101	0.00799	0.002
5	ULSFO	0.2%	0.06	0.01	0.5	0.0010	1.7	0.006	0.003	0.005	0.000	0.008	0.00083	0.003
6	ULSFO	0.7%	0.04	0.01	1.1	0.0009	1.5	0.002	0.003	0.006	0.000	0.009	0.00109	0.002

[1] Samples for EC, OC, and S PM had n=2

Table F-05 Summary of auxiliary boiler average results for selected species (g/kg-fuel), n=3

Fuel	Load %	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	eBC
MGO	60.0%	1.68	0.01	3174	0.0766	0.040	0.0002	0.035	0.000	0.035	0.00036
ULSFO	52.0%	2.28	0.13	3178	0.1431	0.029	0.0004	0.016	0.000	0.016	0.00011

[1] Samples for EC, OC, and S PM had n=2

Table F-06 Summary of auxiliary boiler standard deviation (σ=1) results for selected species (g/kg-fuel), n=3

Fuel	Load %	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	eBC
MGO	0.0%	0.01	0.00	0.1	0.0056	0.030	0.00000	0.013	0.000	0.013	0.00003
ULSFO	0.0%	0.05	0.09	0.2	0.0010	0.004	0.00002	0.001	0.000	0.000	0.00004

[1] Samples for EC, OC, and S PM had n=2

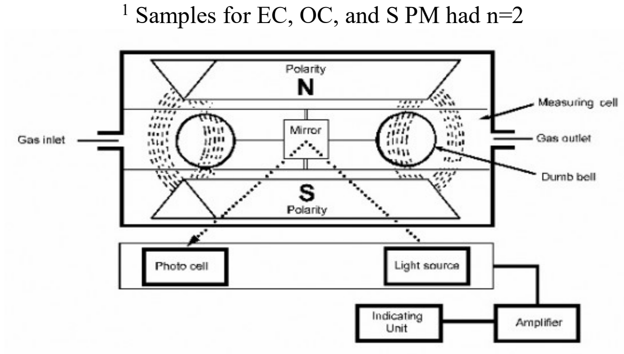

Figure F-07 Oxygen paramagnetic O2 sensing diagram.

[1] The Auxiliary boiler test showed a large negative O2 concentration for the ULSFO fuel at low load (high CO2 concentration). It is believed there may be some sensing issues under these conditions. The measuring system is "null-balanced". First the "zero" position of the suspension assembly, as measured in nitrogen, is sensed by a photo-sensor that receives light reflected from a First, when oxygen is introduced to the cell, the torque acting upon the suspension assembly is balanced by a re-storing torque due to the feedback current in the coil. The feedback current is directly proportional to Second, the electromagnetic feedback "stiffens" the suspension, damping it heavily and increasing its natural frequency, making the suspension resilient to shock

