Emissions Evaluation of an Auxiliary Boiler on a 2014 Suezmax Tanker

Final Report

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Acronyms and Abbreviations

σ	standard deviation
AE	auxiliary engine
BC	black carbon
BTEX	benzene, toluene, ethylbenzene and xylene
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
DNPH	dinitrophenylhydrazine
DT	dilution tunnel
eBC	equivalent black carbon
DWT	deadweight tonnage
EC	elemental carbon defined by thermal optical methods
EP	exhaust pipe
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
fs	fuel specific
HCLD	heated chemiluminescence detector
HFO	heavy fuel oil
IMO	International Maritime Organization
ISO	International Organization for Standardization
kPa	kilo Pascal
lpm	liters per minute
ULSFO	low sulfur heavy fuel oil
MDO	marine diesel oil
ME	main engine
MGO	marine gas oil
MFC	mass flow controller
ms	milliseconds
MSS	Micro Soot Sensor
NDIR	non-dispersive infrared absorption
NIOSH	National Institute of Occupational Safety and Health 5040 protocol
NIST	National Institute for Standards and Technology
NO_x	nitrogen oxides
O_2	oxygen
OC	organic carbon defined by 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
rBC	refractory nature of BC
SP	sampling probe
SRL	sample reporting limit
scfm	standard cubic feet per minute
S	sulfur
SO_2	sulfur dioxide
SO_x	sulfur oxide
Stdev.	Standard deviation one sigma
TGNMO	total gaseous non-methane organics
TT	transfer tube
UCR	University of California at Riverside
ULSFO	ultra-low sulfur fuel oil
VOC	volatile organic compound
VN	venturi

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Executive Summary

Introduction: More than ten years have passed since UCR measured the emissions from a large auxiliary boiler on a Suezmax tanker while it unloaded about one million barrels of crude. Modern vessels use newer auxiliary boiler designs, so it is of interest to measure their emissions and compare these emissions to previous studies to quantify the change in emissions over time. The Alfa Laval unit used in this testing is an Aalborg OL large capacity auxiliary boiler with a super heater, representative of a modern auxiliary boiler for tankers. The tests were performed on a Suezmax class vessel, which is the same as the previous vessel and still representative of tankers calling at the ports of California. Alfa Laval is a market share leader so data from this unit should provide an important perspective on the emissions from widely-used tanker auxiliary boilers with the latest technology advances. Further, ships operating within California waters now use low-sulfur distillate fuels so results from this test will show the combined effects of a modern auxiliary boiler design used in combination with cleaner California fuels.

Methods: The test methods utilized International Organization for Standardization (ISO) 8178-4 sampling protocols. The auxiliary boiler was evaluated at one load representative of normal operation for the vessel (65% of maximum capacity). The emissions measured were regulated gaseous, speciated hydrocarbons C2-C12, aldehydes and ketones, metals, particulate matter mass less 2.5 um ($PM_{2.5}$), and particulate matter (PM) composition which included elemental and organic carbon (EC and OC) PM. Other methods and practices, sampling dilution, and calculations such as dry to wet correction, followed ISO and Code of Federal Regulations (CFR) recommendations.

***Objectives*:** The primary aim of this work is to study the in-use emissions from a modern tanker auxiliary boiler utilizing California approved marine gas oil (MGO) low sulfur fuel.

Results gaseous: The auxiliary boiler carbon dioxide (CO_2) emissions were 3,171 g/kg-fuel which is similar to previous testing of a different modern auxiliary boiler on a container vessel (Johnson et al 2019). The close agreement suggests the relative measurements for CO_2 concentration and exhaust flow were similar, indicatingthe results presented here are representative of a properly performed test. However, the nitrogen oxide (NO_x) emissions averaged 3.00 ± 0.18, carbon monoxide (CO) 0.101 ± 0.001, and sulfur dioxide (SO_2) 0.965 g/kg-fuel, which were lower than the previous testing The NO_x emissions were slightly higher, within 50%, to previous testing of a modern container vessel auxiliary boiler tested on low sulfur MGO and ultra-low sulfur fuel oil (ULSFO) fuels (Johnson et al 2019), but over two times lower (2.2) than the emissions on an older tanker vessel auxiliary boiler tested on high sulfur HFO fuel (Agrawal et al 2008).

Results PM: The $PM_{2.5}$ emissions were 0.023 ± 0.004 g/kg-fuel and were slightly lower compared to previous testing of a different modern container vessel auxiliary boiler tested on low sulfur MGO and ultra-low sulfur fuel oil (ULSFO) fuels, but over 100 times lower (131) than the $PM_{2.5}$ emissions on an older tanker auxiliary boiler tested on high sulfur heavy fuel oil (HFO). The PM composition was mostly organic carbon (98%) and about 2% elemental carbon (EC) for the auxiliary boiler emissions in this study. The equivalent black carbon (eBC) emissions were 0.0012±0.0004 g/kg-fuel and were about the same for a container vessel auxiliary boiler (Johnson et al 2019). eBC was not measured during the 2008 testing, but elemental carbon (EC) was. The EC emissions during the modern auxiliary boiler testing was 0.0006±0.0003 g/kg-fuel which was

about 250 times lower than the EC emission reported for the older auxiliary boiler tested on high sulfur HFO (Agrawal et al 2008).

Brake specific emissions: The brake specific emissions from the Suezmax tanker are 0.007, 0.917, and 0.006 g/kWhr for $PM_{2.5}$, NO_x, and reactive organic gases (ROG), respectively. The conversion from fuel specific to brake specific emissions assumes the $bsCO_2$ emissions are 970 g/kWhr and the fuel carbon weight fraction is 0.8682.

Results Toxics: The auxiliary boiler emissions for formaldehyde, acetaldehyde and acrolein were 0.422, 0.396, and 1.843 mg/kg-fuel. These results compare well with the modern auxiliary boiler operating on MGO fuel test from a container vessel. Modern auxiliary boilers operating on MGO fuels appear to have lower acetaldehyde and acetone emissions compared to older auxiliary boiler tested on HFO fuels. The photochemical assessment monitoring stations (PAMS) measurements, were below the detection limit of the measurement method and thus, could not be compared properly to the previous testing on an older auxiliary boiler tested on high sulfur HFO fuel. The metals emissions were low, and below detection limits of the method except for ten metals. Of these ten, sulfur was dominate with emissions of 3.59 mg/kg-fuel. Selected metals, such as vanadium and alumimun, were 99% lower in this study compared to the auxiliary boiler utilizing high sulfur HFO (Agrawal et al 2008).

Summary: Modern auxiliary boilers operating on lower sulfur MGO fuels have lower NO_x and total PM mass compared to older auxiliary boilers operating on high sulfur fuels. These results show the benefit of modern auxiliary boilers operating on low sulfur MGO fuels.

1 Background

1.1 Introduction

Global shipping represents over 80% of the volume and 70% of the value of goods (UNCTAD, 2015 and 2017) transported indicating 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), trace metals, and other ions (such as nitrate and ammonium). Propulsion main engines are the main source of emissions during transit, but while unloading product at berth, auxiliary engines and auxiliary boilers are the main source of emissions.

More than ten years have passed since emissions were measured from a large auxiliary boiler on a Suezmax tanker while it discharged about one million barrels of crude. Results of that project were peer reviewed and published (Agrawal et al 2008). The results included regulated and nonregulated emissions factors for criteria pollutants CO, NO_x, SO_x and $PM_{2.5}$, a greenhouse gas (carbon dioxide (CO_2)), speciated hydrocarbons needed for human health risk assessments, and a detailed analysis of the PM into its primary constituents (ions, elements, organic, and elemental carbon (EC and OC)). This previous test, performed in 2007, utilized a high sulfur heavy fuel oil (HFO). Due to concerns about ship emissions near ports, the International Maritime Organization (IMO) reduced the maximum sulfur limit for marine fuels in 2012 to 3.5 wt% and in 2020 to 0.5 wt% with the plan of reducing both SO_x and PM emissions (Fridell 2016, MARPOL 2017). Further, ships operating within California waters are required to use low-sulfur distillate fuels (0.1% sulfur content in Emission Control Areas) so results from this test will show the combined effects of a modern auxiliary boiler design used in combination with cleaner California fuels (Marine Gas Oil (MGO) or Marine Diesel Oil (MDO)[1].

There is very little research in the public domain on auxiliary boiler emission factors. In 2017, Starcrest, who prepares air quality reports for the Ports of Los Angeles and Long Beach, reported the emission factors from auxiliary boilers and in their report referenced a study in 2002 for which the data source was based on experiments performed in the 1980s. Prior to now, the work presented by Agrawal in 2007 was the only in-use source of auxiliary boiler emissions available. However, Agrawal's work concerned high sulfur fuels and is not representative of current auxiliary boiler operation while a vessel is at-berth. Thus, the work presented in this project is very important for the emission factors from modern auxiliary boilers and is of interest to CARB.

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

Marine boilers originally were used for main ship propulsion and for auxiliary uses. As the diesel engine entered the marine industry, the main propulsion switched from steam boiler driven to diesel fueled. Today, there is only one boiler on a vessel, but these boilers are still referred to as auxiliary boilers based on their historical usage. As such, UCR will utilize auxiliary boilers to describe the auxiliary boiler tested. Auxiliary boilers are used for supplying steam and hot water for non-propulsion uses such as fuel heating, galley, cabin space heating, and to drive steam turbines on tankers that offload petroleum crude oil in ports. Boilers can range in size—for example, container vessels and roll-on-roll-off auxiliary boilers tend to be smaller than the ones found on tanker vessels. The auxiliary boiler tested in this research had a fuel consumption and exhaust flow rate ten times larger than the container vessel auxiliary boiler.

There are three main manufacturers of marine auxiliary boilers: 1) Alfa Laval Aalborg, 2) KangRim Heavy Industries Co., and 3) Hyundai Heavy Industries (Alfa Laval 2020). Alfa Laval is a market share leader at more than half the market. KangRim is a spin-off company from Alfa Laval and utilizes many of the same designs as Alfa Laval boilers, suggesting the Alfa Laval design and performance represent the largest installation of ocean-going vessels for tanker and container vessel markets (Alfa Laval 2020). The boiler tested in this project was a 2014 Alfa Laval Aalborg OL large capacity auxiliary boiler equipped with a KBSD 4150 top fired steam atomizing burner. The data from this study will provide an important perspective on the emissions from widely-used auxiliary boilers with the latest advances in technology.

Auxiliary boilers vary in size based on the amount of crude that needs discharging. Tankers vary by the amount of crude they can carry which is typically defined by the passage of different water ways. The auxiliary boiler tests were performed on a Suezmax class vessel which discharges about twice the crude compared to the Panamax class vessel. The Suezmax boiler is also larger than the Panamax vessel by about 70%. Both vessel classes have a similar call frequency at California ports, where in 2016 both the Suezmax and Panamax tankers represented 32% and 30% of the total calls for tanker visits to California's top three ports, respectively [2] [3].

1.2 Objective

The objective of this research is to evaluate the emissions from a modern auxiliary boiler on a panama class tanker ship while it offloads crude oil in Richmond, California while the main engine is off. The testing followed the same protocol as used in the earlier study, except in this study the nonregulated air toxics were measured with Suma Canisters. Following the same protocol of the earlier study will allow a direct comparison of emissions and provide information on the changes in emissions over time.

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[2] CARB 2019 Update to Inventory for Ocean-Going Vessels At Berth: Methodology and Results https://ww3.arb.ca.gov/regact/2019/ogvatberth2019/apph.pdf

[3] ICF International, Chevron Richmond Long Wharf Shipping Emissions Model, Final Report February 7, 2014. Prepared by ICF for Chevron Products Company.

2 Approach

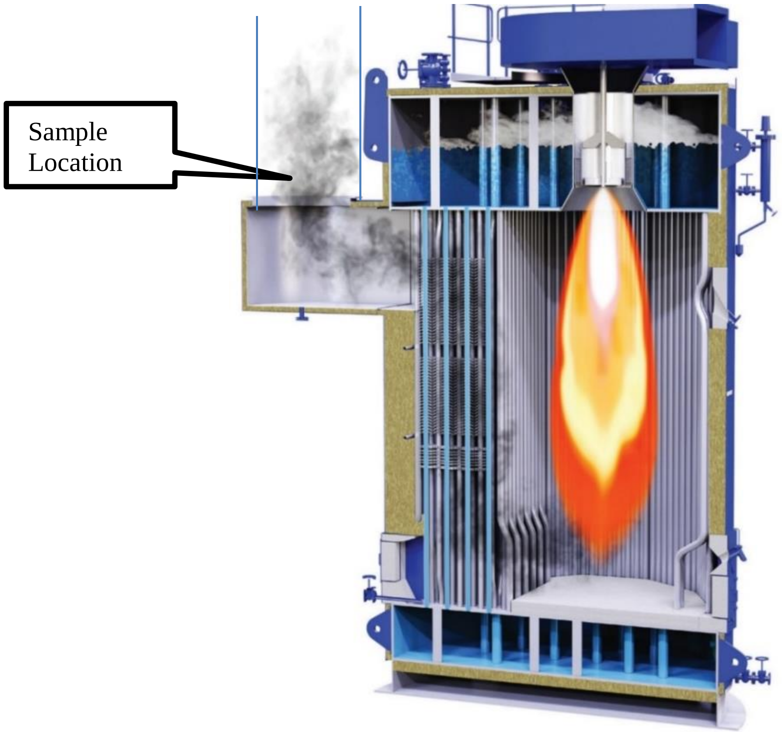
This section outlines the in-use emissions testing approach for the modern auxiliary boiler on a Suezmax class tanker vessel. This section describes the test article (boiler, fuel, and load point), sampling approach (sample location, sample discussions, and test protocol), measurements (gaseous and PM measurement methods, toxic sampling approach), calculations (exhaust flow determination), and a discussion of the assumptions used in the data analysis. The test article sections cover design details of the boiler operation. The sampling approach describes where the samples were collected from the exhaust, any impact this location may have on the measurement, and the test protocol. The measurements section describes the measurement methods for the gaseous, PM (mass and composition), and toxics samples. The corrections and assumptions section provide a discussion on the data and analysis used in this report.

2.1 Test article

The boiler, fuel, and test matrix are described in this section.

2.1.1 Auxiliary Boiler

The auxiliary boiler tested is an Alfa Laval large capacity auxiliary boiler (2xAalborg OL 50,000 kg/h) installed on a 2014 crude Suezmax class tanker vessel with a 155,720 DWT capacity with an overall length of 275m by 48 m breadth. This boiler design includes a super heater unit, 2xAalborg XW-S with a steam rating of 50,000kg/h. The boiler operation is automatically controlled. A diagram is presented in Figure 2-1 and the OL model specifications are provided in Table 2-1.



Source Alfa Laval

Figure 2-1 Design diagram of large frame boiler series

Auxiliary boilers are made up of three main parts: the burner section, the heat exchange, and the automation. The burner section and integrated controls have the greatest impact on the emissions from boilers. There are three main types of burners found on auxiliary boilers: steam atomization, rotary cup atomization, and high-pressure atomization. The steam atomization burner is Alfa Laval's most representative type of burners and most representative of modern auxiliary boilers. The steam enters the center of the burner nozzle and the fuel oil feeds in from the cylindrical outer region and they mix under high pressure and mix to for a fine atomized spray in the combustion chamber, see Figure 2-2. The auxiliary boiler tested was a model KBSD 4150 high pressure top fired steam atomizing burner.

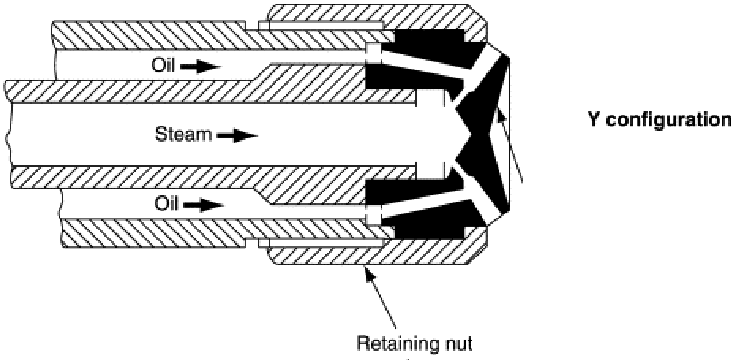
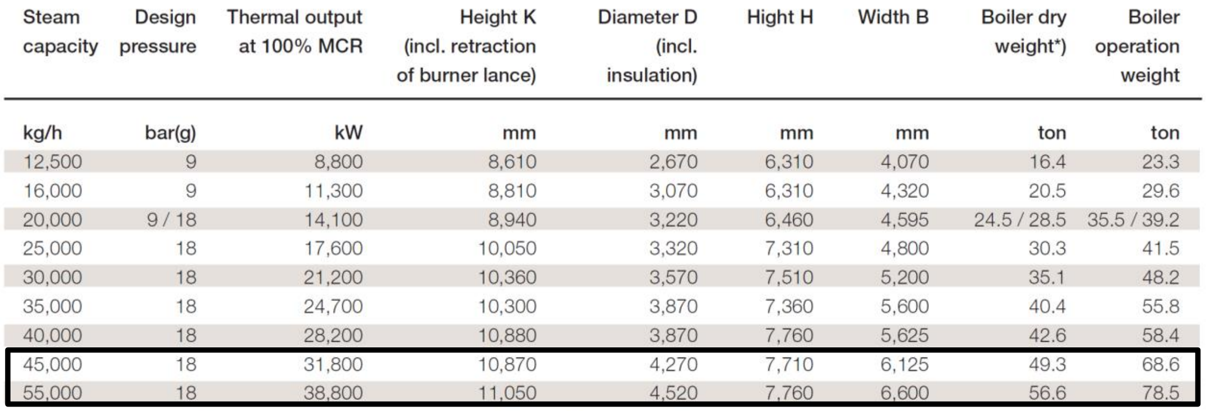


Figure 2-2 Steam atomizing burner **(N CHIGIER, 1979[4])**

The test unit represents one of the larger boilers made by Alfa Laval. According to Alfa Laval's brochure, the unit tested, rated at 50,000kg/h steam capacity, is a boiler near the highest level of steam production that is commercially offered. This suggests the boiler emissions will be of interest to regulators since it is one of the higher emission rate boilers in mass per unit time for this type of tanker activity.

Table 2-1 List of Alfa Laval large frame boilers, 50,000 kg/h tested)



Steam capacity	Design pressure	Thermal output at 100% MCR	Height K (incl. retraction of burner lance)	Diameter D (incl. insulation)	Hight H	Width B	Boiler dry weight*)	Boiler operation weight
kg/h	bar(g)	kW	mm	mm	mm	mm	ton	ton
12,500	9	8,800	8,610	2,670	6,310	4,070	16.4	23.3
16,000	9	11,300	8,810	3,070	6,310	4,320	20.5	29.6
20,000	9 / 18	14,100	8,940	3,220	6,460	4,595	24.5 / 28.5	35.5 / 39.2
25,000	18	17,600	10,050	3,320	7,310	4,800	30.3	41.5
30,000	18	21,200	10,360	3,570	7,510	5,200	35.1	48.2
35,000	18	24,700	10,300	3,870	7,360	5,600	40.4	55.8
40,000	18	28,200	10,880	3,870	7,760	5,625	42.6	58.4
45,000	18	31,800	10,870	4,270	7,710	6,125	49.3	68.6
55,000	18	38,800	11,050	4,520	7,760	6,600	56.6	78.5

Source Alfa Laval

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[4] NORMAN A. CHIGIER, in Energy and Combustion Science, 1979

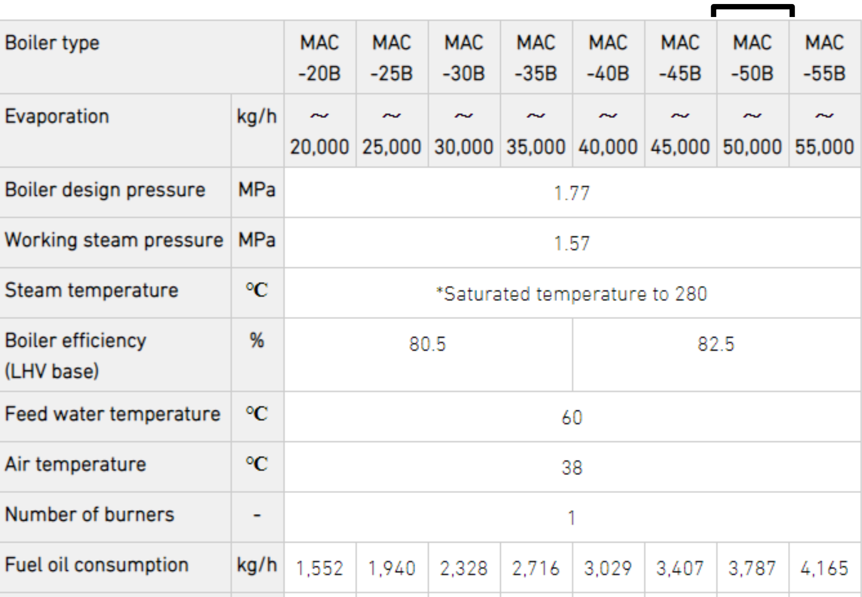
2.1.2 Test fuels

A standard low sulfur marine gas oil (MGO) fuel was used during this testing. The fuel complies with the CARB's Fuel Rule for Ocean-Going Vessels[5], which allows either an MGO or a marine diesel oil (MDO) at or below 0.1% sulfur (S). A fuel sample was taken, and the results show the fuel sulfur was less than 0.1% (S = 0.045% following D4294 and X-ray methods, see Appendix D). The test fuel had a carbon weight fraction of 0.8682 and a hydrogen weight fraction of 0.1286, See Appendix D for analysis report.