Table F-08 Main engine results by test point part 1 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/hr													Fuel Rate	SO2 calc	H20 Fraction	O2 Conc
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	(kg/hr)	g/hr	%	%
12/20/2018	MGO	n/a	2_1	11:00:00	9.0%	178,703	1,298	4,170,979	203	19,934,452	1,433.7	20.6	1145	0.0	1166	1374	1395	26.01	1314	986.2	2.1	16.9
12/20/2018	MGO	n/a	2_2	11:35:00	9.0%	176,140	1,151	4,171,697	173	19,152,996	1,369.7	0.0	0	0.0	0	0	0	27.70	1314	986.2	2.2	16.7
12/20/2018	MGO	n/a	2_3	12:10:00	8.3%	166,443	1,095	3,897,652	164	19,225,336	1,378.2	0.0	0	0.0	0	0	0	22.59	1228	921.6	2.1	16.9
12/20/2018	MGO	n/a	1_1	9:00:00	12.0%	219,824	1,613	5,404,341	245	19,166,150	2,120.6	39.0	1606	0.0	1645	1927	1966	63.51	1701	1276.7	2.8	16.0
12/20/2018	MGO	n/a	1_2	9:35:00	12.0%	218,049	1,620	5,403,791	237	19,995,334	1,828.8	0.0	0	0.0	0	0	0	69.18	1701	1276.7	2.7	16.2
12/20/2018	MGO	n/a	1_3	10:12:00	12.0%	232,405	1,616	5,403,980	200	19,612,242	2,091.9	34.3	1549	0.0	1583	1858	1893	72.28	1701	1276.7	2.7	16.0
12/20/2018	MGO	n/a	3_1	17:25:00	32.3%	427,902	4,603	13,751,106	374	29,553,041	6,435.5	0.0	0	0.0	0	0	0	87.29	4323	3245.8	4.1	13.8
12/20/2018	MGO	n/a	3_2	18:00:00	33.7%	454,619	4,754	14,297,168	325	32,185,561	5,448.3	50.5	4092	0.0	4142	4910	4960	58.35	4495	3374.9	3.9	14.0
12/20/2018	MGO	n/a	3_3	18:35:00	33.0%	451,599	5,221	14,022,714	290	31,683,975	4,798.6	53.1	3529	0.0	3582	4235	4288	68.16	4409	3310.3	3.9	14.0
12/20/2018	MGO	n/a	4_1	19:30:00	44.0%	536,442	6,627	18,534,120	313	43,842,963	6,371.1	36.1	4990	0.0	5026	5988	6024	47.11	5828	4375.6	3.8	14.2
12/20/2018	MGO	n/a	4_2	20:05:00	44.0%	534,968	5,282	18,536,228	229	43,817,069	6,069.7	32.7	4524	0.0	4557	5429	5462	48.15	5828	4375.6	3.8	14.2
12/20/2018	MGO	n/a	4_3	20:20:00	44.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/21/2018	ULSFO	n/a	8_1	4:40:00	9.0%	186,076	1,433	4,268,165	216	20,777,398	2,322	116.1	1974	23	1719	2028	2057	40.89	1344	2345.9	2.1	16.6
12/21/2018	ULSFO	n/a	8_2	5:15:00	9.0%	191,444	1,347	4,266,251	290	23,656,714	2,215	110.8	1883	22	-	-	-	36.94	1344	2345.9	1.8	16.9
12/21/2018	ULSFO	n/a	8_3	5:50:00	9.0%	184,753	1,353	4,268,850	242	19,949,881	2,271	113.6	1930	23	1666	1967	1994	38.15	1344	2345.9	2.1	16.4
12/21/2018	ULSFO	n/a	7_1	3:20:00	13.0%	250,977	1,996	5,948,751	247	22,971,355	2,900	145.0	2465	29	2255	2624	2692	83.28	1873	3267.3	2.5	15.9
12/21/2018	ULSFO	n/a	7_2	3:55:00	12.7%	242,073	1,790	5,809,307	231	22,255,791	2,969	148.5	2524	30	2297	2683	2745	76.33	1829	3190.5	2.5	15.8
12/21/2018	ULSFO	n/a	7_3	4:10:00	12.7%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/20/2018	ULSFO	n/a	5_1	23:35:00	32.0%	451,854	4,604	13,929,481	341	36,506,034	6,245	312.2	5308	62	4745	5625	5683	89.49	4381	7644.1	3.5	14.5
12/21/2018	ULSFO	n/a	5_2	0:10:00	32.7%	460,868	4,596	14,209,070	352	37,805,733	6,644	332.2	5647	66	4889	5807	5857	86.46	4469	7797.7	3.4	14.6
12/21/2018	ULSFO	n/a	5_3	0:45:00	33.0%	465,925	4,299	14,349,833	300	37,733,015	6,752	337.6	5739	68	-	-	-	96.69	4513	7874.5	3.4	14.5
12/21/2018	ULSFO	n/a	6_1	1:50:00	43.0%	546,277	6,128	18,545,112	402	51,122,881	8,075	403.7	6864	81	6181	7370	7409	52.85	5833	10178.0	3.3	14.7
12/21/2018	ULSFO	n/a	6_2	2:25:00	42.0%	539,978	5,387	18,126,254	370	50,071,645	8,030	401.5	6826	80	6073	7237	7279	75.78	5701	9947.7	3.3	14.7
12/21/2018	ULSFO	n/a	6_3	2:40:00	42.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table F-09 Main engine results by test point part 2 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/kWhr													Calculated g/kWHr			NOx Cor.
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	BSFC		SO2_fuel	Kh
12/20/2018	MGO	n/a	2_1	11:00:00	9.0%	27.49	0.20	642	0.0312	3,066	0.221	0.011	0.19	0.002	0.179	0.211	0.215	0.00400	202.0		0.1517	0.912
12/20/2018	MGO	n/a	2_2	11:35:00	9.0%	27.09	0.18	642	0.0266	2,946	0.211	0.011	0.18	0.002	-	-	-	0.00426	202.0		0.1517	0.914
12/20/2018	MGO	n/a	2_3	12:10:00	8.3%	27.65	0.18	647	0.0273	3,194	0.229	0.011	0.19	0.002	-	-	-	0.00375	203.9		0.1531	0.914
12/20/2018	MGO	n/a	1_1	9:00:00	12.0%	25.36	0.19	623	0.0283	2,211	0.245	0.012	0.21	0.002	0.190	0.222	0.227	0.00733	196.2		0.1473	0.968
12/20/2018	MGO	n/a	1_2	9:35:00	12.0%	25.15	0.19	623	0.0273	2,307	0.211	0.011	0.18	0.002	-	-	-	0.00798	196.2		0.1473	0.972
12/20/2018	MGO	n/a	1_3	10:12:00	12.0%	26.81	0.19	623	0.0231	2,262	0.241	0.012	0.21	0.002	0.183	0.214	0.218	0.00834	196.2		0.1473	0.972
12/20/2018	MGO	n/a	3_1	17:25:00	32.3%	18.32	0.20	589	0.0160	1,265	0.276	0.014	0.23	0.003	-	-	-	0.00374	185.1		0.1390	0.975
12/20/2018	MGO	n/a	3_2	18:00:00	33.7%	18.69	0.20	588	0.0134	1,323	0.224	0.011	0.19	0.002	0.170	0.202	0.204	0.00240	184.8		0.1388	0.973
12/20/2018	MGO	n/a	3_3	18:35:00	33.0%	18.94	0.22	588	0.0121	1,329	0.201	0.010	0.17	0.002	0.150	0.178	0.180	0.00286	185.0		0.1389	0.973
12/20/2018	MGO	n/a	4_1	19:30:00	44.0%	16.88	0.21	583	0.0098	1,379	0.200	0.010	0.17	0.002	0.158	0.188	0.190	0.00148	183.4		0.1377	0.971
12/20/2018	MGO	n/a	4_2	20:05:00	44.0%	16.83	0.17	583	0.0072	1,379	0.191	0.010	0.16	0.002	0.143	0.171	0.172	0.00151	183.4		0.1377	0.969
12/20/2018	MGO	n/a	4_3	20:20:00	44.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	0.969
12/21/2018	ULSFO	n/a	8_1	4:40:00	9.0%	28.6	0.22	656.5	0.033	3,196	0.357	0.018	0.30	0.011	0.264	0.312	0.316	0.00629	206.8		0.36	0.955
12/21/2018	ULSFO	n/a	8_2	5:15:00	9.0%	29.4	0.21	656.2	0.045	3,639	0.341	0.017	0.29	0.010	-	-	-	0.00568	206.8		0.36	0.955
12/21/2018	ULSFO	n/a	8_3	5:50:00	9.0%	28.4	0.21	656.6	0.037	3,068	0.349	0.017	0.30	0.010	0.256	0.302	0.307	0.00587	206.8		0.36	0.956
12/21/2018	ULSFO	n/a	7_1	3:20:00	13.0%	26.7	0.21	633.4	0.026	2,446	0.309	0.015	0.26	0.009	0.240	0.279	0.287	0.00887	199.4		0.35	0.967
12/21/2018	ULSFO	n/a	7_2	3:55:00	12.7%	26.5	0.20	634.9	0.025	2,432	0.325	0.016	0.28	0.010	0.251	0.293	0.300	0.00834	199.8		0.35	0.959
12/21/2018	ULSFO	n/a	7_3	4:10:00	12.7%	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	0.959
12/20/2018	ULSFO	n/a	5_1	23:35:00	32.0%	19.5	0.20	602.6	0.015	1,579	0.270	0.014	0.23	0.008	0.205	0.243	0.246	0.00387	189.5		0.33	0.965
12/21/2018	ULSFO	n/a	5_2	0:10:00	32.7%	19.5	0.19	602.1	0.015	1,602	0.282	0.014	0.24	0.008	0.207	0.246	0.248	0.00366	189.4		0.33	0.965
12/21/2018	ULSFO	n/a	5_3	0:45:00	33.0%	19.5	0.18	601.9	0.013	1,583	0.283	0.014	0.24	0.008	-	-	-	0.00406	189.3		0.33	0.965
12/21/2018	ULSFO	n/a	6_1	1:50:00	43.0%	17.6	0.20	597.0	0.013	1,646	0.260	0.013	0.22	0.008	0.199	0.237	0.239	0.00170	187.8		0.33	0.969
12/21/2018	ULSFO	n/a	6_2	2:25:00	42.0%	17.8	0.18	597.4	0.012	1,650	0.265	0.013	0.22	0.008	0.200	0.239	0.240	0.00250	187.9		0.33	0.969
12/21/2018	ULSFO	n/a	6_3	2:40:00	42.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-		-	0.967

Table F-10 Main engine results by test point part 3 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/kg-fuel (kg/tonne-fuel)													Vessel
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	knots
12/20/2018	MGO	n/a	2_1	11:00:00	9.0%	136.04	0.99	3175.2	0.1543	15175	1.091	0.0157	0.87	0.0000	0.887	1.046	1.062	0.0198	11.4
12/20/2018	MGO	n/a	2_2	11:35:00	9.0%	134.09	0.88	3175.8	0.1316	14580	1.043	-	-	-	-	-	-	0.0211	-
12/20/2018	MGO	n/a	2_3	12:10:00	8.3%	135.58	0.89	3175.0	0.1337	15661	1.123	-	-	-	-	-	-	0.0184	-
12/20/2018	MGO	n/a	1_1	9:00:00	12.0%	129.26	0.95	3177.9	0.1441	11270	1.247	0.0229	0.94	0.0000	0.967	1.133	1.156	0.0373	14.7
12/20/2018	MGO	n/a	1_2	9:35:00	12.0%	128.22	0.95	3177.6	0.1391	11758	1.075	-	-	-	-	-	-	0.0407	-
12/20/2018	MGO	n/a	1_3	10:12:00	12.0%	136.66	0.95	3177.7	0.1179	11533	1.230	0.0201	0.91	0.0000	0.931	1.093	1.113	0.0425	14.7
12/20/2018	MGO	n/a	3_1	17:25:00	32.3%	98.97	1.06	3180.6	0.0866	6836	1.489	-	-	-	-	-	-	0.0202	-
12/20/2018	MGO	n/a	3_2	18:00:00	33.7%	101.13	1.06	3180.4	0.0724	7160	1.212	0.0112	0.91	0.0000	0.921	1.092	1.103	0.0130	38.9
12/20/2018	MGO	n/a	3_3	18:35:00	33.0%	102.42	1.18	3180.2	0.0657	7186	1.088	0.0120	0.80	0.0000	0.812	0.960	0.973	0.0155	38.1
12/20/2018	MGO	n/a	4_1	19:30:00	44.0%	92.04	1.14	3180.0	0.0537	7522	1.093	0.0062	0.86	0.0000	0.862	1.027	1.034	0.0081	50.4
12/20/2018	MGO	n/a	4_2	20:05:00	44.0%	91.79	0.91	3180.4	0.0394	7518	1.041	0.0056	0.78	0.0000	0.782	0.932	0.937	0.0083	50.4
12/20/2018	MGO	n/a	4_3	20:20:00	44.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/21/2018	ULSFO	n/a	8_1	4:40:00	9.0%	138.4	1.07	3174.6	0.1604	15,454	1.727	0.0864	1.47	0.0173	1.279	1.508	1.530	0.0304	27.0
12/21/2018	ULSFO	n/a	8_2	5:15:00	9.0%	142.4	1.00	3173.2	0.2158	17,596	1.648	0.0824	1.40	0.0165	-	-	-	0.0275	-
12/21/2018	ULSFO	n/a	8_3	5:50:00	9.0%	137.4	1.01	3175.1	0.1799	14,838	1.689	0.0845	1.44	0.0169	1.239	1.463	1.483	0.0284	27.0
12/21/2018	ULSFO	n/a	7_1	3:20:00	13.0%	134.0	1.07	3176.8	0.1322	12,267	1.549	0.0774	1.32	0.0155	1.204	1.401	1.438	0.0445	37.6
12/21/2018	ULSFO	n/a	7_2	3:55:00	12.7%	132.4	0.98	3177.0	0.1262	12,171	1.624	0.0812	1.38	0.0162	1.256	1.468	1.501	0.0417	36.8
12/21/2018	ULSFO	n/a	7_3	4:10:00	12.7%	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/20/2018	ULSFO	n/a	5_1	23:35:00	32.0%	103.1	1.05	3179.6	0.0779	8,333	1.425	0.0713	1.21	0.0143	1.083	1.284	1.297	0.0204	88.1
12/21/2018	ULSFO	n/a	5_2	0:10:00	32.7%	103.1	1.03	3179.5	0.0788	8,460	1.487	0.0743	1.26	0.0149	1.094	1.299	1.311	0.0193	89.8
12/21/2018	ULSFO	n/a	5_3	0:45:00	33.0%	103.2	0.95	3179.7	0.0664	8,361	1.496	0.0748	1.27	0.0150	-	-	-	0.0214	-
12/21/2018	ULSFO	n/a	6_1	1:50:00	43.0%	93.7	1.05	3179.3	0.0689	8,764	1.384	0.0692	1.18	0.0138	1.060	1.263	1.270	0.0091	117.3
12/21/2018	ULSFO	n/a	6_2	2:25:00	42.0%	94.7	0.94	3179.4	0.0649	8,783	1.408	0.0704	1.20	0.0141	1.065	1.269	1.277	0.0133	114.6
12/21/2018	ULSFO	n/a	6_3	2:40:00	42.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table F-11 Auxiliary engine results by test point part 1 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/hr													FuelRate	SO2 calc	H20 Fraction	O2 Conc
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	(kg/hr)	g/hr	%	%
12/15/2018	MGO	-	3_1	15:47:00	26.1%	6,797	1,514	586,453	-4	927,686	221.6	-	-	-	-	-	-	155.7	186	-	4.8	12.8
12/15/2018	MGO	-	3_2	15:55:00	25.8%	6,646	1,534	581,670	-1	921,331	216.4	137.3	66.6	0.0	203.9	79.9	217.2	155.2	184	138.3	4.8	12.8
12/15/2018	MGO	-	3_3	16:03:00	25.7%	6,536	1,488	579,620	-3	923,724	222.7	131.2	69.9	0.0	201.1	83.9	215.1	152.2	184	137.8	4.8	12.8
12/15/2018	MGO	-	1_1	14:00:00	53.4%	12,771	1,339	1,001,593	5	1,489,799	183.4	-	-	-	-	-	-	111.9	316	-	5.1	12.6
12/15/2018	MGO	-	1_2	14:23:00	53.8%	12,991	1,329	1,008,044	1	1,498,509	179.8	96.6	71.4	0.0	168.0	85.7	182.3	111.7	318	239.1	5.1	12.6
12/15/2018	MGO	-	1_4	14:59:00	53.4%	12,661	1,346	1,001,414	-1	1,484,839	172.7	100.7	79.1	0.0	179.8	94.9	195.6	109.2	316	237.5	5.1	12.6
12/15/2018	MGO	-	2_1	15:14:00	63.5%	14,902	1,425	1,155,435	-3	1,682,083	160.2	-	-	-	-	-	-	91.7	365	-	5.1	12.5
12/15/2018	MGO	-	2_2	15:21:00	62.9%	14,531	1,443	1,146,371	-2	1,670,309	167.4	86.4	98.3	0.0	184.7	118.0	204.4	105.4	362	271.9	5.1	12.5
12/15/2018	MGO	-	2_3	15:28:00	62.5%	14,385	1,519	1,140,597	-3	1,654,399	163.1	84.3	90.7	0.0	175.1	108.9	193.2	94.8	360	270.5	5.1	12.4
12/17/2018	ULSFO	-	4_1	12:27:00	27.5%	7,178	1,927	622,328	36	975,139	312	-	-	-	-	-	-	145.82	197	-	4.8	12.7
12/17/2018	ULSFO	-	4_2	12:36:00	27.9%	7,259	1,936	628,777	33	983,776	344	128.5	147.2	0.0	275.7	176.6	305.1	156.98	199	346.6	4.8	12.7
12/17/2018	ULSFO	-	4_3	12:43:30	27.7%	7,269	1,938	626,270	31	974,721	207	74.7	85.1	0.0	159.9	102.2	176.9	159.46	198	345.2	4.9	12.7
12/17/2018	ULSFO	-	6_1	14:17:00	54.2%	13,393	1,279	1,040,442	12	1,563,882	315	-	-	-	-	-	-	63.76	328	-	5.0	12.5
12/17/2018	ULSFO	-	6_2	14:26:00	54.5%	13,320	1,274	1,045,103	15	1,567,241	296	56.1	180.0	0.0	236.1	215.9	272.0	62.38	329	574.3	5.0	12.5
12/17/2018	ULSFO	-	6_3	14:36:00	54.1%	13,179	1,289	1,038,821	12	1,559,682	304	62.0	189.4	0.0	251.4	227.3	289.3	64.46	327	570.9	5.0	12.5
12/17/2018	ULSFO	-	5_1	13:38:00	64.5%	15,440	1,360	1,202,234	13	1,787,244	311	60.1	196.6	0.0	256.7	235.9	296.0	56.74	379	660.6	5.0	12.5
12/17/2018	ULSFO	-	5_2	13:48:00	63.4%	15,308	1,354	1,184,032	11	1,759,715	303	51.5	176.8	0.0	228.3	212.2	263.7	59.53	373	650.6	5.0	12.5
12/17/2018	ULSFO	-	5_3	13:58:00	63.3%	15,215	1,352	1,183,128	14	1,757,797	311	-	-	-	-	-	-	56.64	373	-	5.0	12.5