2.1.3 Test matrix

Typically, a test matrix includes a range of loads, but boiler operation tends to be a constant load with periods of on/off control to maintain steam pressure. For example, when off-loading product, the fuel rate is increased to meet that demand and the boiler turns on and off based on steam needs. During vessel transit, the load is reduced and the duty cycle is reduced to meet that lower steam demand. During these different demands the boiler load is constant where the duty cycle varies (ie how long the boiler is on then off) in order to meet the pressure needs. It is estimated the boiler operates at 65% load when offloading product and 55% load when in transit. During off-loading product, the boiler produces the highest steam rate for the turbine pump need during land-based transfers of products (as tested during this project). As the land-based tanks reach capacity, the boiler fuel rate slows slightly to accommodate a switch-over in the storage tanks.

Figure 2-3 shows the steam rate and fuel consumption for a different, but similarly sized auxiliary marine boiler made by Mitsubishi. The 50,000 kg/h Mitsubishi steam rate boiler shows a maximum fuel oil consumption of 3,787 kg/hr. This agrees with discussions with Alfa Laval on fuel rate needs for steam loads. If we assume the maximum consumption between manufacturers is similar, we can estimate the load on the boiler tested as a percentage of maximum. The measured fuel consumption during this testing was 2,495 kg/hr, suggesting the boiler was operated at an estimated 65% of its maximum design load.



Boiler type		MAC -20B	MAC -25B	MAC -30B	MAC -35B	MAC -40B	MAC -45B	MAC -50B	MAC -55B
Evaporation	kg/h	~ 20,000	~ 25,000	~ 30,000	~ 35,000	~ 40,000	~ 45,000	~ 50,000	~ 55,000
Boiler design pressure	MPa	1.77							
Working steam pressure	MPa	1.57							
Steam temperature	°C	*Saturated temperature to 280							
Boiler efficiency (LHV base)	%	80.5				82.5			
Feed water temperature	°C	60							
Air temperature	°C	38							
Number of burners	-	1							
Fuel oil consumption	kg/h	1,552	1,940	2,328	2,716	3,029	3,407	3,787	4,165

Figure 2-3 Heat loads and fuel rates for different sized boilers

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[5] https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessel-fuel-regulation

(source Mitsubishi Heavy Ind.)[6]

The crew suggested the boiler could be operated at this "65%" state and also at a slightly lower steam rate. As such, there was a desire to test at two load points (65% and something lower around 50%), however due to time limitations, we only tested the higher 65% load condition and not the lower load condition. The 65% load is used for offloading product and the lower state is used during transit, where the transit represents a much lower duty cycle suggesting the 65% load is more representative of at-berth auxiliary boiler emissions. The data in this report represents the 65% load case at a fuel consumption rate of 2,495 kg/hr.

Fuel consumption for the auxiliary boiler was measured by the vessel and provided to the UCR research team. Discussions with the crew suggested the boiler operates in different modes 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 65%.
- **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 the 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.

During this testing, the auxiliary boiler was found in the Auto/Auto mode for the 65% 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 product off loading, fuel heating, galley, and cabin space heating. A boiler steam load is managed by operating at the recommended 65% fuel rate, then cycling the auxiliary boiler on and off to achieve different steam needs. As such, the 65% load was considered a representative load point and representative of typical tanker auxiliary boilers. The duty cycle was not measured as part of this research and should be considered for future projects to help understand boiler emission inventory.

2.2 Sampling approach

This section provides a discussion of the sample locations (PM representativeness and accessibility), and the test protocol (methods of sampling).

2.2.1 Sample locations

Sampling utilized UCR's partial dilution tunnel system, as outlined in ISO 8178-1, with a direct connection to the exhaust sample, see Appendix A for more details. The South Coast Air Quality Management District has a guidance document for the evaluation of boilers, but this procedure is

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[6] https://www.mhi-mme.com/products/boilerturbine/auxiliary_boilers.html#tab03_2 Auxiliary boiler project specifications.

for compliance limitations of a concentration versus flue stack dilution[7]. The AQMD test protocol corrects for oxygen concentration in the reported emissions limits because of variabilities in dilution. This is not a mass-based method and is not recommended for in-use testing where mass can be quantified like in the ISO method. Although the ISO method was designed for engine testing, in 2012 CARB contracted UCR to develop an in-use test method for the evaluation of ocean-going vessel engines and boilers. The UCR recommended in-use marine method is based on ISO 8178 and is used for all of UCRs testing campaigns on ocean-going vessels (CARB 2012). Several points of access to the exhaust were identified during a site visit months before the testing campaign. The recommended location identified was near the top of the boiler stack where a cross-plume smoke meter was installed. The plume smoke meter was disconnected during testing and reinstalled afterwards, see Figure 2-5 and Figure 2-6. This location is free of bends and was a good location for sampling of at least two stack diameters.

Figure 2-4 Platform space available for equipment (smoke meter shown)

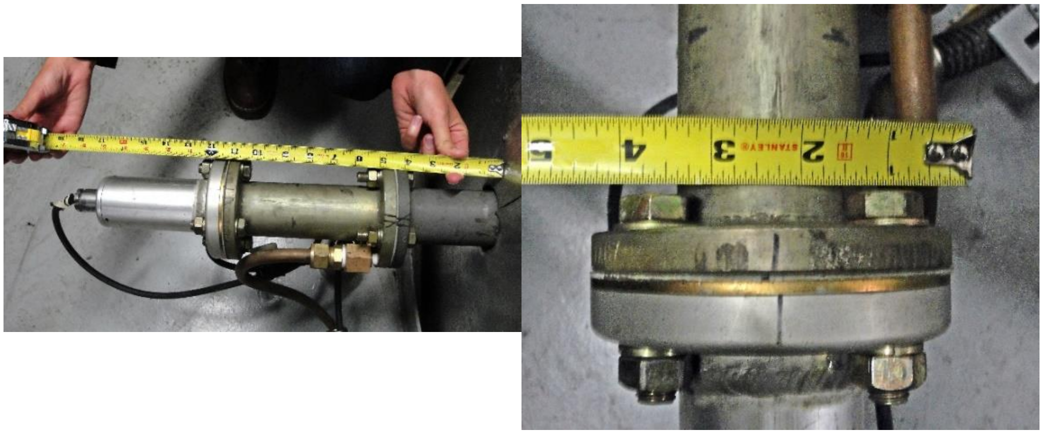

Figure 2-5 Dimensions for probe length and flange size

There were no sample ports prior to the heat exchanging surfaces where one could measure the boiler emissions directly, as can be seen by the boiler layout shown in Figure 2-1. UCR, therefore, utilized the cross-plume smoke meter sample location as the only practical sample location. The length of the sample probe needed to be 12 inches to access a well-mixed exhaust sample using good engineering judgment (which is 10% inside the wall of the exhaust stack where the flow is

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[7] SCAQMD, Source Test Protocol For Determining Oxygen Corrected Pollutant Concentrations From Combustion Sources with High Stack Oxygen Content, Based on Carbon Dioxide Emissions. March 3, 2011

well mixed). The dimensions show the probe design should be 12 inches, see Figure 2-5 and Figure 2-6.

The dilution tunnel length with the installed cyclone was interfering with the vessel stack to the left in the figure shown below, see Figure 2-6. The tunnel would fit with the cyclone removed. Since this was the only suitable sample location the cyclone had to be removed in order to collect any samples from the boiler. The impact of this decision is provided in Section 2.5.

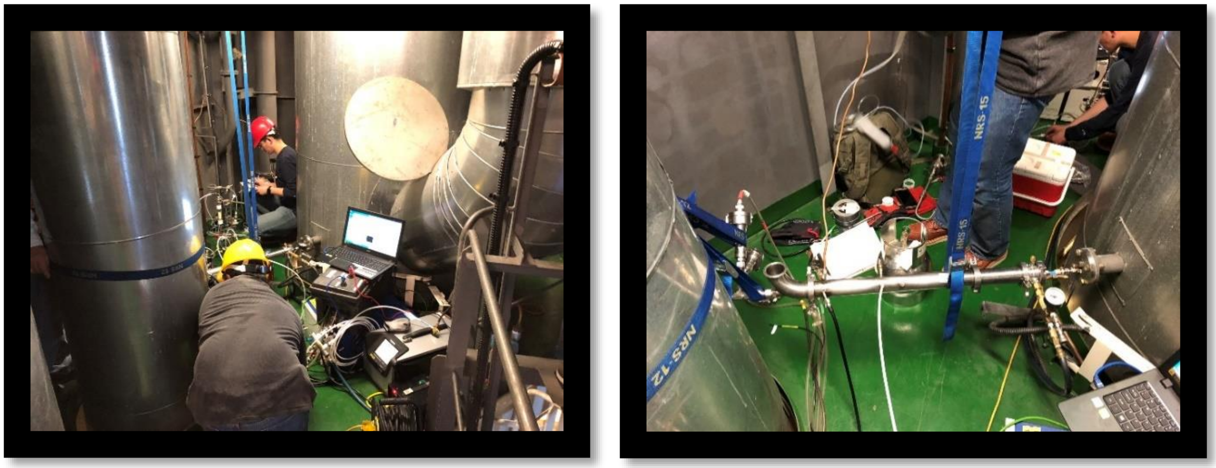
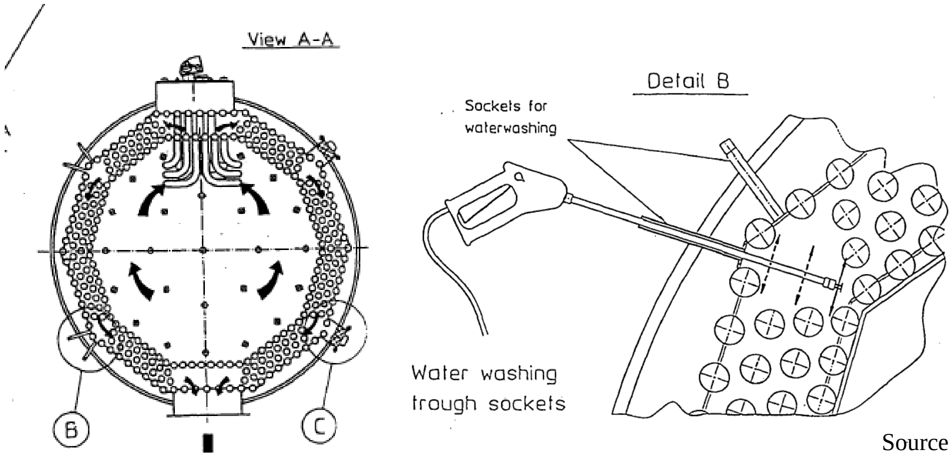


Figure 2-6 Boiler tunnel setup: thermopile probe removed for sampling

2.2.2 PM fouling discussion

Sampling after a heat exchanging surfaces, like a boiler, can be a source for PM adsorption and desorption because these surfaces heat and cool in the presence of PM where thermophoretic loss/accumulation (Hind 2nd Edition 1999) can be significant. During boiler-on conditions, the hot boiler exhaust gas heats the cool boiler tubes and PM can adsorb on the surfaces. As the tube surfaces can get hot, PM may start to desorb. Then, during periods of boiler-off condition (reduced water heating), the heat exchanger surfaces will cool until the next cycle. The adsorption and desorption of PM on a boiler surface can be described by thermophoretic loss models in Hind (2nd Edition 1999). When PM is adsorbed onto the surface, stack PM emission factors can be underestimated over short periods of time (measured in hours). The sample location for this testing was collected just after the boiler exhaust in the flue stack, see Figure 2-1.

The boiler manufacturer includes cleaning recommendations for the heat exchanger surfaces. According to the Aalborg manual, the boiler cleaning is performed by routine air blasts and occasional water blasts. The rate of cleaning varies with the quality of the fuel and the indications from the installed smoke meter. The water blasts are performed when boiler performance declines. There are several access ports for these water blast ports, see Figure 2-7. According to discussions with the crew the boiler was in a clean state, thus suitable for our emissions testing.



Source Alfa Laval

Figure 2-7 Cleaning setup for an Aalborg boiler

2.2.3 *Test protocol*

The boiler load 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. For this testing, however, only one load point was performed so there were not conditions to wait for. In general, at each steady state test mode, the protocol recommends the following:

- Allow the gaseous emissions to stabilize before measurement at each test mode (minimum 10 minutes as per ISO). Since there was only one mode this requirement was maintained.
- Measure gaseous and PM concentrations for at least 3 minutes and no longer than 30 minutes (such that approximately 500µg of filter mass is collected at a minimum dilution ratio of 4:1). If filter weights are expected to be light, one may choose to increase sampling times to get higher filter weights. Due to the very light weight filters (averaging around 100 µg) additional sampling time was utilized for the testing up to 40 minutes.
- Measure direct stack exhaust mass flow rate via EPA Method 2. Additionally, UCR recorded the fuel consumption of the boiler using discussions with vessel crew.
- Calculate emission factors from the measured pollutant concentration data and calculated mass flow rates.

2.3 Measurements

Like other marine tests, the measurement of exhaust concentrations followed CARB[8] and IMO[9] protocols (see Appendix A for an in-depth description of UCR's marine sampling system). A dilution tunnel is connected directly to the exhaust stack without the need for a transfer line. 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.

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[8] California Air Resources Board, *Recommended Emissions Testing Guidelines for Ocean-going Vessels*, https://ww2.arb.ca.gov/sites/default/files/2019-11/ogv%20test%20guidelines_ADA.pdf (2012)

[9] ISO 8178-1 Reciprocating internal combustion engines - Exhaust emission measurement - Part 1: *Test-bed measurement of gaseous and particulate exhaust emissions*

An overview of UCR's partial dilution system is shown in Figure 2-8. 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 the 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. UCR's marine testing is directly connected to the stack so to minimize PM losses. The dilution ratio targeted and verified for this testing project was 10:1 and the actual dilution ratio was 7:1.

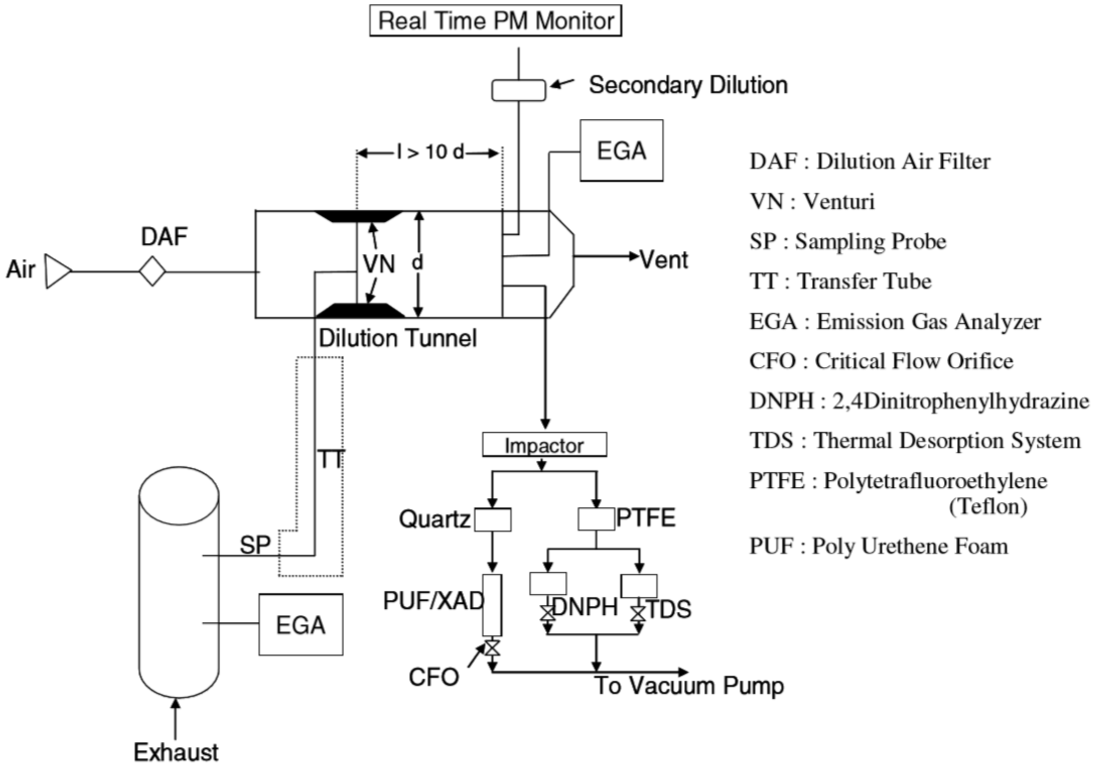

Figure 2-8 Sample schematic utilized

[1] For this testing the TDS and PUF were not utilized and Suma canisters were collected from the secondary dilution system. Additionally, raw Suma canister grab samples were collected and analyzed.

ISO cautions that the advantages of partial flow dilution systems can be a source of sampling 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. UCR includes standard methods, such as no transfer tube and dilution ratio verification for each marine application to ensure these concerns are managed properly. See Appendix A for more details.

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 diluted exhaust tunnel was measured with a Horiba PG-350. Nitrogen Oxides (NO_x) utilize a chemiluminescence detector (CLD), carbon monoxide (CO), carbon dioxide (CO_2) and sulfur dioxide (SO_2) utilize non-dispersive infrared absorption (NDIR) with cross flow modulation, and oxygen (O_2) which utilizes a galvanic sensor. Major features of the PG-350 include a built-in sample conditioning system (5 deg C) with sample pumps, data storage on a flash drive, integrated mist and particle filters, and a thermoelectric cooler. The performance of the PG-350 was tested and verified under the U.S. EPA and Environmental Technology Verification (ETV) programs.

Gaseous concentrations were measured directly from the dilution tunnel and from raw exhaust during dilution ratio verification. Dry-to-wet corrections were performed using calculated water concentration from the exhaust and the dilution tunnel.

Table 2-2 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	

[1] Measurement methods are non-dispersive infrared (NDIR) and chemiluminescence detection (CLD)

Particulate Matter (PM) mass: 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 less than 2.5 µm diameter ($PM_{2.5}$) is measured from the diluted exhaust gas according to the Code of Federal Regulations (CFR) 40 CFR Part 1065. UCR utilizes 47 mm 2µm pore Teflon filters (Whatman Teflo) weighed offline with UCR’s UPX2 Mettler Toledo micro balance (0.1 µg resolution) in a temperature, humidity, and particle-controlled environment. The microbalance is operated following the weighing procedures of the CFR. Before and after collection, the filters are conditioned for a minimum of 24 hours in an environmentally controlled room (RH = 45%, T = 21 C, 9.5 C dew point) and weighed daily until two consecutive weight measurements were within 3µg.

PM Composition: The project measured PM composition which comprises elemental carbon (EC) and organic carbon (OC). OC/EC analysis was performed on samples collected on 2500 QAT-UP Tissuquartz Pall (Ann Arbor, MI) 47 mm filters that are preconditioned at 600°C for 5 h. A 1.5 cm2 punch is cut out from the quartz filter and analyzed with a Sunset Laboratory (Forest Grove, OR) Thermal/Optical Carbon Aerosol Analyzer according to the NIOSH 5040 reference method. The PM composition filters were sampled from UCR dilution tunnel at a targeted flow rate of 15 slpm.

Equivalent black carbon (eBC). Bond et al (2013) provided a definition of black carbon (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 filter samples.

2.3.2 Toxics

CARB utilizes speciation estimates from boiler emissions that are used in the emission inventory and air quality models. These models are lacking toxic data from marine boilers. As such, additional toxic samples were utilized for the boiler tests. These included aldehydes and ketones, speciated hydrocarbons, and metals. All the toxic samples were collected from the dilution tunnel as shown in Figure 2-8. Additionally, two speciated hydrocarbon samplers were collected directly from the raw stack to improve measurement sensitivity.

Total Gaseous Non-Methane Organics (TGNMO) concentrations are often measured using a total hydrocarbon analyzer with a field ionization detector. However, these devices have a flame and are not usually allowed on a tanker vessel. For this project, diluted exhaust samples were collected in SUMMA® canisters, equipped with flow controllers and subsequently analyzed for TGNMO at Atmospheric Analysis and Consulting (AAC) an off-site laboratory.

PAMS The photochemical assessment monitoring stations (PAMS) measurements are based on the list of 63 ozone forming hydrocarbons tracked by US EPAs network, see list below. AAC also analyzed the SUMMA canisters for volatile organic compounds (VOC's) and benzene, toluene, ethylbenzene and xylene (BTEX) to process the total PAMS impact of the speciated hydrocarbons (HCs). They used the TO-12/PAMS method which provides the data for VOCs including light toxics (BTEX and butadiene) and the PAMS profile needed for air quality modeling. With this method, the analysis provides concentrations of the following hydrocarbons.

Ethylene
Acetylene
Ethane
Propylene
Propane
Isobutane
1-Butane
N-Butane
Trans-2-Butene
Cis-2-Butene
Isopentane
1-Pentane
N-Pentane
Isoprene
Trans-2-Pentene
Cis-2-Pentene
2,2-Dimbutane
Cyclopentane
2,3-Dimenthylbutane
2-Methylpentane
3-Methylpentane
1-Hexane
N-Hexane
Methylcyclopentane
2,4-Dimethylpentane
Benzene
Cyclohexane
2-Methylhexane
2,3-Dimethylpentane
3-Methylhexane
2,2,4-Trimethylpentane
N-Heptane
Methylcyclohexane
2,3,4-Trimethylpentane
Toluene
2-Methylheptane
3-Methylheptane
N-Octane
Ethylbenzene
M/P-Xylenes
Styrene
O-Xylene
N-Nonane
Isopropylbenzene
N-Propylbenzene
M-Ethyltoluene
P-Ethyltoluene
1,3,5-Trimethylbenzene
O-Ethyltoluene
1,2,4-Trimethylbenzene
N-Decane
1,2,3-Trimethylbenzene
M-Diethylbenzene
P-Diethylbenzene
N-Undecane
N-Dodecane

Note in the earlier tanker measurement project, VOC adsorbed molecules starting about C_4 (butadiene) through C_{12}, were collected on a multi-bed carbon bed composed of molecular sieve, activated charcoal, and carbotrap resin. The VOC included toxics such as 1,3 butadiene; benzene; toluene; ethylbenzene and xylenes. This method was not used during this testing campaign.

Aldehydes and ketones: Carbonyls (aldehydes and ketones) were collected on 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA) behind the Teflon filter. A critical flow orifice was used to control the 1.0 LPM flow through the cartridge. Sampled cartridges were sealed and stored at a cold temperature and later extracted using 5 mL of acetonitrile with the liquid then injected into Agilent 1100 series high performance liquid chromatograph (HPLC) equipped with a diode array detector. The HPLC column was similar to a 5µm Deltabond AK resolution (200cm x 4.6mm ID) with upstream guard column. The HPLC sample injection, and operating conditions are set up according to the specifications of the SAE 930142 HP protocol (Siegl, W et al 1993). The DNPH samples were collected from the dilution tunnel. Due to time limitations and sample difficulties only one valid sample was collected.

Metals: The metals analysis was performed on the Teflon PM samples using X-Ray Fluorescence (XRF) from an offline analytical method (EPA IO-3.3 June 1999 methods). The filters were first weighed then sent out for XRF analysis. The method offers analysis of elements (Na through Pb) represented by 38 elements, see Table 2-3. 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.

Table 2-3 List of elements resulting from the XRF analysis

Sodium	Na	Magnesium	Mg	Aluminum	Al	Silicon	Si
Vanadium	V	Chromium	Cr	Manganese	Mn	Iron	Fe
Cobalt	Co	Arsenic	As	Selenium	Se	Bromine	Br
Rubidium	Rb	Phosphorus	P	Strontium	Sr	Palladium	Pd
Silver	Ag	Cadmium	Cd	Lanthanide	Ln	Tin	Sn
Antimony	Sb	Barium	Ba	Lanthanum	La	Titanium	Ti
Lead	Pb	Sulphur	S	Chlorine	Cl	Potassium	K
Calcium	Ca	Mercury	Hg	Nickle	Ni	Copper	Cu
Zinc	Zn	Gallium	Ga	Germanium	Ge	Yttrium	Y
Zirconium	Zr	Molybdenum	Mo				

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 (**utilized**)
2. Carbon Balance Method (not available, lacking measured fuel consumption**)**
3. Air and Fuel Measurement Method (not available)
4. Fuel rate and carbon balance method for exhaust flow (**utilized**)
5. Air Pump method (not possible on boilers, only engines)

Although there are four accepted methods for measuring flow rate, the direct measurement approach was most suitable for boiler testing. Direct exhaust flow measurement is complex and requires long straight sections which are not typically available on OGVs exhaust systems. Thus, direct measurement has not been a preferred method at UCR for engine exhaust flow, where fuel flow measurement has been utilized. For this boiler, there was a suitable straight section for good exhaust flow direct measurement. Thus, direct flow measurement (#1) was utilized for accurate emissions calculations.

The direct measurement system utilized in this project was a type S Pitot tube is used to measure the differential pressure between the counter-flow (static pressure) and parallel-flow (dynamic pressure) directions. This method follows EPA Method 2, see Section 2.4.2 and Appendix E for details.

2.3.4 Boiler

The boiler output was not available for recording and only a single mode was utilized given the short time frame allowed on the vessel. The boiler was operated under normal usage conditions in a high load operation maintaining bulk fuel temperature. It is estimated based on the recorded fuel rate that the boiler load was around 65% of its total capacity.

2.4 Calculations

The calculations are described in this section.

2.4.1 Emission factors

The emissions were collected at the one 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). The result is based on the measured mass flow in the exhaust stack, the measured concentration of species, divided by the fuel rate calculated by the carbon balance method utilizing the MGO fuel as specified in Section 2.1.2. An overall single emission factor representing the boiler was determined by dividing the integrated mass of emissions (g/hr) by the integrated fuel rate (kg-fuel/hr) to get an emission factor of g/kg-fuel for each species presented.

2.4.2 Exhaust flow

The exhaust flow calculation follows EPA Method 2 which utilizes a type S Pitot tube to measure the differential pressure between the counter-flow (static pressure) and parallel-flow (dynamic pressure) directions, see Figure 2-9. Velocity is calculated using Bernoulli's principle, which states that the pressure in a stream of fluid is reduced as the speed of the flow is increased. The velocity calculation is based off of the temperature, molecular weight of the exhaust gas, static pressure, dynamic pressure, and relative humidity. Measurement of the differential pressure and temperature were repeated at the sampling site several times at different depths inside the duct, including the near side of the duct, in the middle of the duct, and the far side of the duct, see Appendix E for detailed exhaust flow calculation.

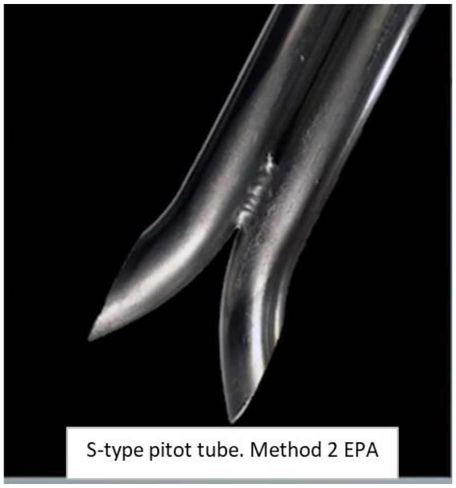

Figure 2-9 S-type pitot tube for EPA Method 2

2.5 Corrections and assumptions

Ship testing is very complex-not everything goes as planned, but given the limited access to these vessels testing continues. The work area is limited to the available space and sample access area. The setup time is constrained by the vessel schedule. The instrument setup is time consuming and requires a complete setup for every vessel, which involves removing instruments transported in boxes, assembling the systems, and verifying all the systems are properly working. This occurs after climbing ladders and finding power and air sources spread out over the vessel.

This section was added to discuss three issues that occurred while testing the boiler. These issues may impact the emissions where this section provides context to the quality of the reported data.

2.5.1 Emissions stability

There was a small stability issue that occurred at the start of sampling that may impact the gaseous emissions slightly and the eBC more significantly. Figure 2-10 shows the real-time gaseous and eBC emissions during the boiler testing with marks indicating when batched samplers were collected. The stability issue can be seen by the slight increase in CO_2 and NO_x concentration for the first hour of testing, see Figure 2-10 between 10:30 and 11:30 (note this was after 1-2 hours of boiler stabilizing). The change in NO_x concentration is small (1 ppm NO_x) and larger for CO_2 (1.5% CO_2), but the Test 1 MSS soot measurement (eBC) is five times higher than the steady state measured soot measurement of Test 2, see the grey trace in Figure 2-10. It is not clear what happened between 10:30 and 11:30, but it seems there was a slight change in fuel usage (CO_2 change) and unstable eBC emission (BC desorption, fueling, or other). There was also an impact in the PM filters as can be seen by the color of the filters, see Figure 2-11. The first filter, Test #1, was darker then Test #2 and #3 supporting what was visible with the real time MSS soot sensor. The overall PM filter mass, however, did not change significantly, as discussed in the next sub section.

Previous testing on a container vessel modern boiler showed that soot concentration (eBC method) was very stable and averaged about 0.01 mg/m3 during the 8 hours of sampling over three separate days (Johnson et al 2019). This would suggest the more representative eBC value is the one between 11:50 and 12:10 for test 1. As such, a re-analysis of the real time data was performed to collect the data for the stable time segment. A re-analysis of the gaseous emissions was also collected for this time period. The original sample durations are shown by orange circles and bars, the modified time segments are denoted by the green circles, see Figure 2-11. The results presented in this are based on the analysis during the green circles. The details of the original and modified data are provided in Appendix F.

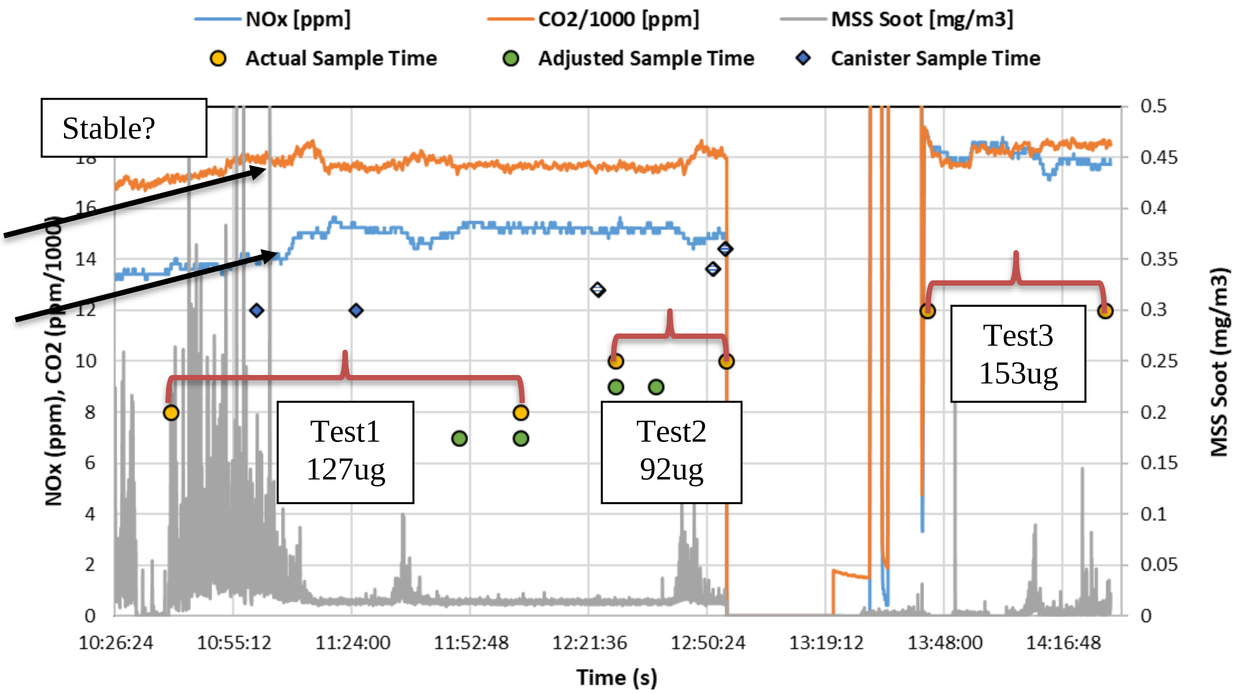

Figure 2-10 Real time emissions for tests 1, 2, and 3

[1] Orange circles are the original sample times for PM filters, The blue triangles are the stop and stop of the SUMA canisters, green are the revised sample averaging times for the eBC and gaseous emissions.

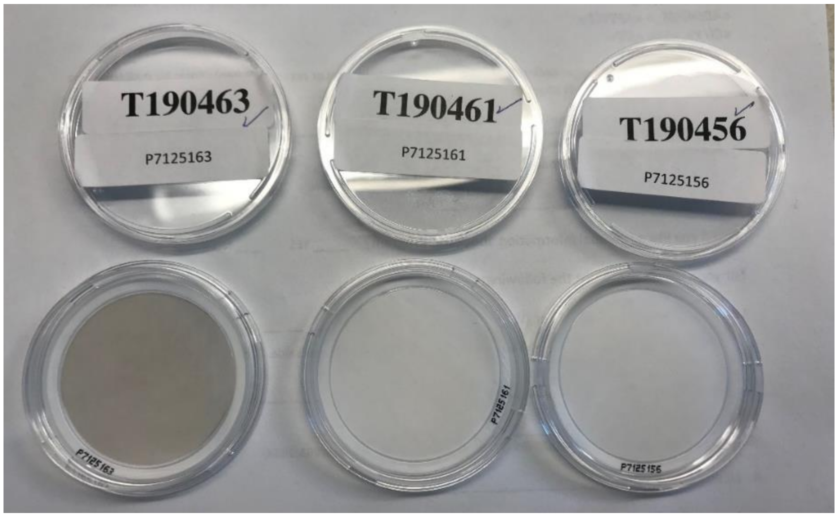

Figure 2-11 Sample filters Test 1, 2, and 3

[1] The filter weights were 127, 153, and 92 ug from left to right.

2.5.2 Filter spotting

During the dilution tunnel installation, the PM cyclone would not fit due to space limitations so it had to be removed, see discussion in Section 2.2.1. Cyclones were introduced into PM samplers to prevent collecting wall accumulated particles, debris in the exhaust, and other objects not emitting directly from the combustion process. Typically, a properly sampled PM filter would not show visible spotting. The spotting on these filters cannot be seen easily with-out some type of magnification, see Figure 2-11 vs Figure 2-12. The mass impact due to the spotting is believed to be small because 2.6% of the total PM resulted from EC and 97.4% was from OC and the spotting would likely be soot based accumulation particles. Additionally, the PM mass for the darker filter is less than the PM mass for the other two filters showing that the color of the filter isn't what is causing the higher PM filter weights.

The results for the PM mass filters are presented "as is" where these values maybe be artificially high by 5% due to the filter # 1 eBC instability and the PM spotting. Also, these PM mass emission rates are similar to the recent boiler UCR tested on a container ship and these PM mass emission rates are much lower than a similar crude tanker tested in 2008 (Agrawal et al 2008), so the data is of value to report.

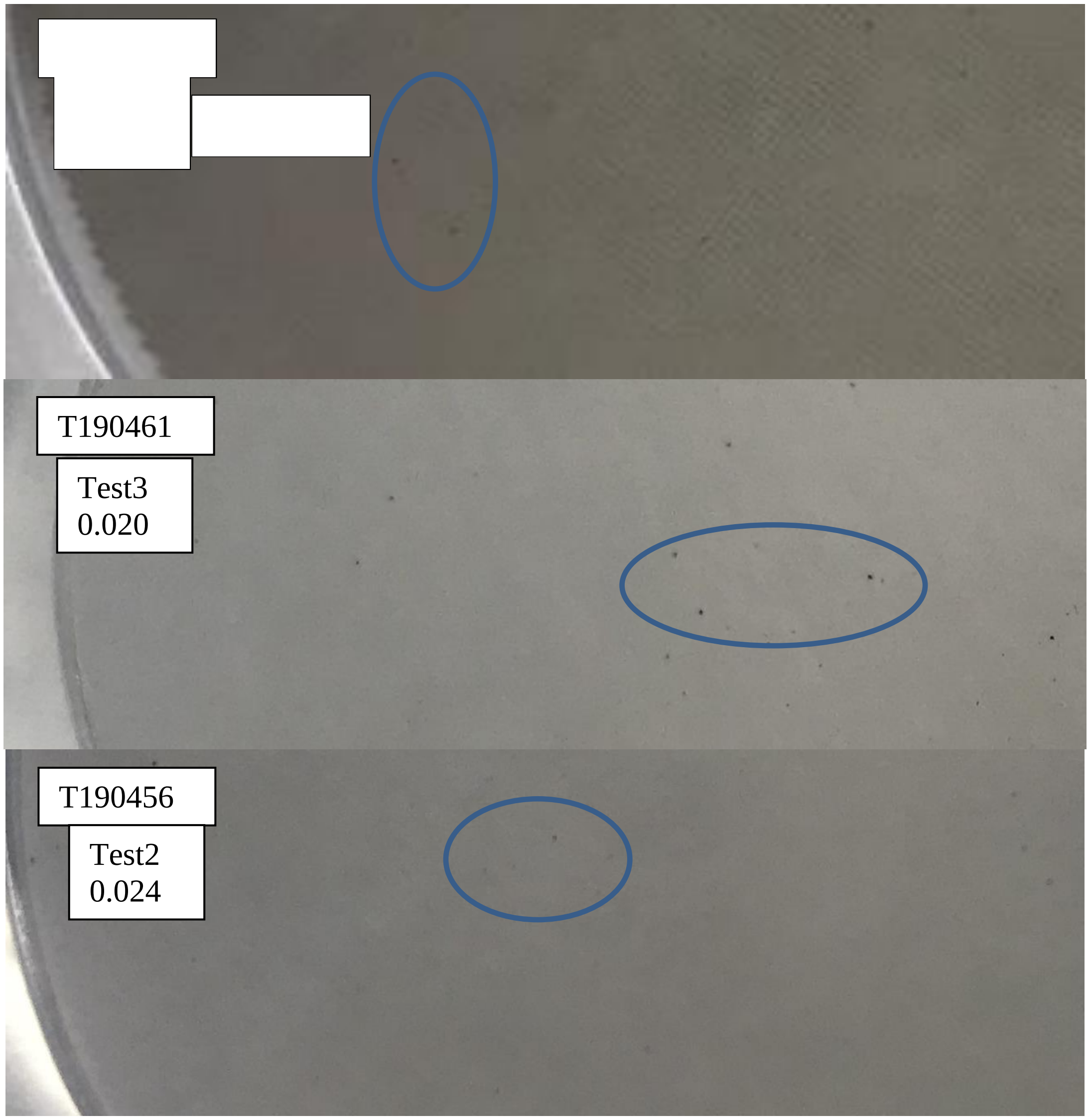

Figure 2-12 Filter spotting for tests 1, 2, and 3 (most observed spotting)

2.5.3 Toxics

SUMA canisters samplers were collected from the dilution tunnel between 11:01 and 12:24 and from the raw exhaust after 12:50, see Table 2-4. The dilute samples resulted in detectable quantities of C2-C4 analytes, but for the raw, undiluted samples, all the analyte responses below C5 were below the Sample Reporting Limit (SRL), see Table 2-5. The EPA 3C analysis showed 1.5% CO2 in the dilute measurement and 10.5% CO2 in the raw stack sample, suggesting the samplers were labeled and analyzed correctly. This suggests there may be a contamination in the dilution air utilized for the dilute BTEX samples.