Table F-12 Auxiliary engine results by test point part 2 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/kWhr													Calculated g/kWHr			NOx Cor.
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	BFSC		SO2_fuel	Kh
12/15/2018	MGO	-	3_1	15:47:00	26.1%	9.06	2.02	782	-0.0048	1,237	0.296	-	-	-	-	-	-	0.20754	271.3		-	1.013
12/15/2018	MGO	-	3_2	15:55:00	25.8%	8.97	2.07	785	-0.0018	1,243	0.292	0.185	0.090	0.002	0.275	0.108	0.293	0.20947	272.7		0.187	1.013
12/15/2018	MGO	-	3_3	16:03:00	25.7%	8.87	2.02	786	-0.0034	1,253	0.302	0.178	0.095	0.002	0.273	0.114	0.292	0.20646	273.3		0.187	1.013
12/15/2018	MGO	-	1_1	14:00:00	53.4%	8.34	0.87	654	0.0033	972	0.120	-	-	-	-	-	-	0.07301	213.0		-	1.012
12/15/2018	MGO	-	1_2	14:23:00	53.8%	8.41	0.86	653	0.0007	970	0.116	0.063	0.046	0.002	0.109	0.056	0.118	0.07233	212.6		0.155	1.012
12/15/2018	MGO	-	1_4	14:59:00	53.4%	8.27	0.88	654	-0.0009	969	0.113	0.066	0.052	0.002	0.117	0.062	0.128	0.07128	213.0		0.155	0.999
12/15/2018	MGO	-	2_1	15:14:00	63.5%	8.18	0.78	634	-0.0014	923	0.088	-	-	-	-	-	-	0.05032	205.3		-	0.999
12/15/2018	MGO	-	2_2	15:21:00	62.9%	8.05	0.80	635	-0.0009	925	0.093	0.048	0.054	0.002	0.102	0.065	0.113	0.05839	205.6		0.151	0.999
12/15/2018	MGO	-	2_3	15:28:00	62.5%	8.02	0.85	636	-0.0019	922	0.091	0.047	0.051	0.002	0.098	0.061	0.108	0.05283	205.9		0.151	0.999
12/17/2018	ULSFO	-	4_1	12:27:00	27.5%	9.1	2.44	789.4	0.046	1,237	0.396	-	-	-	-	-	-	0.18496	271.9		-	1.022
12/17/2018	ULSFO	-	4_2	12:36:00	27.9%	9.1	2.42	785.7	0.041	1,229	0.430	0.161	0.184	0.005	0.344	0.221	0.381	0.19617	270.2		0.43	1.022
12/17/2018	ULSFO	-	4_3	12:43:30	27.7%	9.1	2.44	787.1	0.039	1,225	0.260	0.094	0.107	0.005	0.201	0.128	0.222	0.20042	270.9		0.43	1.026
12/17/2018	ULSFO	-	6_1	14:17:00	54.2%	8.6	0.82	669.3	0.008	1,006	0.202	-	-	-	-	-	-	0.04102	217.3		-	1.030
12/17/2018	ULSFO	-	6_2	14:26:00	54.5%	8.5	0.82	668.6	0.009	1,003	0.190	0.036	0.115	0.004	0.151	0.138	0.174	0.03991	217.0		0.37	1.030
12/17/2018	ULSFO	-	6_3	14:36:00	54.1%	8.5	0.83	669.6	0.008	1,005	0.196	0.040	0.122	0.004	0.162	0.147	0.186	0.04155	217.4		0.37	1.024
12/17/2018	ULSFO	-	5_1	13:38:00	64.5%	8.3	0.73	649.2	0.007	965	0.168	0.032	0.106	0.004	0.139	0.127	0.160	0.03064	209.5		0.36	1.026
12/17/2018	ULSFO	-	5_2	13:48:00	63.4%	8.4	0.74	651.1	0.006	968	0.167	0.028	0.097	0.004	0.126	0.117	0.145	0.03274	210.2		0.36	1.030
12/17/2018	ULSFO	-	5_3	13:58:00	63.3%	8.4	0.74	651	0.0	968	0.171	-	-	-	-	-	-	0.03118	210.2		-	1.030

Table F-12 Auxiliary engine results by test point part 3 of 3.

Date	Fuel	ATS	Test	Start Time	Load	g/kg-fuel (kg/tonne-fuel)												
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	kNOx	CO	CO2	SO2	O2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC
12/15/2018	MGO	-	3_1	15:47:00	26.1%	36.61	8.15	3158.6	-0.0196	4996	1.1937	-	-	-	-	-	-	0.8383
12/15/2018	MGO	-	3_2	15:55:00	25.8%	36.08	8.33	3158.3	-0.0073	5003	1.1748	0.7455	0.3616	0.0000	1.1071	0.4339	1.1794	0.8428
12/15/2018	MGO	-	3_3	16:03:00	25.7%	35.62	8.11	3158.6	-0.0137	5034	1.2137	0.7150	0.3810	0.0000	1.0960	0.4572	1.1722	0.8293
12/15/2018	MGO	-	1_1	14:00:00	53.4%	40.83	3.91	3165.7	-0.0070	4609	0.4390	-	-	-	-	-	-	0.2512
12/15/2018	MGO	-	1_2	14:23:00	53.8%	40.13	3.98	3165.6	-0.0044	4612	0.4622	0.2387	0.2715	0.0000	0.5102	0.3258	0.5645	0.2911
12/15/2018	MGO	-	1_4	14:59:00	53.4%	39.92	4.22	3165.3	-0.0095	4591	0.4526	0.2340	0.2518	0.0000	0.4859	0.3022	0.5362	0.2631
12/15/2018	MGO	-	2_1	15:14:00	63.5%	40.36	4.23	3165.1	0.0162	4708	0.5796	-	-	-	-	-	-	0.3535
12/15/2018	MGO	-	2_2	15:21:00	62.9%	40.79	4.17	3165.2	0.0033	4705	0.5645	0.3032	0.2243	0.0000	0.5275	0.2691	0.5723	0.3507
12/15/2018	MGO	-	2_3	15:28:00	62.5%	40.02	4.26	3165.1	-0.0044	4693	0.5458	0.3184	0.2499	0.0000	0.5683	0.2999	0.6183	0.3451
12/17/2018	ULSFO	-	4_1	12:27:00	27.5%	36.5	9.80	3165.5	0.1830	4,960	1.5884	-	-	-	-	-	-	0.7417
12/17/2018	ULSFO	-	4_2	12:36:00	27.9%	36.5	9.75	3165.6	0.1649	4,953	1.7343	0.6468	0.7409	0.0000	1.3878	0.8891	1.5360	0.7903
12/17/2018	ULSFO	-	4_3	12:43:30	27.7%	36.7	9.79	3165.5	0.1584	4,927	1.0446	0.3777	0.4304	0.0000	0.8081	0.5165	0.8941	0.8060
12/17/2018	ULSFO	-	6_1	14:17:00	54.2%	40.9	3.90	3175.0	0.0358	4,772	0.9598	-	-	-	-	-	-	0.1946
12/17/2018	ULSFO	-	6_2	14:26:00	54.5%	40.5	3.87	3175.0	0.0444	4,761	0.9005	0.1704	0.5467	0.0000	0.7171	0.6561	0.8265	0.1895
12/17/2018	ULSFO	-	6_3	14:36:00	54.1%	40.3	3.94	3174.9	0.0358	4,767	0.9303	0.1896	0.5789	0.0000	0.7685	0.6947	0.8843	0.1970
12/17/2018	ULSFO	-	5_1	13:38:00	64.5%	40.8	3.59	3175.5	0.0356	4,721	0.8215	0.1588	0.5192	0.0000	0.6780	0.6230	0.7818	0.1499
12/17/2018	ULSFO	-	5_2	13:48:00	63.4%	41.1	3.63	3175.5	0.0298	4,719	0.8134	0.1381	0.4742	0.0000	0.6123	0.5690	0.7071	0.1597
12/17/2018	ULSFO	-	5_3	13:58:00	63.3%	40.8	3.63	3175.5	0.0384	4,718	0.8337	-	-	-	-	-	-	0.1520

Table F-13 Auxiliary boiler non-toxic results by test point part 1 of 2.