The raw samples were used in the report analysis and this finding doesn't impact the overall discussion. Future BTEX samples will consider this impact on our sampling system especially when testing for lighter HC fuels.

Table 2-4 Summary of BETX sampling locations

BTEX				
Start Time	Dur	Flow	ID	Comment
hh:mm	min	slpm		
11:01	24	0.5	BTX6123	Dil tunnel
12:24	28	0.5	BTX6121	Dil tunnel
12:52	3	-	BTX6124	Raw stack grab
12:55	3	-	BTX6126	Raw stack grab

Table 2-5 Summary of BTEX concentrations C2-C4 dilute vs stack discussion

Analyte	MM		Diulte		Stack	
			#1	#2	#3	#4
Ethylene	28.1	C2H4	<SRL	<SRL	<SRL	<SRL
Acetylene	26.0	C2H2	1.88	<SRL	<SRL	<SRL
Ethane	30.1	C2H6	3.32	3.12	<SRL	<SRL
Propylene	42.1	C3H6	<SRL	<SRL	<SRL	<SRL
Propane	44.1	C3H8	16.1	9.16	<SRL	<SRL
Isobutane	58.1	C4H10	7.14	10.5	<SRL	<SRL
1-Butene	56.1	C4H8	<SRL	<SRL	<SRL	<SRL
1,3-Butadiene	54.1	C4H6	<SRL	<SRL	<SRL	<SRL
n-Butane	58.1	C4H10	2.24	3.44	<SRL	<SRL

3 Results

The emission results for the Alfa Laval auxiliary boiler installed on a tanker are described in this section. The results are based on the operation of the boiler under in-use conditions during fuel off-load in a Northern California port. The estimated load condition is 65%. There were some data corrections performed and these corrections are explained in Section 2.5. This section presents the results of the final data set, where all data points are available in Appendix F.

The result section is divided into three sub sections: gaseous, PM (PM mass and composition and BC), and toxics. All error bars and standard deviations (stdev) presented are based on one sigma (σ) uncertainty.

3.1 Gaseous

The gaseous emissions include NO_x, CO, CO_2, and SO_2. The SO_2 emissions were both measured and calculated where the calculated values are used in this report due to a sampling issue for SO_2, see Appendix F Figure 1 for details. The gaseous emissions are shown in Table 3-1 (averages), Table 3-3 (stdev) and Figure 3-1. Figure 3-2 shows the NO_x and CO emission per test point. The boiler fuel specific CO_2 ($fsCO_2$) emissions were 3171 g/kg-fuel. This is similar (with-in 2%) to previous testing of a modern auxiliary boiler on a container vessel. The close agreement suggests both boiler tests were performed under similar conditions.

The fuel specific NOx ($fsNO_x$) emissions averaged 3.00 ± 0.18, CO 0.10 ± 0.001, and SO_2 0.96 g/kg-fuel. The $fsNO_x$ emissions were slightly higher, within 50%, to previous testing of a modern container vessel auxiliary boiler tested on low sulfur MGO and ULSFO fuels (0.038 S and 0.089 S respectively) (Johnson et al 2019), but over two times lower (2.2) than the emissions on a tanker vessel auxiliary boiler tested on high sulfur HFO fuel (2.85% S) (Agrawal et al 2008). The CO emissions were 6.9 times lower than the boiler operating on HFO fuel. The boiler SO_2 emissions were lower for the low sulfur fuel compared to a high sulfur HFO fuels, lower by a factor of 58 (Agrawal et al 2008). The main difference is a result of the sulfur weight fraction in the fuel and possibly viscosity differences.

Table 3-1 Summary of Emissions Measured by UCR (ave)

Boiler	Carb. FC	Units	Average Species					
Load	kg/hr		NOx	CO	CO2	calc. SO2	PM2.5	PM_eBC
65%	2537.5	g/hr	7348.5	250.8	7778318	2367.4	55.9	3.1
65%	2537.5	g/kg-fuel	3.00	0.101	3170.6	0.965	0.023	0.0012

Table 3-2 Summary of Emissions Measured by UCR (stdev)

Boiler	Carb. FC	Units	Stdev Species					
Load	kg/hr		NOx	CO	CO2	calc. SO2	PM2.5	PM_eBC
65%	2537.478	g/hr	0.545	0.030	377.581	0.000	0.002	0.0030
65%	2537.478	g/kg-fuel	0.180	0.001	3.401	0.050	0.004	0.0004

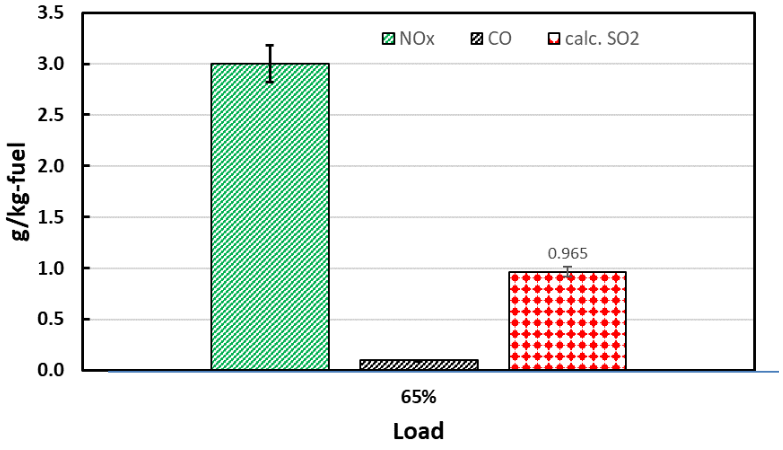

Figure 3-1 Average NOx, CO, and SO2 boiler emissions (g/kg-fuel)

[1] SO_2 is calculated from sulfur in the fuel and fuel usage with error bars for SO2 represented by a fixed uncertainty.

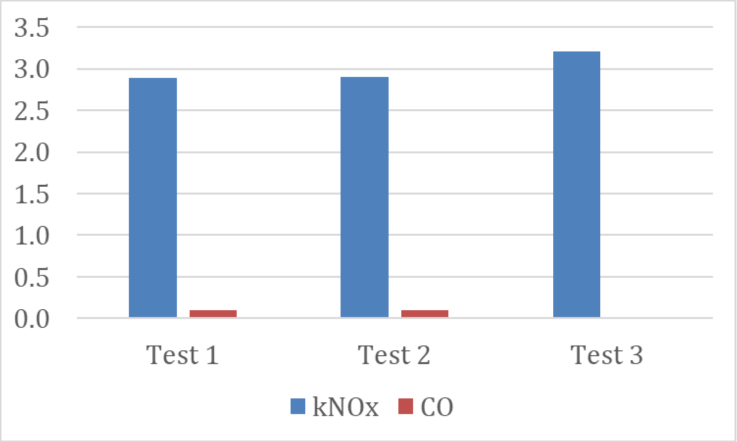

Figure 3-2 NOx, CO, and SO2 boiler emissions (g/kg-fuel), by test

[1] Since SO_2 was calculated from fuel, sulfur it is not in this figure.

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 a description of the PM measurement method and definitions.

The average $PM_{2.5}$ mass and eBC emissions for the boiler are shown in Table 3-3 and Figure 3-3 with the standard deviation data in Table 3-4. Figure 3-4 shows the PM emissions for each test point. The average $PM_{2.5}$ emissions were 0.023 ± 0.004 g/kg-fuel and the eBC emissions were 0.0012±0.0004 g/kg-fuel. The $PM_{2.5}$ emissions were slightly lower, within 50%, to previous testing of a modern auxiliary boiler tested on low sulfur MGO and ULSFO fuels (Johnson et al 2019), but over 100 times lower (131) than the PM emissions on a boiler tested on high sulfur HFO fuel (2.87 g/kg-fuel), (Agrawal et al 2008).

The speciated PM (EC, OC, and Sulfate) emissions are shown in Table 3-3 and Figure 3-3. The PM_EC was 0.59 mg/kg-fuel and the OC_PM was 21 mg/kg-fuel. The fraction of EC compared to the sum of EC+OC is 2.2% suggesting the EC fraction is low for the boiler emissions and OC fractions are larger. The sulfate PM is estimated from the fuel sulfur level at 11 mg/kg-fuel for a fuel sulfur level of 0. 0483%. With the estimated sulfur the PM composition is calculated to be approximately 68.5% organic, 30% sulfate, and 1.5% elemental.

The boiler eBC emissions were higher (70%) than the previous testing of a modern boiler (Johnson et al 2018), but the soot concentration in the stack was similar and near the detection limits of the measurement method. This suggests the difference between the eBC emissions from the two modern boilers may be a result of detection limits and exhaust flow. eBC emissions were not measured with a micro soot sensor during the 2008 tanker testing, but NIOSH EC mass was measured during both testing campaigns. The boiler EC emissions was 235 times lower than the EC emission reported for the tanker operating on high sulfur fuels (Agrawal et al 2008). Johnson has shown the EC measurement method at ratios of EC/OC < 5%, like in Agrawal's study, are less accurate (Johnson et al 2016), thus it is not clear the benefit of the eBC or EC measurement difference between the modern and older boilers.

Table 3-3 Summary of PM composition measured by UCR (ave)

Boiler	Carb. FC	Units	Average Species					
Load	kg/hr		PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor
65%	2537.5	g/hr	1.439	53.772	-	55.211	64.526	65.966
65%	2537.5	g/kg-fuel	0.00059	0.022	0.011	0.033	0.026	0.038

[1] PM_S is represented as hydrated sulfate ions (H20SO46.55H20), PM_TC is the sum of PM_EC+PM_OC+PM_S, PM_ OCcor = 1.2*PM_OC to correct for the hydrogen bonding estimate, and PM_TCcor = PM_EC+PM_OCcor_PM_S and should represent the total PM mass and, thus, be comparable to $PM_{2.5}$

Table 3-4 Summary of of PM composition measured by UCR (stdev)

Boiler	Carb. FC	Units	Stdev Species					
Load	kg/hr		PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor
65%	2537.5	g/hr	0.001	0.004	-	0.003	0.004	0.004
65%	2537.5	g/kg-fuel	0.00033	0.004	-	0.004	0.005	0.004

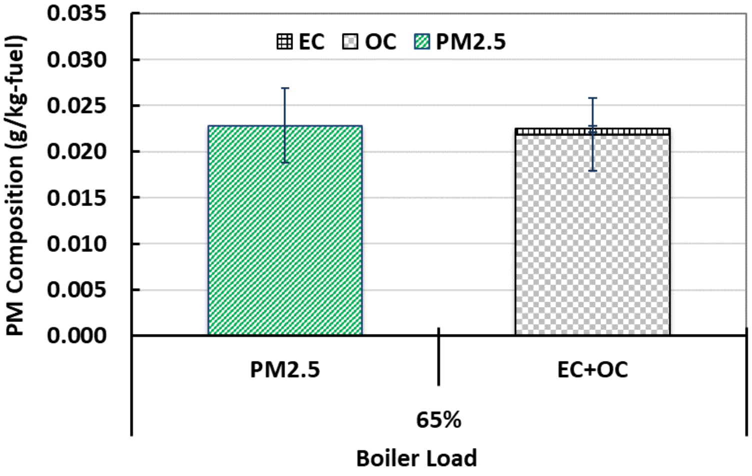

Figure 3-3 Averaged $PM_{2.5}$ and eBC emissions (g/kg fuel)

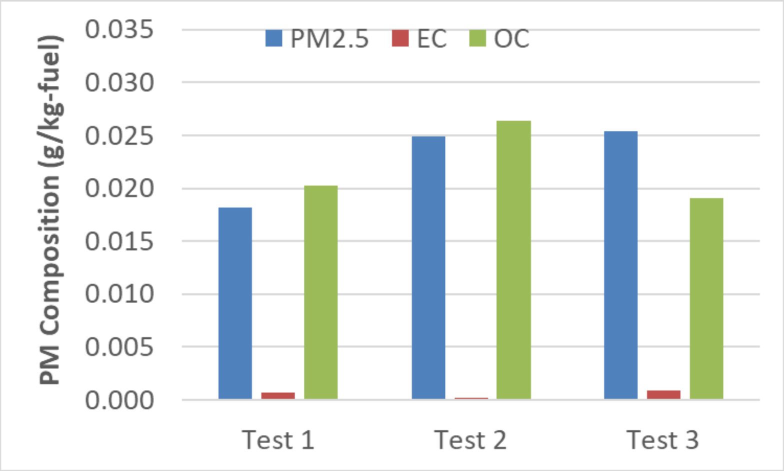

Figure 3-4 $PM_{2.5}$ and eBC emissions (g/kg fuel), by test

3.3 Toxics

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

Aldehydes and ketones: The aldehydes and ketones are presented in Table 3-5. Only Formaldehyde, Acetaldehyde and Acrolein were analyzed, other species were not reported. The boiler emissions for Formaldehyde, Acetaldehyde and Acrolein were 0.422, 0.396, and 1.843 mg/kg-fuel. These results compare well with the modern boiler operating on MGO fuel from a container vessel. Both modern boilers operating on MGO fuel (container and tanker) emission results showed lower Formaldehyde emissions compared to the container boiler emissions when operating on low sulfur HFO fuel. Additionally, modern boilers operating on MGO fuels appear to have lower Acetaldehyde and Acetone emissions compared to the boiler tested by Agrawal (Agrawal et al 2008).

Table 3-5 Average Aldehydes and ketone emissions by fuel by test load.

Fuel	Load	Fuel Use kg/hr	Units	Formaldehyde			Acetaldehyde			Acrolein		
MGO	65%	2537	mg/hr	1053.4	±	-	989.1	±	-	4598.1	±	-
MGO	65%	2537	mg/kg-fuel	0.422	±	-	0.396	±	-	1.843	±	-

[1] Statistical student t.test was not performed due to only one sample collected. Expected uncertainty is ± 15%.

BTEX speciated hydrocarbons: The total PAMS, total non-methane hydrocarbons (TNMHC), ROG and selected species are presented in Table 3-6. The total PAMS were low and just above the Sample Report Limit (SRL) at 2 ppb and the total NMHC were 249 ppb on average. On a mass basis, the total PAMS and TNMHC (TNMHC represents reactive organic gases ROG) were 0.0108 and 1.68 mg/kg-fuel, see Table 3-7. Other selected speciated HCs (C4-C8) are shown in Table 3-7 which were all below the SRL where the values reported represent an upper limit to their measurement this is why they are reported with the "<" sign. The speciated HCs (C4-C8) are higher during this modern boiler test compared to those reported by Agrawal (Agrawal et al 2008). One reason for the higher emissions in this testing may be due to different sample detection limits between the laboratories. The full report of speciated HCs (C2-C12) is provided in

Appendix F. Also, during the previous study, Polycyclic aromatic hydrocarbons (PAHs) were collected which were not collected in this study so that comparison is not available.

Table 3-6 EPA 3C, total PAMS, and TNMHC results, raw stack

Analyte	Stack EPA 3C		
	#1	#2	Ave
Dilution Factor	1.97	1.79	1.88
H2	<2.0%	<1.8%	<1.8%
Ar/O2	7.5%	7.5%	7.5%
N2	82.0%	82.0%	82.0%
CO	<0.2%	<0.2%	<0.2%
CO2	10.4%	10.5%	10.5%
CH4	<0.2%	<0.2%	<0.2%
1,3 Butadiene (ppbC)	<SRL	<SRL	<SRL
Total PAMS (ppbC)	1.99	2.04	2.02
TNMHC (ppbC)	309	189	249

Table 3-7 Selected speciated hydrocarbons (C4-C8) mg/kg-fuel

Analyte	Conc. ppb	mg/kg-fuel
1,3-Butadiene	<SRL	< 0.00987
Benzene	<SRL	< 0.00951
Toluene	<SRL	< 0.00961
m/p-Xylenes	<SRL	< 0.00969
Ethylbenzene	<SRL	< 0.00969
o-Xylene	<SRL	< 0.00969
Total PAMS	2.02	0.01084
TNMHC	249.0	1.683

[1] Total PAMS and TNMHC utilized propane for molar mass. For other species see Appendix F for the full list

Metals: Selected metal results for the boiler at 65% load are shown in Table 3-8 and Table 3-9. The full list of metal results can be found in Appendix F. Only ten metals showed emissions above detection limits. Sulphur showed the highest emissions at 3.59 mg/kg-fuel. This accounted for nearly 62% of the total metal emissions. Silicon showed the next highest emission rate followed by Calcium at 1.04 and 0.18 mg/kg-fuel, respectively. Chromium, phosphorus, copper, vanadium, iron, nickel, and zinc also showed detectible emissions. These results compare well with the metal emission rates of the modern auxiliary boiler operating on MGO fuel from a container vessel, but were over 99% lower than the emissions from a boiler operated on HFO fuel (Agrawal et al 2008).

Table 3-8 Average selected metals with 1 σ error bars, 1 of 2

Fuel	Units	Cr			Cu			Si			P			S		
MGO	mg/hr	60.4	±	26.7	27.0	±	5.8	2593.8	±	460.0	167.0	±	30.5	8960.0	±	1672.4
MGO	mg/kg-fuel	0.02	±	0.01	0.01	±	0.00	1.04	±	0.18	0.07	±	0.01	3.59	±	0.67

Table 3-9 Average selected metals with 1 σ error bars, 2 of 2.

Fuel	Units	Ca			V			Fe			Zn			Ni		
MGO	mg/hr	458.3	±	39.0	358.2	±	8.6	312.5	±	108.0	143.4	±	29.7	54.6	±	9.8
MGO	mg/kg-fuel	0.18	±	0.02	0.14	±	0.00	0.13	±	0.04	0.06	±	0.01	0.02	±	0.00

4 Discussion (g/kWhr)

The auxiliary boiler emission comparison between historical data and the 2019 UCR measurements are presented in this section. Table 4-1 shows the results from the ENTEC study (2002), the CARB At-Berth baseline, and the CARB At-Berth regulation in units of g/kWhr (CARB 2019). The emission factors from the Suezmax tanker and the 13,000 TEU container vessel auxiliary boilers are also presented in Table 4-1, but in their measured units of g/kg-fuel. If we assume that a boiler operates at a brake specific CO_2 emission of 970 g/kWhr, as reported by ENTEC (2002), and we utilize the measured carbon weight fraction of the MGO fuel of 0.8682 (see Appendix D, Figure D-5) the conversion from kg-fuel to g/kWhr is 0. 3058. Thus, to convert from 0.035 gPM/kg-fuel we multiply by 0.3058 kg-fuel/kWhr which equals 0.011 g/kWhr, see Table 4-1.

The brake specific emissions from the Suezmax tanker are 0.007, 0.917, and 0.006 g/kWhr for $PM_{2.5}$, NO_x, and ROG, respectively. The brake specific emissions from the container vessel are 0.011 and 0.5 g/kWhr for $PM_{2.5}$ and NO_x, respectively. ROG was not collected on the container vessel, but is expected to have similar ROG emissions as the tanker because both auxiliary boilers were from Alfa Laval, they used similar fuels, and the gaseous and PM emissions were relatively similar.

Table 4-1 Summary of auxiliary boiler emissions and regulations (g/kWhr and g/kg-fuel)

Source	Source Year	Type	Units	Fuel S	PM10	PM2.5	Nox	SOx	CO	HC
ENTEC 2002	1980	Land	g/kWhr	0.047	0.132	0.095	2.00	0.300	0.200	0.1000
ENTEC 2002	1980	Land	g/kWhr	0.1		0.100	2.00			0.1000
At-berth Baseline	1980	Land	g/kWhr	0.1		0.170	2.00			0.1100
At-berth Reg 80%	1980	Land	g/kWhr			0.030	0.40			0.0200
UCR Meas	2019	12,000 TEU	g/kg-fuel	0.047		0.035	1.64	0.064	0.056	-
			g/kWhr			0.011	0.500	0.020	0.017	-
UCR Meas	2019	Suezmax	g/kg-fuel	0.047		0.023	3.00	0.965	0.067	0.0020
			g/kWhr			0.007	0.917	0.295	0.021	0.0006

[1] The "At-Berth Baseline" was taken from the CARB 2019 At-Berth draft regulation where the $PM_{2.5}$ baseline is reported at 0.17 g/kWhr (assuming 0.1% fuel sulfur). The "At-Berth Reg 80%" represents the regulatory emissions limits for future at-berth boiler emissions which is set to 0.03 g/kWhr for $PM_{2.5}$.