Date	Fuel	ATS	Test	Start Time	Load	g/hr												FuelRate Carb.	SO2 calc	H20 Fraction	O2 Conc
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	(kg/hr)	g/hr	%	%
12/18/2018	MGO	-	1_1	17:39:00	60.0%	293	2.49	548,121	12	-	-	-	-	-	-	-	0.07	173	132.5	10.2	6.8
12/18/2018	MGO	-	1_2	17:56:00	60.0%	291	1.61	548,104	14	11.8	0.0	7.6	0.0	7.6	9.1	9.2	0.06	173	132.5	10.0	7.1
12/18/2018	MGO	-	1_4	18:47:00	60.0%	289	1.61	548,105	13	7.3	0.0	4.4	0.0	4.5	5.3	5.4	0.06	173	132.5	10.0	7.0
12/19/2018	ULSFO	-	4_1	13:10:00	52.0%	333	35.9	477,422	21.7	3.6	-	-	-	-	-	-	0.02	150	249.6	11.7	4.8
12/19/2018	ULSFO	-	4_2	13:46:00	52.0%	346	14.6	477,459	21.4	4.6	0.1	2.3	0.0	2.3	2.7	2.8	0.01	150	262.9	11.7	4.8
12/19/2018	ULSFO	-	4_3	14:22:00	52.0%	348	10.2	477,466	21.5	4.7	0.1	2.4	0.0	2.5	2.9	2.9	0.02	150	262.9	11.7	4.8

Table F-14 Auxiliary boiler non-toxic results by test point part 2 of 2.

Date	Fuel	ATS	Test	Start Time	Load	g/kg-fuel (kg/tonne-fuel)												Calculated g/kg-fuel			NOx Cor.
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	NOx	CO	CO2	SO2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC			SO2_fuel	Kh
12/18/2018	MGO	-	1_1	17:39:00	60.0%	1.70	0.01	3174	0.0708	-	-	-	0.000	-	-	-	0.00039			0.768	-
12/18/2018	MGO	-	1_2	17:56:00	60.0%	1.68	0.01	3174	0.0819	0.068	0.0002	0.044	0.000	0.044	0.053	0.053	0.00034			0.768	-
12/18/2018	MGO	-	1_4	18:47:00	60.0%	1.67	0.01	3174	0.0770	0.042	0.0002	0.026	0.000	0.026	0.031	0.031	0.00034			0.768	-
12/19/2018	ULSFO	-	4_1	13:10:00	52.0%	2.22	0.24	3178	0.144	0.024	-	-	0.000	-	-	-	0.00010			1.6612	-
12/19/2018	ULSFO	-	4_2	13:46:00	52.0%	2.31	0.10	3178	0.142	0.031	0.0004	0.015	0.000	0.016	0.018	0.019	0.00008			1.7501	-
12/19/2018	ULSFO	-	4_3	14:22:00	52.0%	2.32	0.07	3178	0.143	0.031	0.0004	0.016	0.000	0.016	0.019	0.020	0.00015			1.7501	-

Table F-15 Auxiliary boiler toxic results by test point (DNPH).

Date	Fuel	ATS	Test	Start Time	Load	mg/kg-fuel (mg/tonne-fuel)																
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%MCR	Form.	Acet.	Acro.	Acet.	Prop.	Crot.	Meth.	Buty.	Buta.2	Benz.	Isov.	Vale.	Tolu.-o	Tolu.-m	Tolu.-p	Hexa.	Dimet.
12/18/2018	MGO	-	1_1	17:39:00	60.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/18/2018	MGO	-	1_2	17:56:00	60.0%	0.74	0.50	ND	0.56	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12/18/2018	MGO	-	1_4	18:47:00	60.0%	0.64	0.38	ND	0.30	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12/19/2018	ULSFO	-	4_1	13:10:00	52.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/19/2018	ULSFO	-	4_2	13:46:00	52.0%	4.18	1.06	ND	1.54	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
12/19/2018	ULSFO	-	4_3	14:22:00	52.0%	3.53	0.80	ND	0.69	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[1] DNPH was sampled from a dilution tunnel with the same dilution as the PM. ND stands for non-detect which means these values were below the detection limits of the analytical measurement system.

Table F-16 Auxiliary boiler toxic results by test point (BTEX).

Data is not available due to issues with the off-site analysis method utilized. Future testing will include the BTEX analysis.

Table F-17 Auxiliary boiler toxic results by test point part 1 of 3 (Metals).

Date	Fuel	Test	Start Time	Load	mg/hr															
mm/dd/yyyy	n/a	#	hh:mm:ss	%MCR	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Co	Ni
12/18/2018	MGO	1_1	17:39:00	60.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/18/2018	MGO	1_2	17:56:00	60.0%	0.00	30.90	5.52	36.41	24.28	671.99	5.52	0.00	40.83	24.28	29.79	0.00	0.00	33.10	1.10	3.31
12/18/2018	MGO	1_4	18:47:00	60.0%	0.00	28.93	0.00	25.19	25.19	589.70	3.73	10.26	39.19	0.00	25.19	0.00	0.00	38.26	0.00	1.87
12/19/2018	ULSFO	4_1	13:10:00	52.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/19/2018	ULSFO	4_2	13:46:00	52.0%	33.81	38.12	38.84	64.02	66.89	1481.01	0.00	0.00	74.09	0.00	426.54	0.00	0.00	135.23	0.00	177.66
12/19/2018	ULSFO	4_3	14:22:00	52.0%	14.38	40.25	46.72	57.50	55.35	1157.26	0.00	0.00	58.94	0.00	322.74	0.00	0.00	103.51	0.72	137.29

Table F-18 Auxiliary boiler toxic results by test point part 2 of 3 (Metals).

Date	Fuel	Test	Start Time	Load	mg/hr															
mm/dd/yyyy	n/a	#	hh:mm:ss	%MCR	Cu	Zn	Ga	Ge	As	Se	Br	Rb	Sr	Y	Zr	Nb	Mo	Rh	Pd	Ag
12/18/2018	MGO	1_1	17:39:00	60.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/18/2018	MGO	1_2	17:56:00	60.0%	6.62	8.83	0.00	0.00	0.00	5.52	3.31	0.00	4.41	5.52	0.00	3.31	5.52	26.48	8.83	4.41
12/18/2018	MGO	1_4	18:47:00	60.0%	2.80	11.20	0.00	0.00	0.00	5.60	0.93	1.87	4.67	2.80	0.00	0.00	5.60	14.00	0.00	7.46
12/19/2018	ULSFO	4_1	13:10:00	52.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/19/2018	ULSFO	4_2	13:46:00	52.0%	3.60	11.51	0.00	2.16	0.00	3.60	0.72	1.44	7.91	0.72	0.00	1.44	1.44	5.04	7.91	10.07
12/19/2018	ULSFO	4_3	14:22:00	52.0%	0.72	9.34	0.00	2.88	0.00	0.00	1.44	0.00	2.16	0.00	1.44	5.75	5.03	0.72	5.03	14.38

Table F-19 Auxiliary boiler toxic results by test point part 3 of 3 (Metals).

Date	Fuel	Test	Start Time	Load	mg/hr																	
mm/dd/yyyy	n/a	#	hh:mm:ss	%MCR	Cd	In	Sn	Sb	Te	Cs	Ba	La	Ce	O	Sm	Gd	Pt	Au	Tl	Pb	Bi	U
12/18/2018	MGO	1_1	17:39:00	60.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/18/2018	MGO	1_2	17:56:00	60.0%	16.55	7.72	14.34	1.10	0.00	0.00	51.86	81.65	81.65	101.52	71.72	35.31	5.52	5.52	4.41	2.21	0.00	6.62
12/18/2018	MGO	1_4	18:47:00	60.0%	11.20	0.00	14.00	2.80	4.67	0.00	28.93	13.06	21.46	32.66	9.33	0.00	2.80	5.60	1.87	3.73	0.00	6.53
12/19/2018	ULSFO	4_1	13:10:00	52.0%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12/19/2018	ULSFO	4_2	13:46:00	52.0%	11.51	9.35	25.18	0.00	0.00	0.00	33.09	23.02	0.00	61.86	36.68	18.70	3.60	12.95	6.47	2.88	0.72	7.19
12/19/2018	ULSFO	4_3	14:22:00	52.0%	7.91	0.00	8.63	23.00	6.47	0.00	36.66	5.75	0.72	25.88	17.25	56.07	2.16	6.47	3.59	0.00	3.59	1.44