5 Summary

Emissions measurements were made on a modern auxiliary boiler on a tanker ship while it offloads fuel within a port in Northern California while the main engine was off. The auxiliary boiler was operated on California approved MGO low sulfur fuel and operated at an estimated 65% load. Emissions were measured following ISO and CFR methods for gaseous, and PM (total mass, elemental, and organic carbon species, sulfated PM). Boiler sampling also included toxics to help CARB update its 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 slightly unstable at the start of testing, but were found to be stable for the segments analyzed. The reported data set is representative of valid measurements suggesting the results are representative of a properly operating boiler.
- The boiler fuel flow rate was meausred at 2,495 kg/hr utilizing the measured value provided by the vessel crew. This agrees well with the directly measured exhaust derived fuel flow rate of 2501-2621 kg/hr. The corresponding exhaust flow at the 2,495 kg/hr fuel rate was 38,500 m3/hr.
- The boiler $fsCO_2$ emissions were 3172 g/kg-fuel. This is similar to previous testing of a modern auxiliary boiler on a container vessel.
- The boiler fuel specific SO_2 ($fsSO_2$) emissions averaged 3.00 ± 0.18, CO 0.10 ± 0.001, and SO_2 0.965 g/kg-fuel. The $fsNO_x$ emissions were slightly higher, within 50%, to previous testing of a modern container vessel auxiliary boiler tested on low sulfur MGO and ULSFO fuels, but over two times lower (2.2) than the emissions on a tanker vessel auxiliary boiler tested on high sulfur HFO fuel. The CO emissions were 6.9 times lower than the boiler operating on HFO fuel.
- The boiler $fsSO_2$ emissions were lower for the low sulfur fuel (0.045% S) compared to a high sulfur HFO (2.85 % S) fuels by a factor of 58
- Fuel specific $PM_{2.5}$ ($fsPM_{2.5}$) emissions were 0.023 ± 0.004 g/kg-fuel and were slightly lower to previous testing of a container vessel modern auxiliary boiler tested on low sulfur MGO and ULSFO fuels, but over 100 times lower (131) than the $PM_{2.5}$ emissions on a tanker auxiliary boiler tested on high sulfur HFO fuel. The main difference between boiler PM emissions on low and high sulfur fuels is the sulfur content of the fuel.
- The fuel specific eBC (fseBC) emissions were 0.0012±0.0004 g/kg-fuel and were about the same for a previous container vessel modern auxiliary boiler tested, but about 120 times lower than the fuel specific EC (fsEC) emission reported for an older tanker auxiliary boiler tested on a tanker operating on high sulfur HFO fuel. The methods were not the same and there may be questions for this large difference.
- The fuel specific PM (fsPM) composition (EC, OC, and Sulfate) were 0.56, 22, and 11 mg/kg-fuel (1.5%, 69%, and 29%) respectively. The sulfute PM emissions were calculated based on fuel sulfur levels.

- The metals emissions were low and near detection limits except for 10 metals. The highest emitter was Sulphur at 3.59 mg/kg-fuel. Silicon, Zinc, Calcium, Vanadium, Iron, Phosphorus, Nickle, Copper and Chromium were all above the detection limit as well. These reults compare well with the modern boiler operating on MGO fuel test from a container vessel
- The brake specific emissions from the Suezmax tanker are 0.007, 0.917, and 0.006 g/kWhr for $PM_{2.5}$, NO_x, and reactive organic gases (ROG), respectively. The conversion from fuel specific to brake specific emissions assumes the $bsCO_2$ emissions are 970 g/kWhr and the fuel carbon weight fraction is 0.8682.
- The boiler emissions for formaldehyde, acetaldehyde and acrolein were 0.422, 0.396, and 1.84 mg/kg-fuel. These results compare well with the modern boiler operating on MGO fuel test from a container vessel. Modern boilers operating on MGO fuels appear to have lower Acetaldehyde and Acetone emissions compared to older boiler tested on HFO fuels.
- The total speciated HCs (C2-C12) PAMS and TNMHC were 0.0108 and 1.68 mg/kg-fuel. The PAMS measurements were at the detection limit of the measurement method and thus, could not be compared properly to the previous testing on an older boiler tested on a high sulfur HFO fuel.

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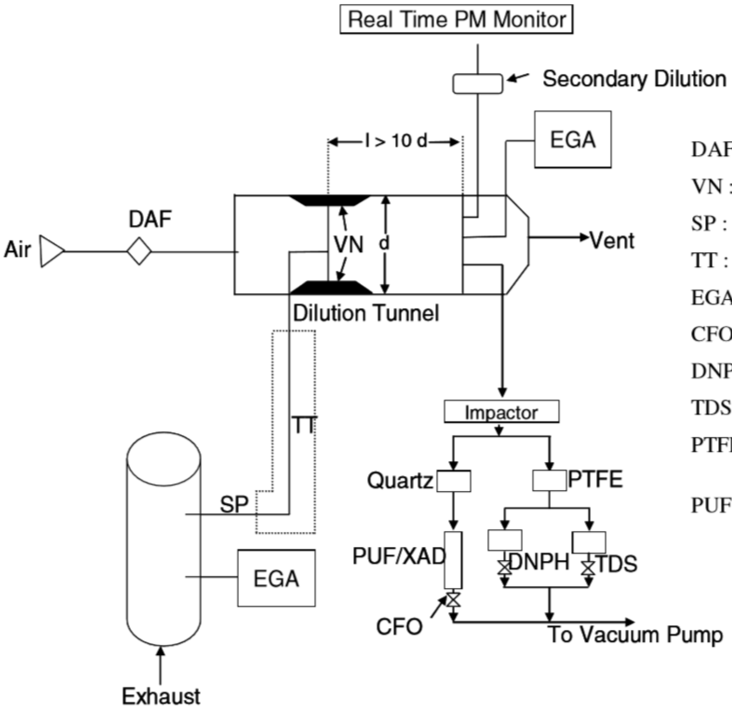
Appendix A – Sample Collection Methods

ISO 8178-1[10] and ISO 8178-2[11] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with variations of engine load and speed provided in ISO 8178- *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[12], 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.



DAF : Dilution Air Filter
VN : Venturi
SP : Sampling Probe
TT : Transfer Tube
EGA : Emission Gas Analyzer
CFO : Critical Flow Orifice
DNPH : 2,4Dinitrophenylhydrazine
TDS : Thermal Desorption System
PTFE : Polytetrafluoroethylene (Teflon)
PUF : Poly Urethene Foam

Figure A-1 Partial Flow Dilution System

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[10] 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

[11] 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

[12] 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.

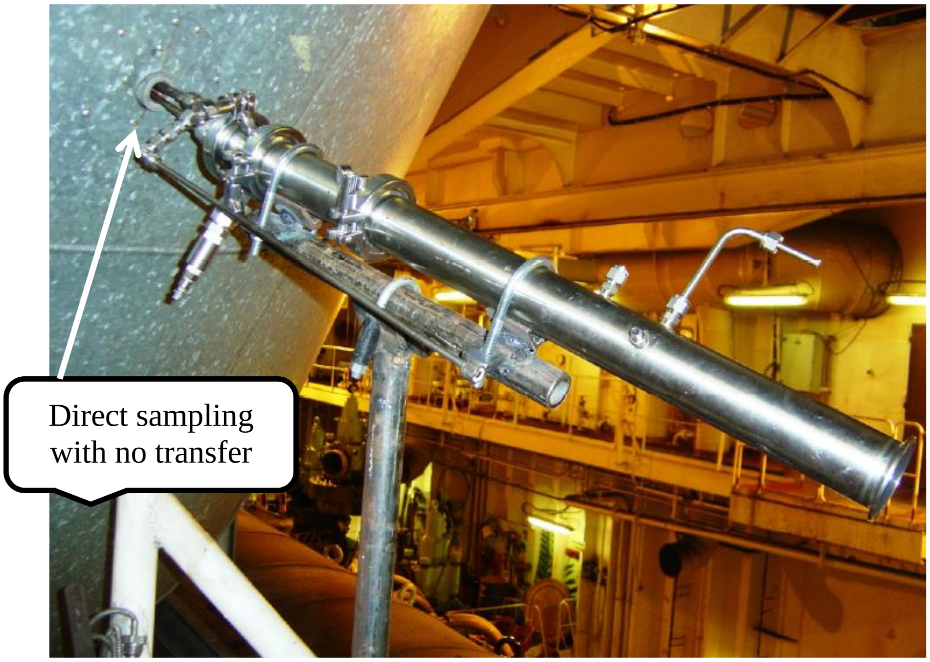


Figure A-2 measurement layout on an engine exhaust stack

Dilution Air System

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

Table A-1 Components of a Sampling System: ISO Criteria & UCR Design

Section	Selected ISO and IMO Criteria	UCR Design
Exhaust Pipe (EP)	In the sampling section, the gas velocity is > 10 m/s, except at idle, and bends are minimized to reduce inertial deposition of PM. Sample collection of 10 pipe diameters of straight pipe upstream is recommended and performed where possible. For some tight configurations use good engineering judgment.	UCR follows the ISO recommendation, when practical.
Sampling Probe (SP) -	The minimum inside diameter is 4 mm and the probe is an open tube facing upstream on the exhaust pipe centerline. No IMO code.	UCR uses a stainless steel tube with diameter of 8mm placed near the center line.
Transfer Tube (TT)	• As short as possible and < 5 m in length; • 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 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, 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.

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

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

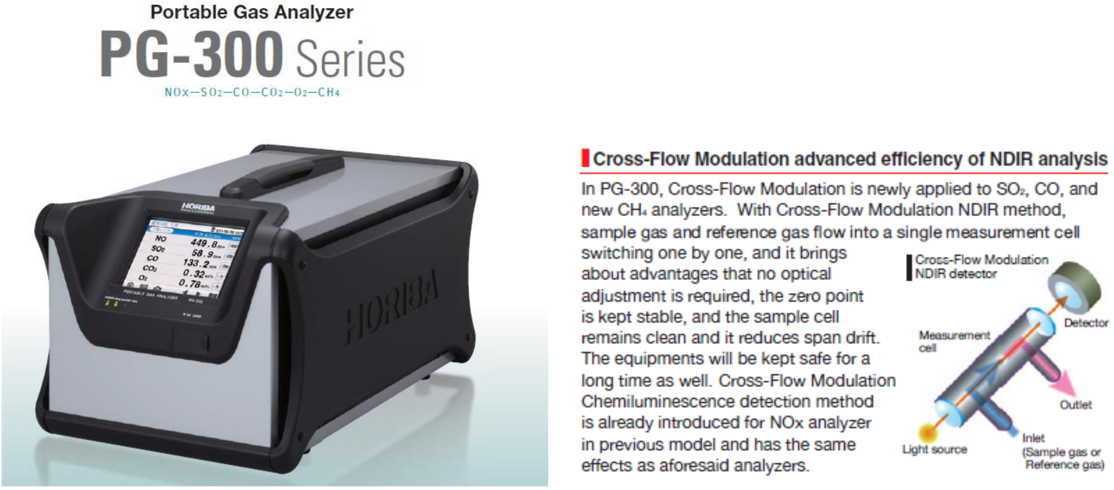
ISO outlines their verification method. Each operating range is checked prior to analysis by using a zero gas and a span gas whose nominal value is more than 80% of full scale of the measuring range. If, for the two points considered, the value found does not differ by more than ±4% of full scale from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

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

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

Measuring Gaseous Emissions: UCR Design

The concentrations of CO, CO_2, NO_x and O_2 in the raw exhaust and in the dilution tunnel are measured with a Horiba PG-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.



Cross-Flow Modulation advanced efficiency of NDIR analysis

In PG-300, Cross-Flow Modulation is newly applied to SO_2, CO, and new CH_4 analyzers. With Cross-Flow Modulation NDIR method, sample gas and reference gas flow into a single measurement cell switching one by one, and it brings about advantages that no optical adjustment is required, the zero point is kept stable, and the sample cell remains clean and it reduces span drift. The equipments will be kept safe for a long time as well. Cross-Flow Modulation Chemiluminescence detection method is already introduced for NOx analyzer in previous model and has the same effects as aforesaid analyzers.

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.

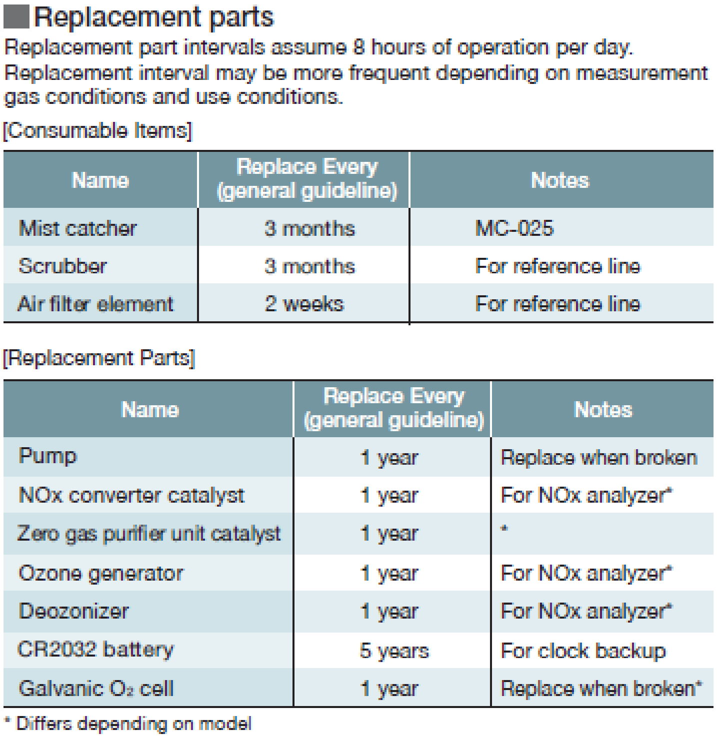
Table A-2 Detector Method and Concentration Ranges for Monitor

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-250

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^{TM} 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 a real-time digital readout and has a built-in data logger. It measures light scattered (90-degree light scattering at 780nm near-infrared) by an 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. This same tunnel was used for DNPH and Canister samples. In addition, UCR collected raw grab samples of the emissions stack.

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

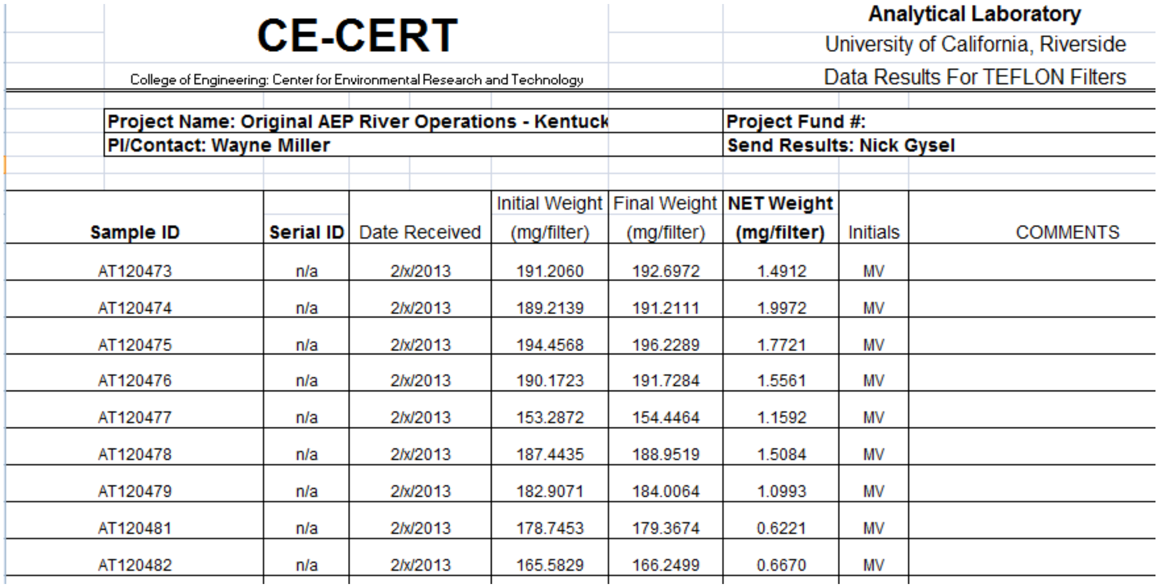
Pre- and post-test calibrations were performed on the gaseous analyzer using NIST traceable calibration bottles. Dilution ratio was monitored and verified at least twice each test day. Leak checks were performed for the total $PM_{2.5}$ system prior to testing for each setup.

Post-test and data validation

Post-test evaluation includes verifying consistent dilution ratios between points and data is compared to other test conditions that are similar.

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, BTEX, and EC/OC. This is 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

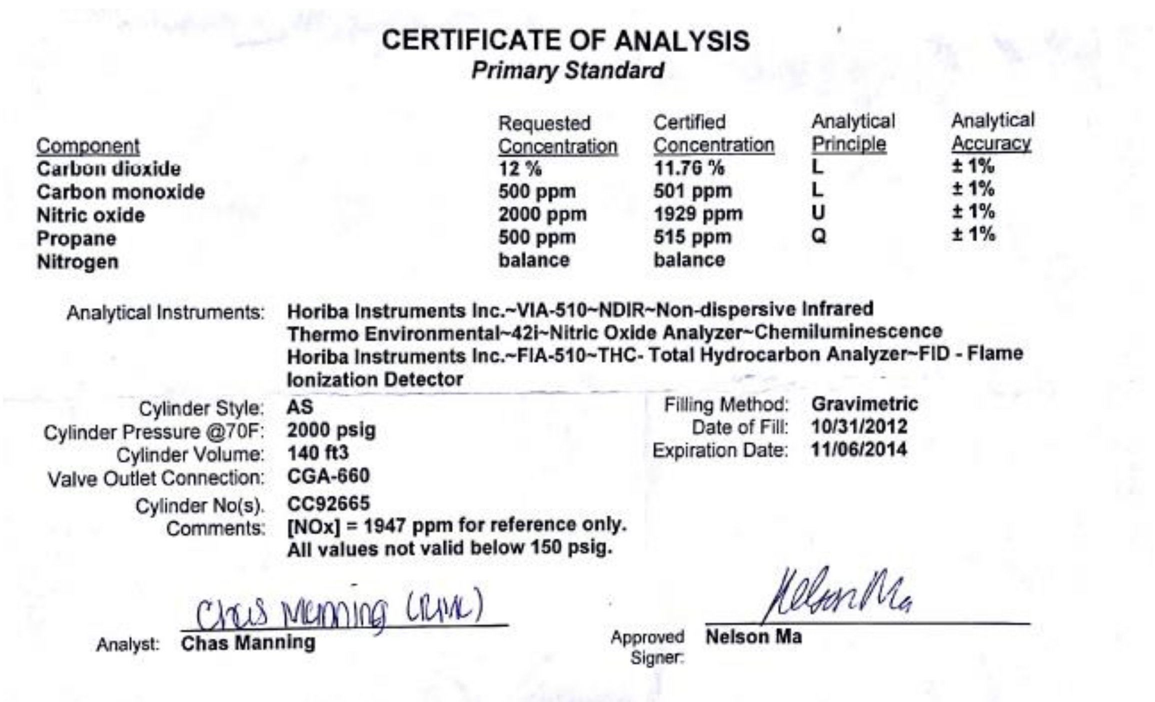
College of Engineering: Center for Environmental Research and Technology

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 example



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 (RMK)
Analyst: **Chas Manning**

Nelson Ma
Approved Signer: **Nelson Ma**

Figure B-2 One percent sample protocol gas analysis example

Appendix C –Test Assumptions

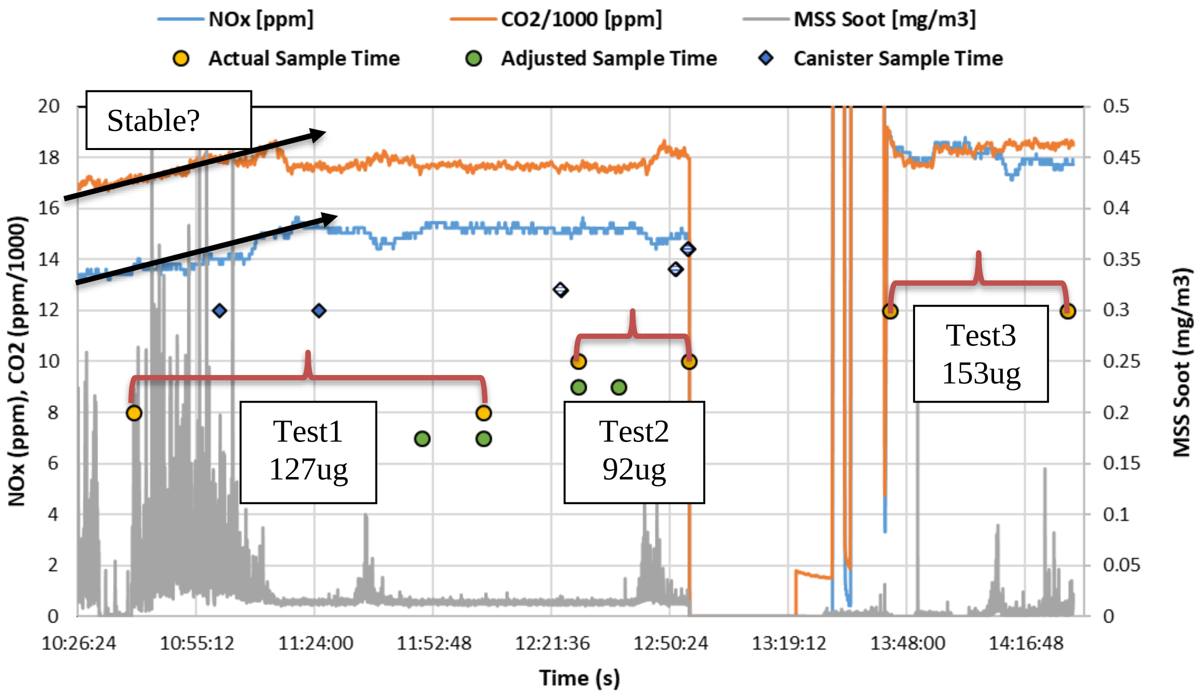


Figure C-1: Real Time Response for selected emissions species with test notes

Initial sample times were chosen based on previous projects and soot levels. Initial sampling was started as soon as possible with a total sample time of 75 minutes. During the second test, a power failure on the ship cut testing short for a total sample time of 27 minutes. The final test sample was started as soon as power was restored and lasted as long as possible for a total testing time of 43 minutes. The real time data shows that all sample times experienced unstable data trends. The first test experienced unstable CO2, NOx, and Soot data at the beginning of the test most likely due to the boiler not being fully warmed up. The second test experienced soot, NOx, and CO2 spikes toward the end of the test. The third test showed elevated levels of CO2 and NOx for unknown reasons.