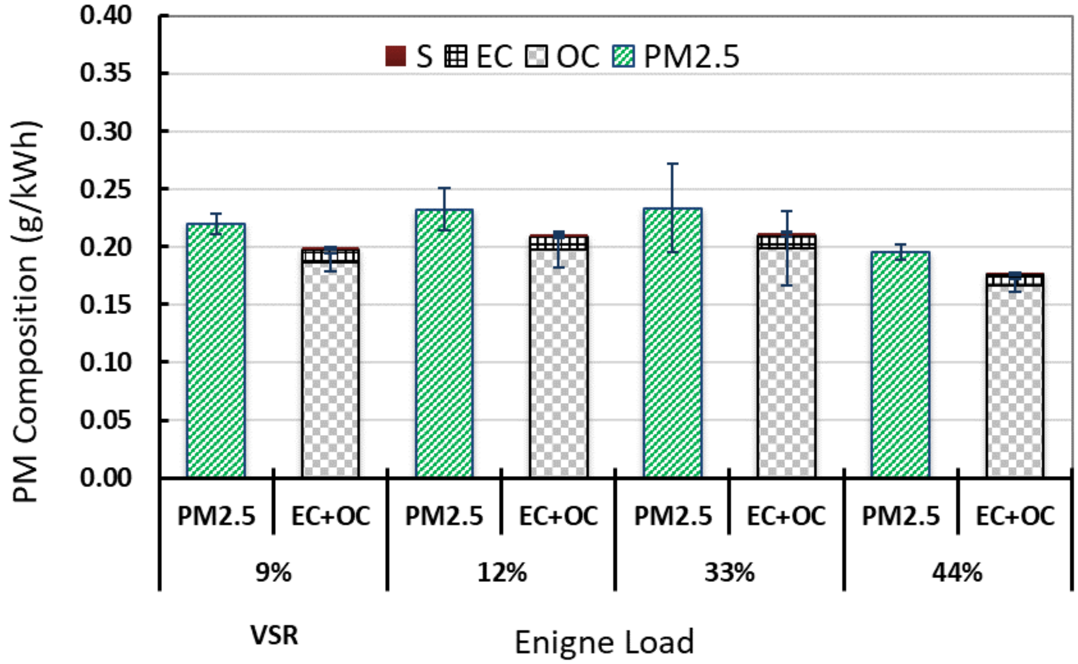

Figure F-18 PM composition MGO Emissions for the ME in g/kWhr

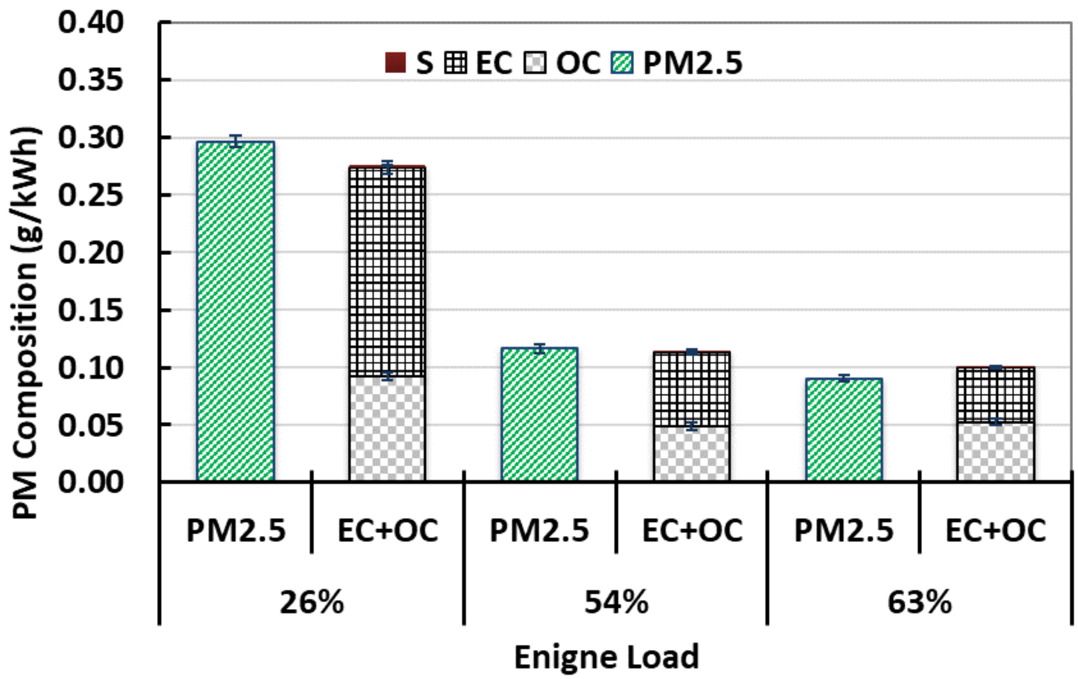

Figure F-19 PM composition MGO Emissions for the AE in g/kWhr

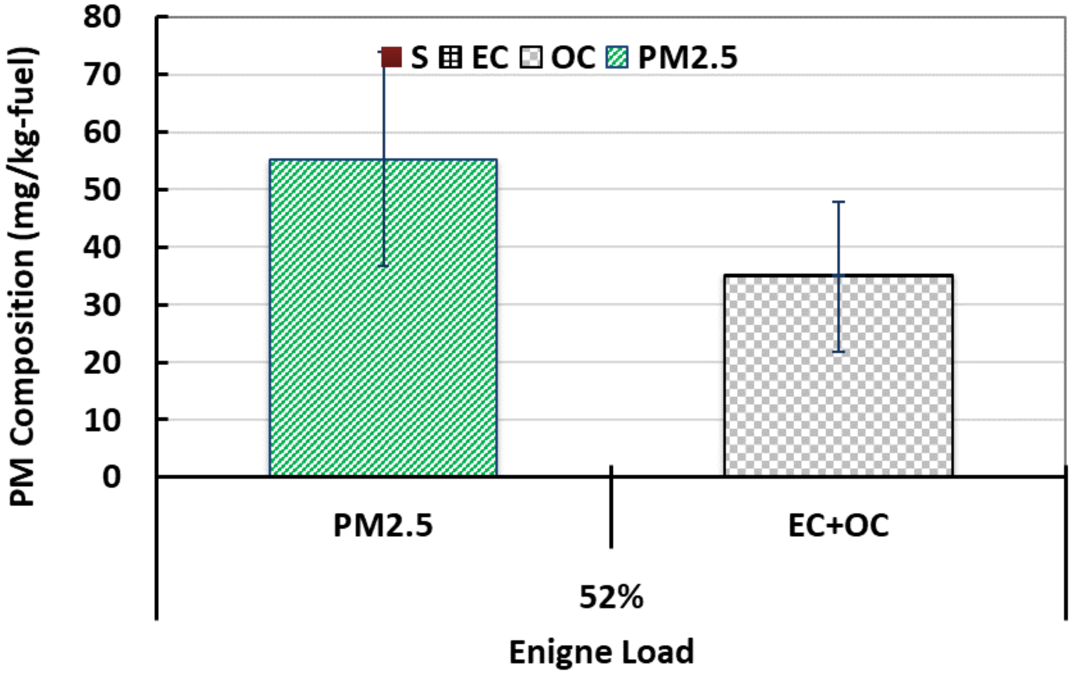

Figure F-20 PM composition MGO Emissions for the Auxiliary boiler in g/kWhr

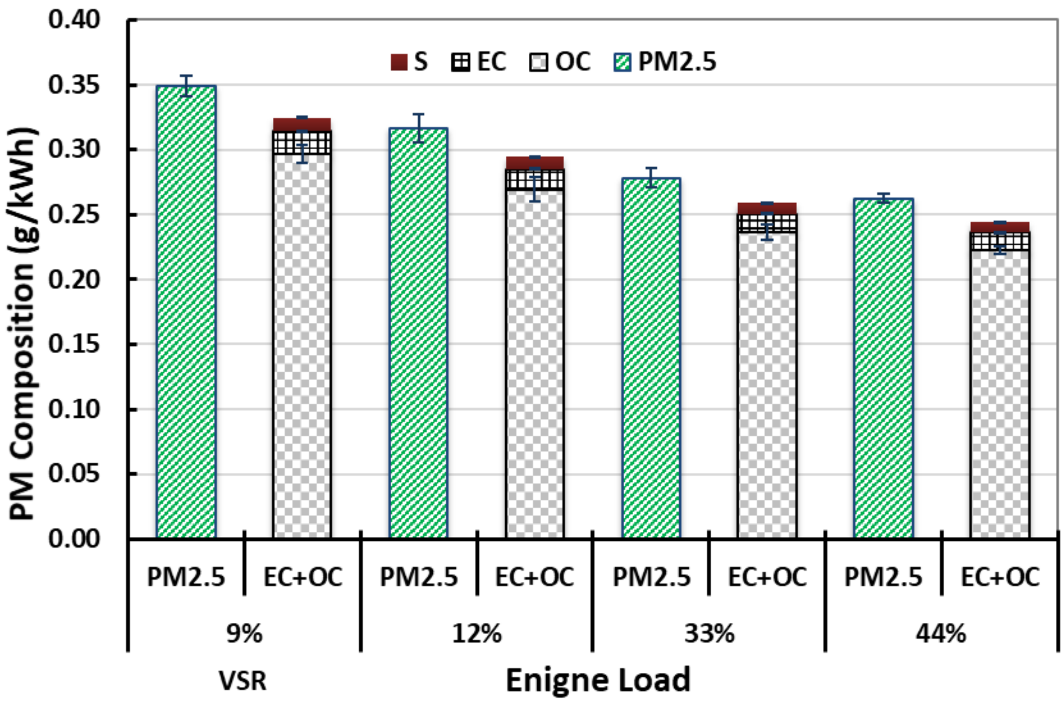

Figure F-21 PM composition ULSFO Emissions for the ME in g/kWhr