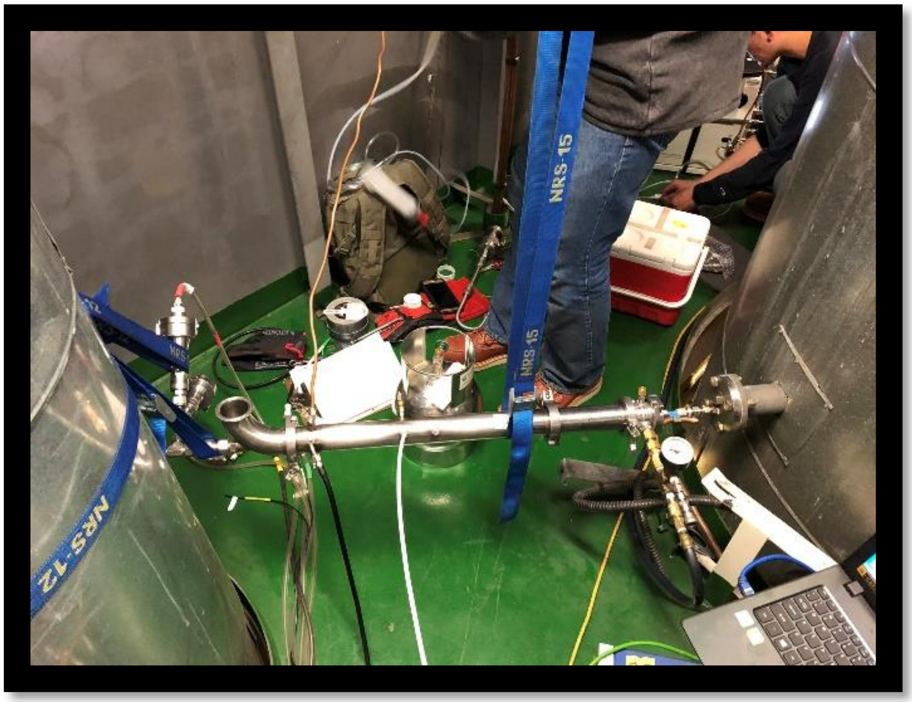


Figure C-2 Installation showing removal of cyclone.

Due to the unstable nature of all 3 test points, modified sampling times were used to capture stable data during the course of testing. PM results were averaged with the soot data from the original tests, and a weighting factor was used to calculate PM mass of the modified sample times.

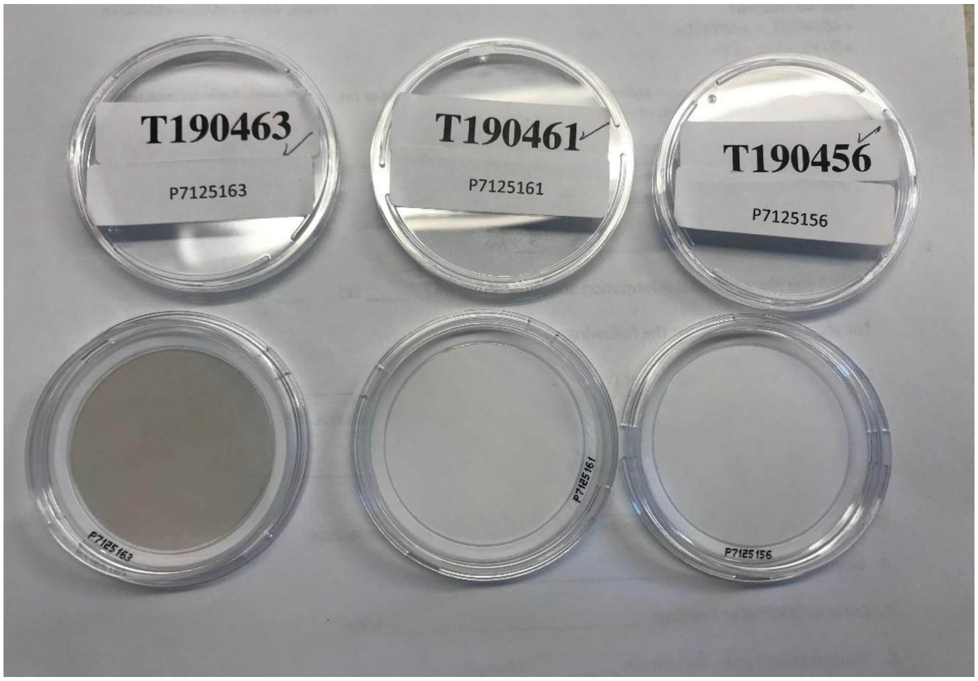


Figure C-3 Sample filters Test 1, 2, and 3

[1] The filter weights were 127, 153, and 92 ug from left to right.

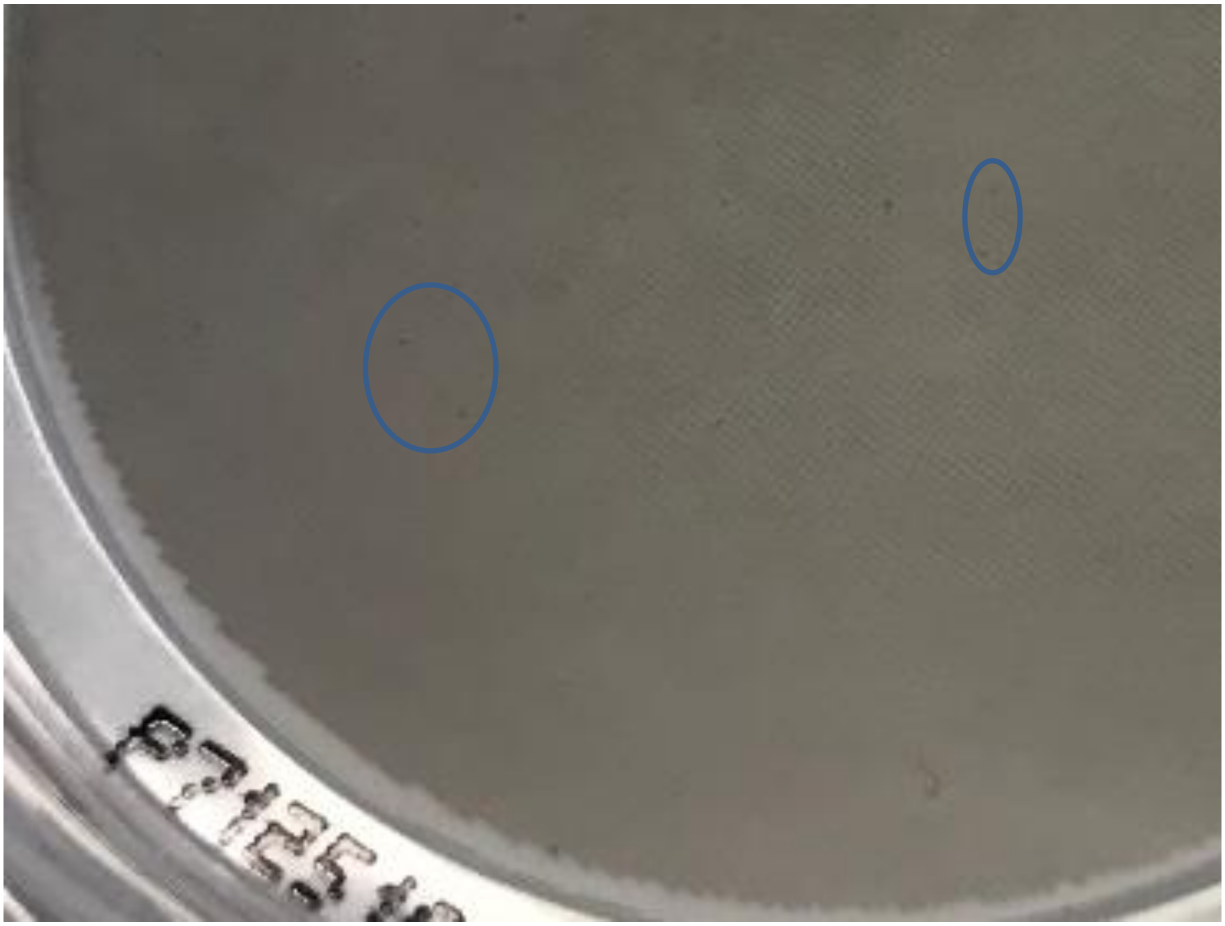


Figure C-4 Sample filter T190463 (medium spotting)


Figure C-5 Sample filter T190461 (heavy-ish spotting)

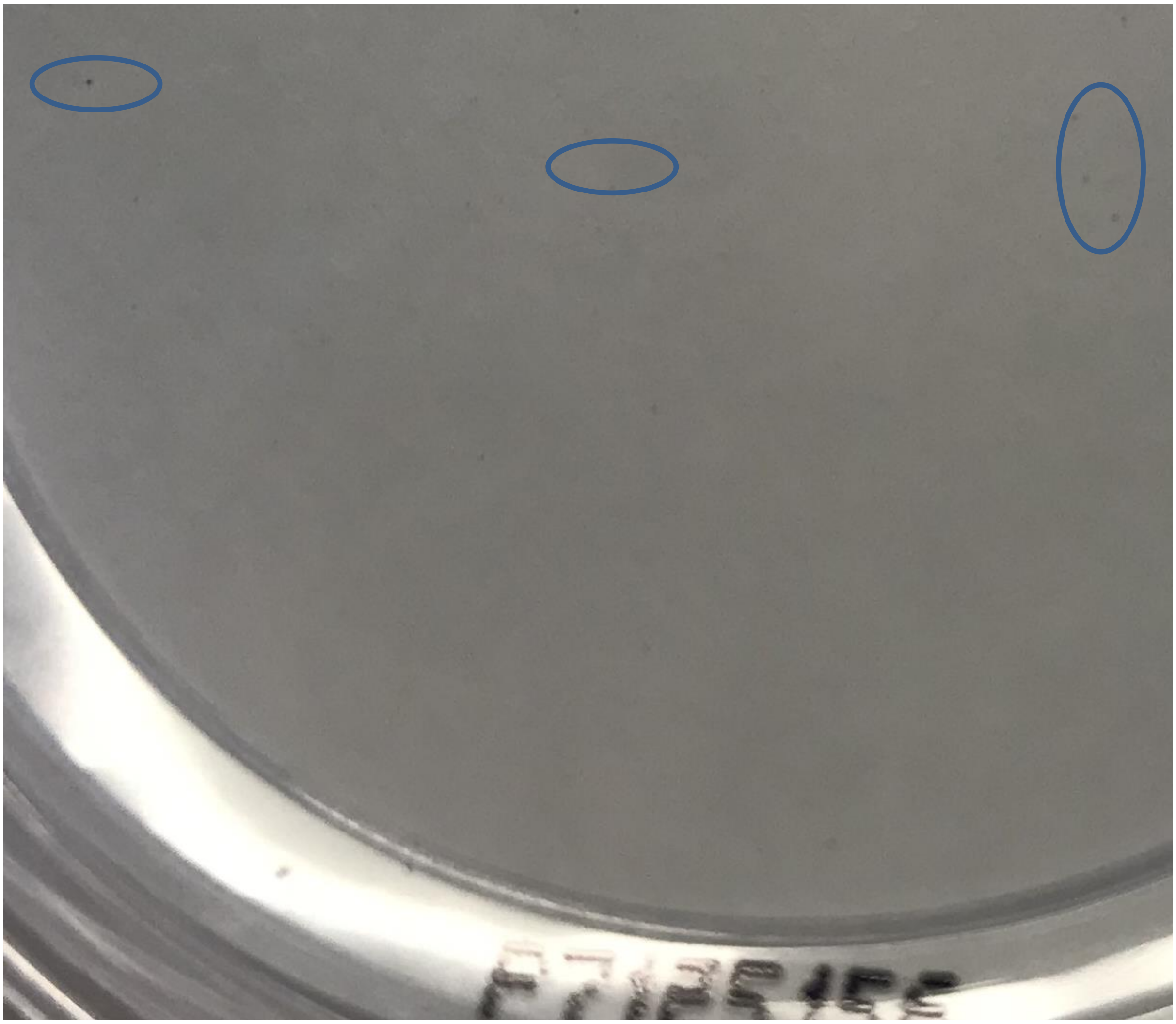
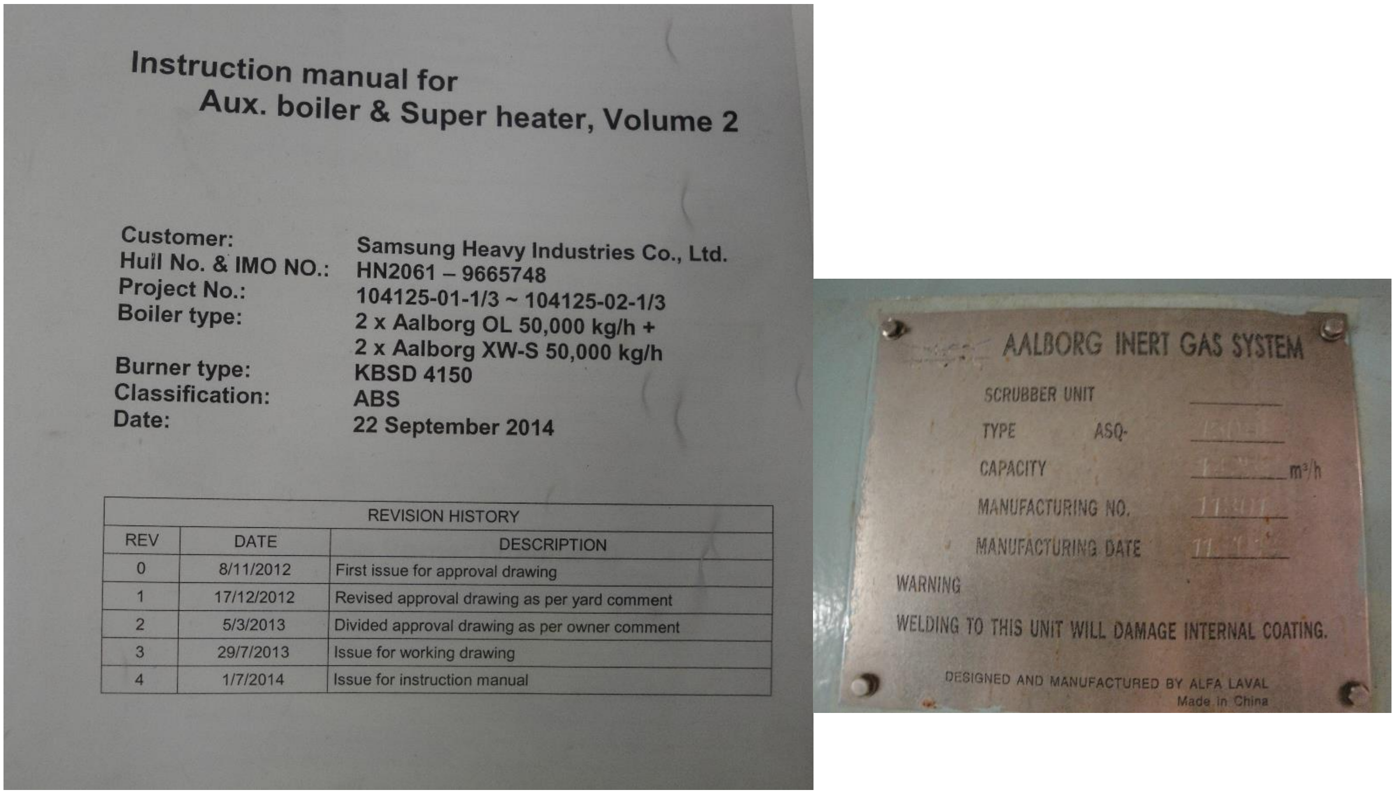


Figure C-5 Sample filter T190456 (light spotting)

Appendix D –Test Details and Data Records

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

- **Boiler records –** The boiler records are shown in Figure D-1 through 4. The Aalborg OL boiler is a vertical two-drum boiler, insulated and pre-assembled. The boiler is top-fired and equipped with steam atomization burner. The control of the burner is fully automatic for the boiler systems and the steam atomizing burner. The boiler is equipped with a super heater, Figure D3, where a wire mesh is utilized to “sponge” and dry the steam before vessel usage. The Source for this information is from the Aalborg OL Boiler SD9210_04#B.1 instruction manual as found on the vessel.
- **Fuel analysis** A fuel sample was collected during our testing and sent out for analysis. The results are shown in the Figure D5.
- **Speciated sample analysis forms.** A copy of the samples sent to the AAC and the methods utilized are shown in figure D6, but integrated results are summarized in Appendix F.



Instruction manual for
Aux. boiler & Super heater, Volume 2

Customer: Samsung Heavy Industries Co., Ltd.
Hull No. & IMO NO.: HN2061 – 9665748
Project No.: 104125-01-1/3 ~ 104125-02-1/3
Boiler type: 2 x Aalborg OL 50,000 kg/h + 2 x Aalborg XW-S 50,000 kg/h
Burner type: KBSD 4150
Classification: ABS
Date: 22 September 2014

REVISION HISTORY		
REV	DATE	DESCRIPTION
0	8/11/2012	First issue for approval drawing
1	17/12/2012	Revised approval drawing as per yard comment
2	5/3/2013	Divided approval drawing as per owner comment
3	29/7/2013	Issue for working drawing
4	1/7/2014	Issue for instruction manual

Figure D-1 Boiler specifications (Aalborg OL Boiler SD9210_04#B.1)

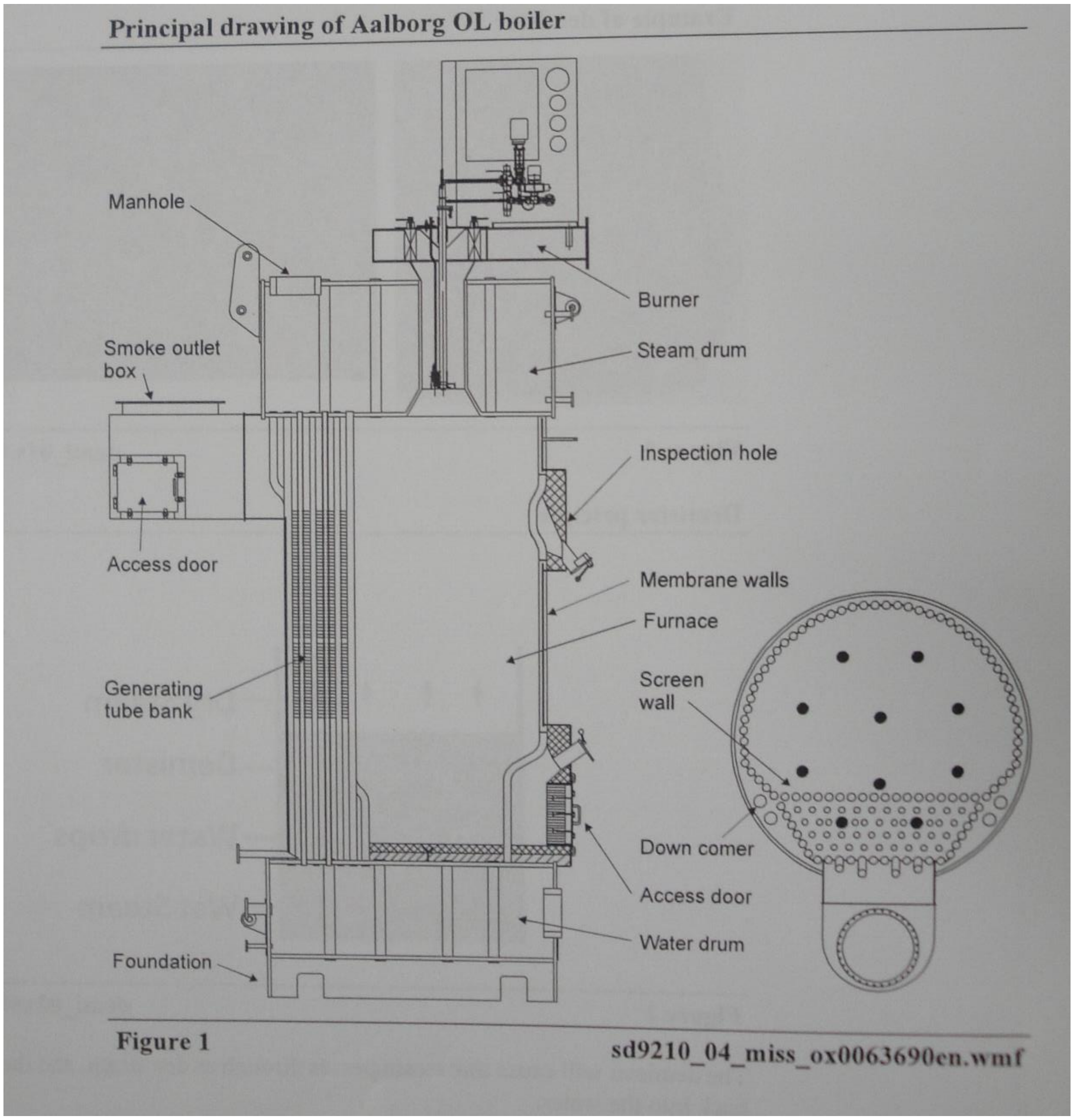


Figure D-2 Boiler layout and details (Aalborg OL Boiler SD9210_04#B.1)

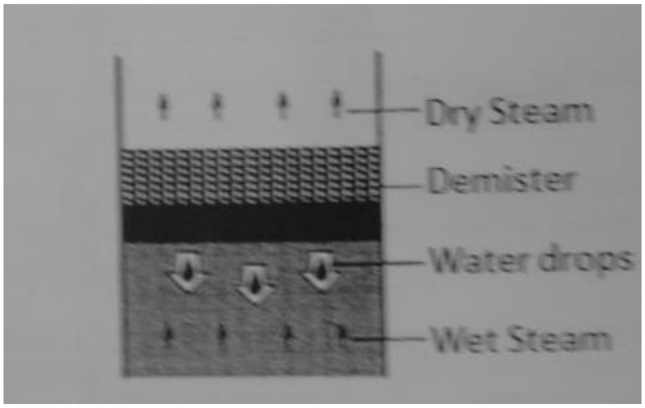
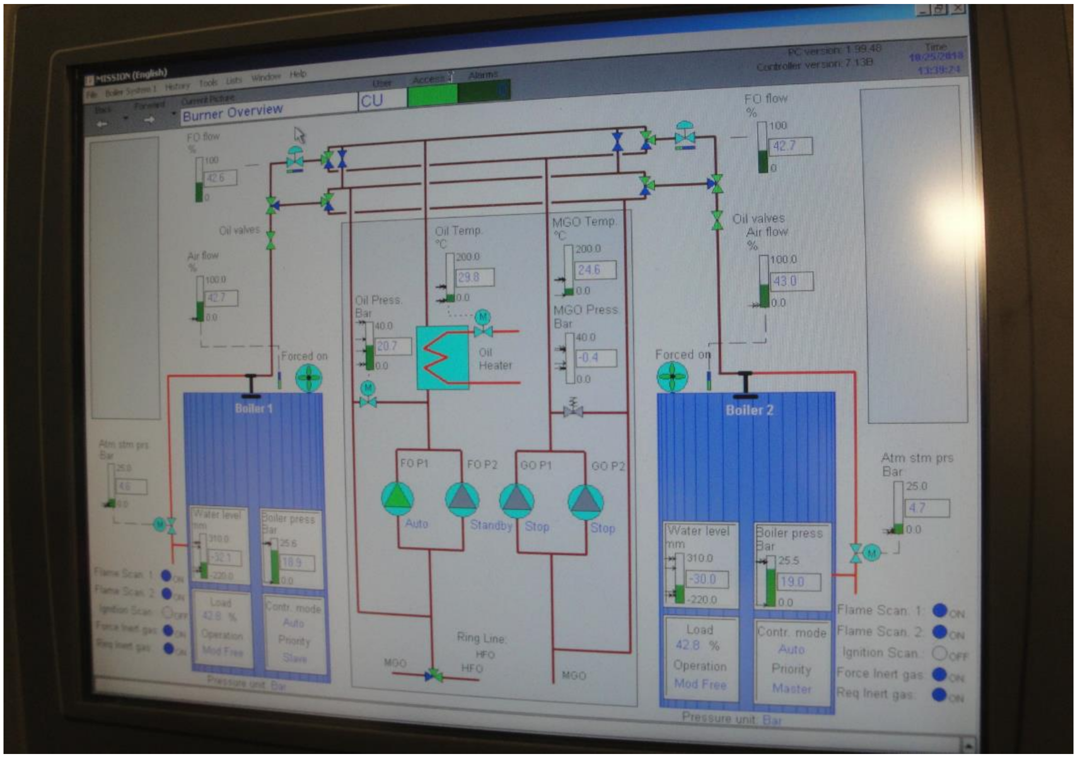


Figure D-3 Boiler layout and details (Aalborg OL Boiler SD9210_04#B.1)



Burner Overview

CU

PC version: 1.99.48

Controller version: 7.13B

Time 10/25/2018 13:39:24

FO flow % 100 42.6 0

Air flow % 100.0 42.7 0.0

Atm stm prs Bar 25.0 4.6 0.0

Water level mm 310.0 -32.1 -220.0

Boiler press Bar 25.6 18.9 0.0

Load 42.8 %

Operation Mod Free

Contr. mode Auto

Priority Slave

Flame Scan 1: ● ON

Flame Scan 2: ● ON

Ignition Scan: ○ OFF

Force Inert gas: ● ON

Req Inert gas: ● ON

Pressure unit: Bar

Oil Temp. °C 200.0 29.8 0.0

Oil Press. Bar 40.0 20.7 0.0

MGO Temp. °C 200.0 24.6 0.0

MGO Press. Bar 40.0 -0.4 0.0

FO P1 Auto

FO P2 Standby

GO P1 Stop

GO P2 Stop

FO flow % 100 42.7 0

Air flow % 100.0 43.0 0.0

Atm stm prs Bar 25.0 4.7 0.0

Water level mm 310.0 -30.0 -220.0

Boiler press Bar 25.5 19.0 0.0

Load 42.8 %

Operation Mod Free

Contr. mode Auto

Priority Master

Flame Scan 1: ● ON

Flame Scan 2: ● ON

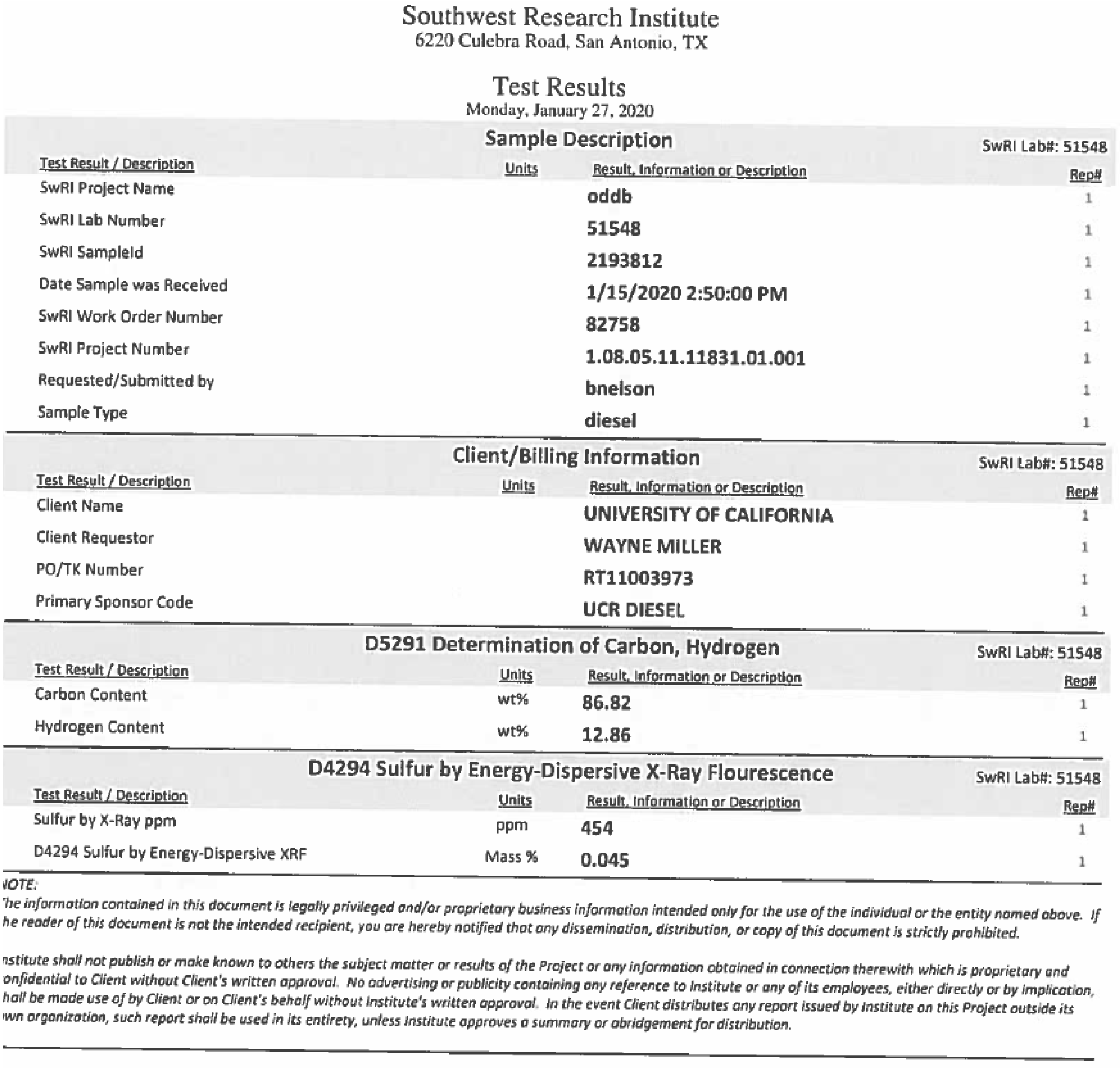
Ignition Scan: ○ OFF

Force Inert gas: ● ON

Req Inert gas: ● ON

Pressure unit: Bar

Figure D-4 Boiler display on the vessel showing controls and features (10/25/2018 13:39)



Southwest Research Institute
6220 Culebra Road, San Antonio, TX

Test Results
Monday, January 27, 2020

Sample Description SwRI Lab#: 51548

Test Result / Description	Units	Result, Information or Description	Rep#
SwRI Project Name		oddb	1
SwRI Lab Number		51548	1
SwRI SampleId		2193812	1
Date Sample was Received		1/15/2020 2:50:00 PM	1
SwRI Work Order Number		82758	1
SwRI Project Number		1.08.05.11.11831.01.001	1
Requested/Submitted by		bnelson	1
Sample Type		diesel	1

Client/Billing Information SwRI Lab#: 51548

Test Result / Description	Units	Result, Information or Description	Rep#
Client Name		UNIVERSITY OF CALIFORNIA	1
Client Requestor		WAYNE MILLER	1
PO/TK Number		RT11003973	1
Primary Sponsor Code		UCR DIESEL	1

D5291 Determination of Carbon, Hydrogen SwRI Lab#: 51548

Test Result / Description	Units	Result, Information or Description	Rep#
Carbon Content	wt%	86.82	1
Hydrogen Content	wt%	12.86	1

D4294 Sulfur by Energy-Dispersive X-Ray Flourescence SwRI Lab#: 51548

Test Result / Description	Units	Result, Information or Description	Rep#
Sulfur by X-Ray ppm	ppm	454	1
D4294 Sulfur by Energy-Dispersive XRF	Mass %	0.045	1

OTE:

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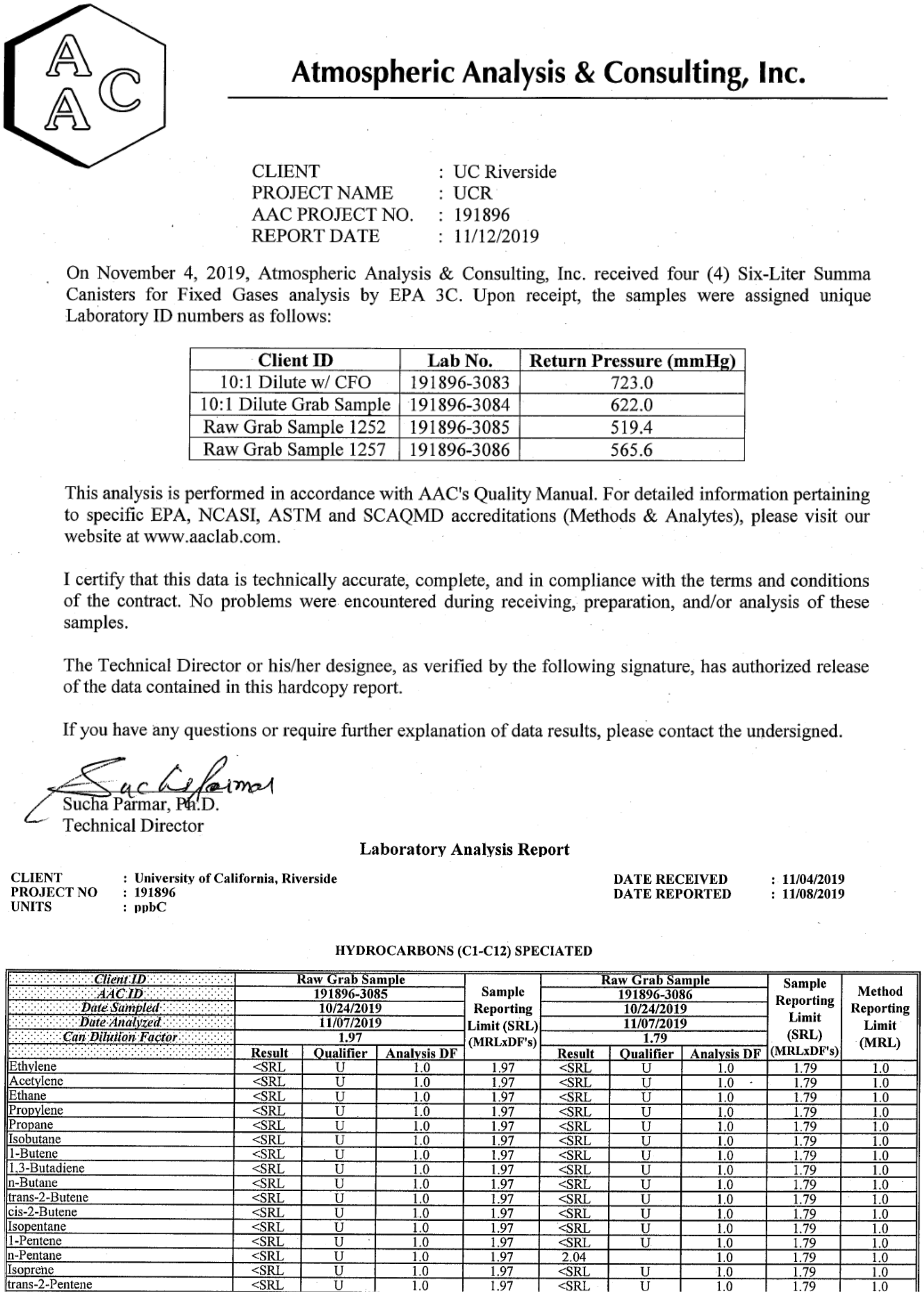
Figure D-5 Fuel analysis records



Atmospheric Analysis & Consulting, Inc.

CLIENT : UC Riverside
PROJECT NAME : UCR
AAC PROJECT NO. : 191896
REPORT DATE : 11/12/2019

On November 4, 2019, Atmospheric Analysis & Consulting, Inc. received four (4) Six-Liter Summa Canisters for Fixed Gases analysis by EPA 3C. Upon receipt, the samples were assigned unique Laboratory ID numbers as follows:

Client ID	Lab No.	Return Pressure (mmHg)
10:1 Dilute w/ CFO	191896-3083	723.0
10:1 Dilute Grab Sample	191896-3084	622.0
Raw Grab Sample 1252	191896-3085	519.4
Raw Grab Sample 1257	191896-3086	565.6

This analysis is performed in accordance with AAC's Quality Manual. For detailed information pertaining to specific EPA, NCASI, ASTM and SCAQMD accreditations (Methods & Analytes), please visit our website at www.aaclab.com.

I certify that this data is technically accurate, complete, and in compliance with the terms and conditions of the contract. No problems were encountered during receiving, preparation, and/or analysis of these samples.

The Technical Director or his/her designee, as verified by the following signature, has authorized release of the data contained in this hardcopy report.

If you have any questions or require further explanation of data results, please contact the undersigned.