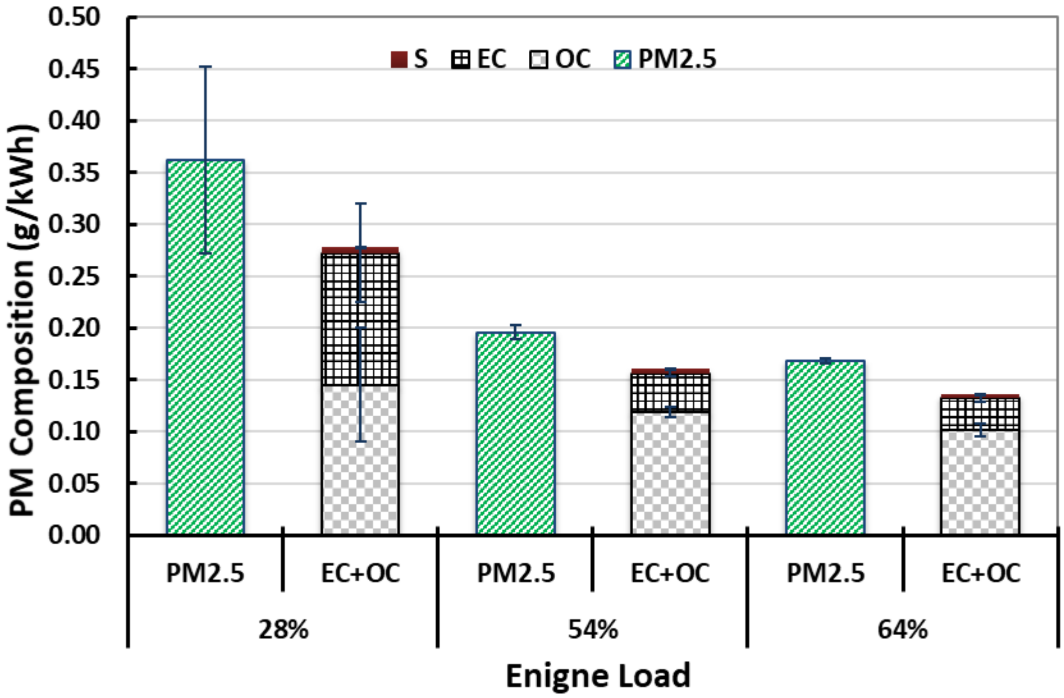

Figure F-22 PM composition ULSFO Emissions for the AE in g/kWhr

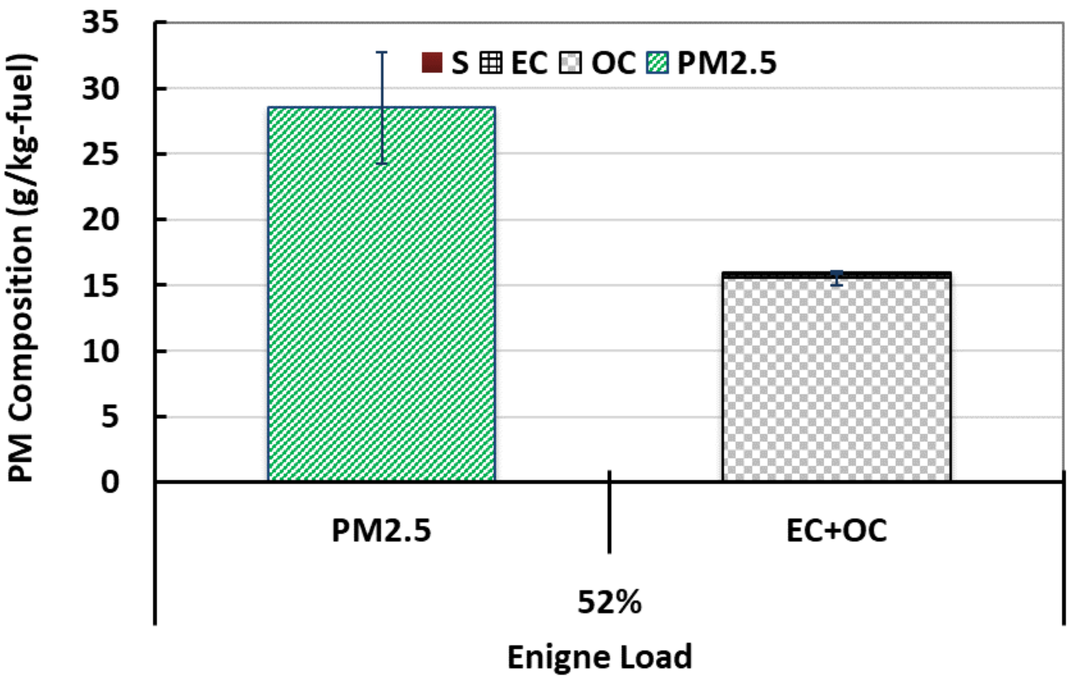

Figure F-23 PM composition ULSFO Emissions for the Auxiliary boiler in g/kg-fuel

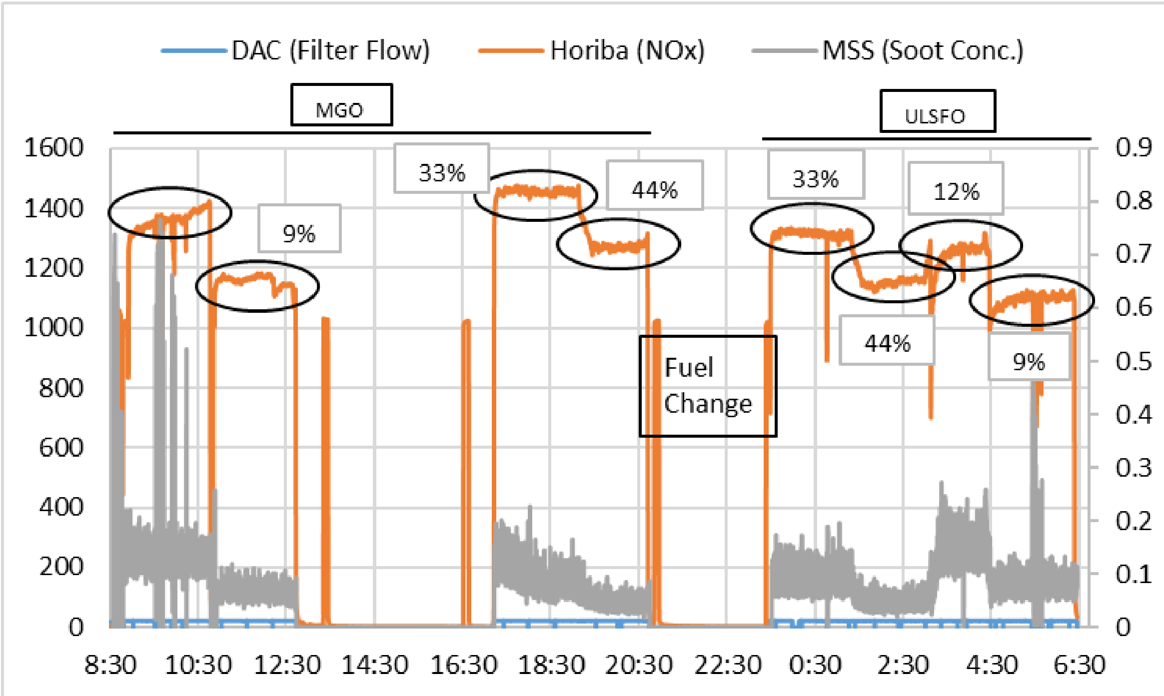

Figure F-24 Measured MSS soot and NO_x emissions for the ME MGO and ULSFO

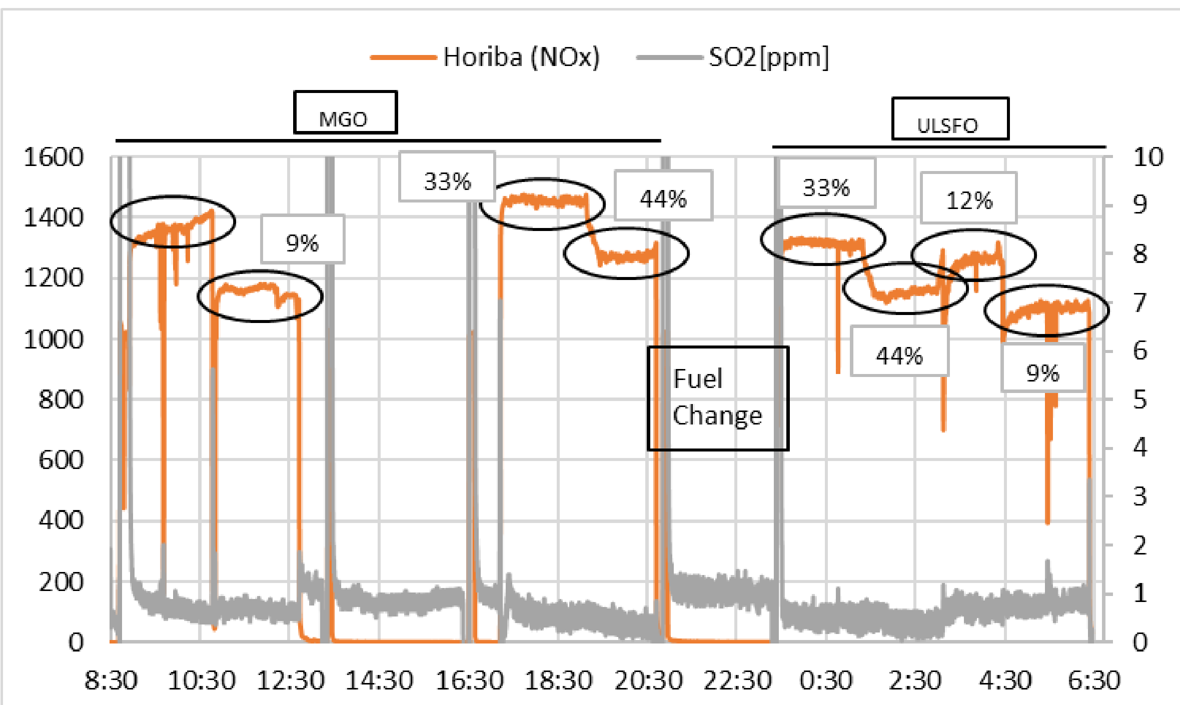

Figure F-25 Measured SO2 soot and NO_x emissions for the ME MGO and ULSFO

[1] SO2 emissions should vary around 7 for the 0.05 S fuel and around 14 ppm for the 0.1 S fuel. For some reason there is no real response to SO2 in the analyzer suggesting something is wrong with the analyzer or the sample collection system for SO2.

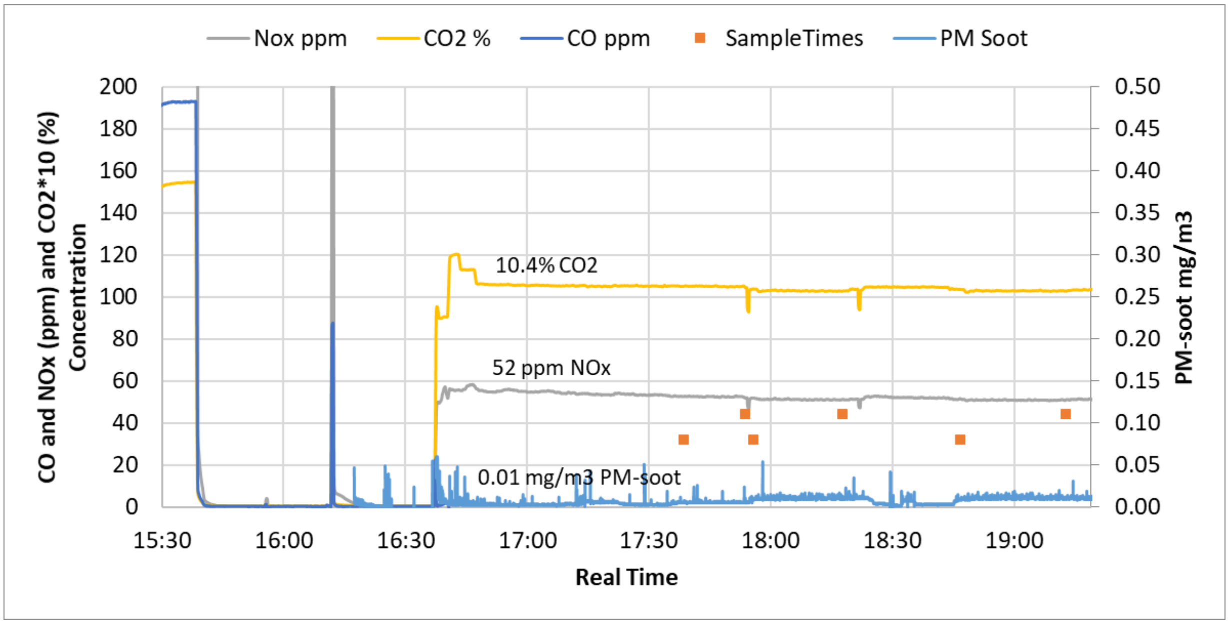

Figure F-26 Measured CO, CO2 and NO_x emissions for the Auxiliary boiler MGO fuel 60% load