Sucha Parmar

Sucha Parmar, Ph.D.
Technical Director

Laboratory Analysis Report

CLIENT : University of California, Riverside
PROJECT NO : 191896
UNITS : ppbC

DATE RECEIVED : 11/04/2019
DATE REPORTED : 11/08/2019

HYDROCARBONS (C1-C12) SPECIATED

Client ID	Raw Grab Sample			Sample Reporting Limit (SRL) (MRLxDF's)	Raw Grab Sample			Sample Reporting Limit (SRL) (MRLxDF's)	Method Reporting Limit (MRL)
AAC ID	191896-3085				191896-3086				
Date Sampled	10/24/2019				10/24/2019				
Date Analyzed	11/07/2019				11/07/2019				
Can Dilution Factor	1.97				1.79				
	Result	Qualifier	Analysis DF		Result	Qualifier	Analysis DF		
Ethylene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
Acetylene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
Ethane	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
Propylene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
Propane	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
Isobutane	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
1-Butene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
1,3-Butadiene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
n-Butane	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
trans-2-Butene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
cis-2-Butene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
Isopentane	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
1-Pentene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
n-Pentane	<SRL	U	1.0	1.97	2.04		1.0	1.79	1.0
Isoprene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0
trans-2-Pentene	<SRL	U	1.0	1.97	<SRL	U	1.0	1.79	1.0

Figure D-6 Suma Canister BTEX analysis report

Appendix E –Exhaust Flow

The calculation follows EPA Method 2 in which a type S Pitot tube is used to measure the differential pressure between the counter-flow (static pressure) and parallel-flow (dynamic pressure) directions. Velocity is calculated using Bernoulli's principle, which states that the pressure in a stream of fluid is reduced as the speed of the flow is increased. The velocity calculation is based off of the temperature, molecular weight of the exhaust gas, static pressure, dynamic pressure, and relative humidity. Measurement of the differential pressure and temperature were repeated at the sampling site several times at different depths inside the duct, including the near side of the duct, in the middle of the duct, and the far side of the duct. The equation below is from the EPA Method 2 documents Equation 2-7 and 2-8.

$$V_s = K_p \, C_p \left[\frac{\sum_{i=1}^{n}\sqrt{\Delta p_i}}{n}\right]\sqrt{\frac{T_{s(abavg)}}{P_s \, M_s}} \qquad .Q = 3600(1 - B_{ws})v_s A\left[\frac{T_{std}P_s}{T_{s(abavg)}P_{std}}\right]$$

Where:

- A = Cross-sectional area of stack, m2 (ft2).
- Bws = Water vapor in the gas stream
- Cp = Pitot tube coefficient, dimensionless.
- K = 0.127 mm H2O (metric units). 0.005 in. H2O (English units).
- Kp = Velocity equation constant.
- Ms = Molecular weight of stack gas, wet basis, g/g-mole (lb/lb-mole).
- n = Total number of traverse points.
- Pg = Stack static pressure, mm Hg (in. Hg).
- Ps = Absolute stack pressure (Pbar + Pg), mm Hg (in. Hg),
- Pstd = Standard absolute pressure, 760 mm Hg (29.92 in. Hg).
- Qsd = Dry volumetric stack gas flow rate corrected to standard conditions, dscm/hr (dscf/hr).
- Ts(abavg) = Average absolute stack temperature, °K (°R).
- Ts = Stack temperature, °C (°deg;F).
- Tstd = Standard absolute temperature, 293 °K (528 °R).
- Vs = Average stack gas velocity, m/sec (ft/sec).
- Δp = Velocity head of stack gas, mm H2O (in. H20).
- Δpi = Individual velocity head reading at traverse point "i", mm (in.) H2O.
- Δpstd = Velocity head measured by the standard pitot tube, cm (in.) H2O.
- Δps = Velocity head measured by the Type S pitot tube, cm (in.) H2O.

Table E-1 Summary of direct measurements from the pitot tube sampling

				Average Pitot DelP			Average Pitot Static P			
Stack Diam mm	Traverse Side B	Time Start (HH:MM)	Load	(inH20)	(mmH20)	(mmH20) ^0.5	(inH20)	(mmH20)	(mmH20) ^0.5	Temp (C)
1098.54	Full	8:16	High	0.11	2.90	1.70	0.40	10.11	0.74	223
1098.54	Mid	8:26	High	0.12	3.09	1.76	0.44	11.27	0.83	225
1098.54	Shallow	8:34	High	0.10	2.54	1.59	0.37	9.36	0.69	220

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 boiler for gaseous and PM emissions. The boiler toxic emissions are also listed below. The EC/OC results were sent to an outside laboratory and were analyzed using the NIOSH thermal optical method.

There were only three test points sampled during this testing. As discussed in Section 2.5, the data needed correction due to good engineering judgement that the full sample was not stable. The gray data represents the corrected data ("adjusted") and the non-gray data in Tables F-1 through F-3 are the original data samples so one can see the impact.

Table F-1 emissions data per test point for the original data and the "adjusted" data (gray).

Date	Project Name	Fuel	ATS	Location	Test Mode	Start Time	Sample Duration	DR	Boiler Load	Fuel Rate cacl OEM	Fuel Rate calc Meas	Fuel Rate Used Calcs	Exh Temp	Filter Temp	Stack Pres	Carb. Bal. Exh Flow I		Measured Meth2 Exh Flow II		Exh Flow Utilized
mm/dd/yyyy	name					hh:mm:ss	min	n/a	Name	kg/hr	kg/hr	kg/hr	C	C	mbar	(scfm)	(m3/hr)	(scfm)	(m3/hr)	m3/hr
10/24/2019	Tanker Boiler Test	MGO	n/a	original	1_1	10:40:00	40.3	7.0	65%	2494.8	2514.5	2494.8	221.8	41.5	0.75	17999	38138	18141	38439	38439
10/24/2019	Tanker Boiler Test	MGO	n/a	original	1_2	12:28:00	27.0	7.0	65%	2494.8	2044.7	2494.8	221.8	42.8	0.91	22135	46901	18141	38439	38439
10/24/2019	Tanker Boiler Test	MGO	n/a	original	1_3	13:44:00	43.0	7.0	65%	2494.8	2595.6	2494.8	221.8	43.6	0.53	17436	36945	18141	38439	38439
10/24/2019	Tanker Boiler Test	MGO	n/a	adjusted	1_1	11:50:00	15.0	7.0	65%	2494.8	2501.0	2494.8	221.8	41.5	0.75	18096	38343	18141	38439	38439
10/24/2019	Tanker Boiler Test	MGO	n/a	adjusted	1_2	12:28:00	10.0	7.0	65%	2494.8	2490.1	2494.8	221.8	42.8	0.91	18175	38511	18141	38439	38631
10/24/2019	Tanker Boiler Test	MGO	n/a	adjusted	1_3	14:08:52	15.0	7.0	65%	2494.8	2621.3	2370.0	221.8	43.6	0.53	17266	36584	18141	38439	34787

Table F-2 emissions data per test point for the original data and the "adjusted" data (gray). (g/hr basis)

Date	Test Group	ATS	Test	Start Time	Boiler Load	g/hr													FuelRate Carb.	SO2 calc	H20 Fraction	dil O2 Conc
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%	NOx	CO	CO2	meas. SO_2	calc. SO_2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	(kg/hr)	g/hr	%	%
10/24/2019	original	n/a	1_1	10:40:00	65%	6,981	312.92	7,954,786	822.6	2,407.5	56.9	7.19	50.47	0.00	57.66	60.56	67.76	15.27	2,495	2407.5	1.3	18.6
10/24/2019	original	n/a	1_2	12:28:00	65%	5,788	205.94	6,467,258	1,689.0	2,407.5	62.9	0.70	65.39	0.00	66.08	78.47	79.16	4.64	2,495	2407.5	1.1	15.1
10/24/2019	original	n/a	1_3	13:44:00	65%	8,500	-	8,212,217	2,485.5	2,407.5	65.5	1.19	49.87	0.00	51.06	59.84	61.03	1.08	2,495	2407.5	1.4	18.6
10/24/2019	adjusted	n/a	1_1	11:50:00	65%	7,209	252.3	7,912,285	480.7	2,407.5	45.4	1.7	50.5	0.0	52.2	60.6	62.3	3.7	2,495	2407.5	1.3	17.7
10/24/2019	adjusted	n/a	1_2	12:28:00	65%	7,236	249.3	7,917,100	521.0	2,407.5	62.2	0.5	65.7	0.0	66.3	78.9	79.4	3.6	2,495	2407.5	1.3	17.7
10/24/2019	adjusted	n/a	1_3	14:08:52	65%	7,601	-	7,505,569	591.3	2,287.2	60.2	2.0	45.1	0.0	47.2	54.2	56.2	1.8	2,370	2287.2	1.4	17.7

Table F-3 emissions data per test point for the original data and the "adjusted" data (gray). (g/kg-hr basis)

Date	Fuel	ATS	Test	Start Time	Boiler Load	g/kg-fuel (kg/tonne-fuel)													Calculated Fuel Usag			NOx Cor.
mm/dd/yyyy	n/a	n/a	#	hh:mm:ss	%	NOx	CO	CO2	meas. SO_2	calc. SO_2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	Ship FC	Carb. FC	-	Kh
10/24/2019	original	n/a	1_1	10:40:00	65%	2.80	0.13	3189	0.330	0.965	0.023	0.003	0.020	0.000	0.023	0.024	0.027	0.0061	2494.8	2514	-	-
10/24/2019	original	n/a	1_2	12:28:00	65%	2.32	0.08	2592	0.677	0.965	0.025	0.000	0.026	0.000	0.026	0.031	0.032	0.0019	2494.8	2045	-	-
10/24/2019	original	n/a	1_3	13:44:00	65%	3.41	-	3292	0.996	0.965	0.026	0.000	0.020	0.000	0.020	0.024	0.024	0.0004	2494.8	2596	-	-
10/24/2019	adjusted	n/a	1_1	11:50:00	65%	2.89	0.10	3172	0.193	0.965	0.018	0.001	0.020	0.000	0.021	0.024	0.025	0.0015	2494.8	2501	-	-
10/24/2019	adjusted	n/a	1_2	12:28:00	65%	2.90	0.10	3173	0.209	0.965	0.025	0.000	0.026	0.000	0.027	0.032	0.032	0.0015	2494.8	2490	-	-
10/24/2019	adjusted	n/a	1_3	14:08:52	65%	3.21	-	3167	0.250	0.965	0.025	0.001	0.019	0.000	0.020	0.023	0.024	0.0008	2494.8	2621	-	-

Table F-4 Average for all gaseous and PM species (g/hr and g/kg-fuel)

		Average Species													Average Calculated Fuel Usag		
Units	Load	NOx	CO	CO2	meas. SO_2	calc. SO_2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	Ship FC	Carb. FC	-
g/hr	65%	7349	251	7778318	531.03	2367.41	55.91	1.44	53.77	0.00	55.21	64.53	65.97	3.06	2453	2537.48	
g/kg-fuel	65%	3.00	0.10	3170.6	0.22	0.97	0.02	0.0006	0.02	0.00	0.02	0.03	0.03	0.0012	-	-	

Table F-5 Standard deviation (1 sigma) for all gaseous and PM species (g/hr and g/kg-fuel)

		Stdev Species													Average Calculated Fuel Usag		
Units	Load	NOx	CO	CO2	meas. SO_2	calc. SO_2	PM2.5	PM_EC	PM_OC	PM_S	PM_TC	PM_OCcor	PM_TCcor	PM_eBC	Ship FC	Carb. FC	-
g/hr	65%	0.54	0.03	377.58	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0030	0.00	297.45	
g/kg-fuel	65%	0.18	0.00	3.40	0.03	0.00	0.00	0.00033	0.00	0.00	0.00	0.00	0.00	0.0004	0.00	72.78	

Table F-6 Summary of results EPA 3C analysis and the selected speciated hydrocarbons

Analyte	Stack EPA 3C		
	#1	#2	Ave
Dilution Factor	1.97	1.79	1.88
H2	<2.0%	<1.8%	<1.8%
Ar/O2	7.5%	7.5%	7.5%
N2	82.0%	82.0%	82.0%
CO	<0.2%	<0.2%	<0.2%
CO2	10.4%	10.5%	10.5%
CH4	<0.2%	<0.2%	<0.2%
1,3 Butadiene (ppbC)	<SRL	<SRL	<SRL
Total PAMS (ppbC)	1.99	2.04	2.02
TNMHC (ppbC)	309	189	249

Table of selected speciated HCs

Analyte	Conc. ppb	mg/kg-fuel
1,3-Butadiene	<SRL	< 0.00987
Benzene	<SRL	< 0.00951
Toluene	<SRL	< 0.00961
m/p-Xylenes	<SRL	< 0.00969
Ethylbenzene	<SRL	< 0.00969
o-Xylene	<SRL	< 0.00969
Total PAMS	2.02	0.01084
TNMHC	249.0	1.683

Table F-7 Detail of the raw suma canister samples speciated HC (C2-C12) results. All values but two are below the detection limit (SRL)

Analyte	MM_C1	Formula	Raw (ppb)		mg/kg-fuel
			ID#1	ID#2	
Ethylene	14.0	C2H4	<SRL	<SRL	< 0.01024
Acetylene	13.0	C2H2	<SRL	<SRL	< 0.00951
Ethane	15.0	C2H6	<SRL	<SRL	< 0.01098
Propylene	14.0	C3H6	<SRL	<SRL	< 0.01024
Propane	14.7	C3H8	<SRL	<SRL	< 0.01073
Isobutane	14.5	C4H10	<SRL	<SRL	< 0.01061
1-Butene	14.0	C4H8	<SRL	<SRL	< 0.01024
1,3-Butadiene	13.5	C4H6	<SRL	<SRL	< 0.00987
n-Butane	14.5	C4H10	<SRL	<SRL	< 0.01061
trans-2-Butene	14.0	C4H8	<SRL	<SRL	< 0.01024
cis-2-Pentane	14.0	C5H10	<SRL	<SRL	< 0.01024
Isopentane	14.4	C5H12	<SRL	<SRL	< 0.01054
1-Pentene	14.0	C5H10	<SRL	<SRL	< 0.01024
n-Pentane	14.4	C5H12	<SRL	2.04	0.01054
Isoprene	13.6	C5H8	<SRL	<SRL	< 0.00995
trans-2-Pentene	14.0	C5H10	<SRL	<SRL	< 0.01024
cis-2-Pentene	14.0	C5H10	<SRL	<SRL	< 0.01024
2,2-Dimethylbutane	14.4	C6H14	<SRL	<SRL	< 0.01049
Cyclopentane	14.0	C5H10	<SRL	<SRL	< 0.01024
2,3-Dimethylbutane	14.4	C6H14	<SRL	<SRL	< 0.01049
2-Methylpentane	14.4	C6H14	<SRL	<SRL	< 0.01049
3-Methylpentane	14.4	C6H14	<SRL	<SRL	< 0.01049
1-Hexene	14.0	C6H12	<SRL	<SRL	< 0.01024
n-Hexane	14.4	C6H14	<SRL	<SRL	< 0.01049
Methylcyclopentane	14.0	C6H12	<SRL	<SRL	< 0.01024
2,4-Dimethylpentane	14.3	C7H16	<SRL	<SRL	< 0.01045
Benzene	13.0	C6H6	<SRL	<SRL	< 0.00951
Cyclohexane	14.0	C6H12	<SRL	<SRL	< 0.01024
2-Methylhexane	14.3	C7H16	<SRL	<SRL	< 0.01045
2,3-Dimethylpentane	14.3	C7H16	<SRL	<SRL	< 0.01045
Total PAMS	14.70	C3H8	1.99	2.04	0.01084
TNMHC	14.70	C3H8	309	189	1.683

Analyte	MM	Formula	Raw (ppb)		mg/kg-fuel
			ID#1	ID#2	
3-Methylhexane	14.3	C7H16	<SRL	<SRL	< 0.01045
2,2,4-Trimethylpentane	14.3	C8H18	<SRL	<SRL	< 0.01043
n-Heptane	14.3	C7H16	<SRL	<SRL	< 0.01045
Methylcyclohexane	14.0	C7H14	<SRL	<SRL	< 0.01024
2,3,4-Trimethylpentane	14.3	C8H18	<SRL	<SRL	< 0.01043
Toluene	13.2	C7H8	<SRL	<SRL	< 0.00961
2-Methylheptane	14.3	C8H18	<SRL	<SRL	< 0.01043
3-Methylheptane	14.3	C8H18	<SRL	<SRL	< 0.01043
n-Octane	14.3	C8H18	<SRL	<SRL	< 0.01043
Ethylbenzene	13.3	C8H10	<SRL	<SRL	< 0.00969
m/p-Xylenes	13.3	C8H10	<SRL	<SRL	< 0.00969
Styrene	13.0	C8H8	<SRL	<SRL	< 0.00951
o-Xylene	13.3	C8H10	<SRL	<SRL	< 0.00969
Nonane	14.3	C9H20	1.99	<SRL	0.01051
Isopropylbenzene	13.4	C9H12	<SRL	<SRL	< 0.00975
.alpha.-Pinene	13.6	C10H16	<SRL	<SRL	< 0.00995
n-Propylbenzene	13.4	C9H12	<SRL	<SRL	< 0.00975
m-Ethyltoluene	13.4	C9H12	<SRL	<SRL	< 0.00975
p-Ethyltoluene	13.4	C9H12	<SRL	<SRL	< 0.00975
1,3,5-Trimethylbenzene	13.4	C9H12	<SRL	<SRL	< 0.00975
o-Ethyltoluene	13.4	C9H12	<SRL	<SRL	< 0.00975
.beta.-Pinene	13.6	C10H16	<SRL	<SRL	< 0.00995
1,2,4-Trimethylbenzene	13.4	C9H12	<SRL	<SRL	< 0.00975
n-Decane	14.2	C10H22	<SRL	<SRL	< 0.01039
1,2,3-Trimethylbenzene	13.4	C9H12	<SRL	<SRL	< 0.00975
m-Diethylbenzene	13.4	C10H14	<SRL	<SRL	< 0.0098
p-Diethylbenzene	13.4	C10H14	<SRL	<SRL	< 0.0098
n-Undecane	14.2	C11H24	<SRL	<SRL	< 0.01038
n-Dodecane	14.2	C12H26	<SRL	<SRL	< 0.01036

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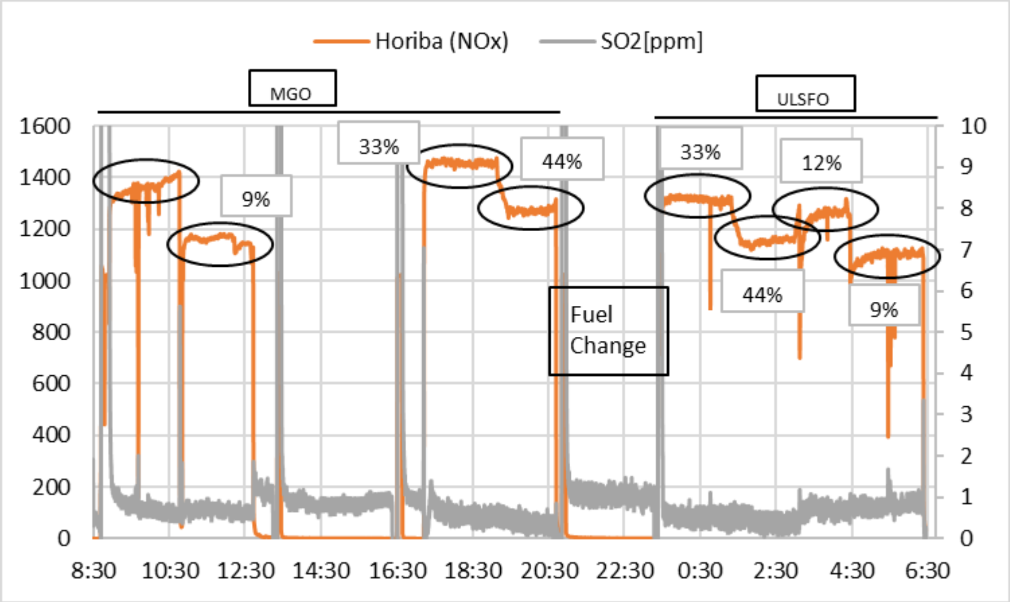
[1] For health risk studies, it is recommended to use the value provided in the mg/kg-fuel column and note that these are conservative values for now and that future research will investigate methods for increasing the measurement sensitivity. Please see https://ww3.arb.ca.gov/regact/2019/ogvatberth2019/appg.pdf for more details on ARB health studies.

Table F-8 Full summary of metal emissions

Date	Fuel	Tes	Start Time	Load	mg/kg-fuel (mg/tonne-fuel)											
mm/dd/yyyy	n/a	#	hh:mm:ss	%MCR	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr
10/24/2019	MGO	1_1	10:40:00	65.0%	0.32	0.02	0.05	1.25	0.06	2.83	0.01	0.00	0.17	0.00	0.15	0.02
10/24/2019	MGO	1_2	12:28:00	65.0%	0.52	0.00	0.05	0.96	0.08	4.08	0.02	0.00	0.20	0.00	0.14	0.04
10/24/2019	MGO	1_3	13:44:00	65.0%	0.26	0.06	0.07	0.91	0.06	3.87	0.00	0.00	0.19	0.00	0.14	0.02

Date	Fuel	Tes	Start Time	Load	mg/kg-fuel (mg/tonne-fuel)												
mm/dd/yyyy	n/a	#	hh:mm:ss	%MCR	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Rb	Sr
10/24/2019	MGO	1_1	10:40:00	65.0%	0.00	0.08	0.00	0.02	0.01	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10/24/2019	MGO	1_2	12:28:00	65.0%	0.00	0.12	0.00	0.02	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10/24/2019	MGO	1_3	13:44:00	65.0%	0.00	0.17	0.00	0.02	0.01	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Date	Fuel	Tes	Start Time	Load	mg/kg-fuel (mg/tonne-fuel)												
mm/dd/yyyy	n/a	#	hh:mm:ss	%MCR	Y	Zr	Mo	Pd	Ag	Cd	In	Sn	Sb	Ba	La	Hg	Pb
10/24/2019	MGO	1_1	10:40:00	65.0%	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10/24/2019	MGO	1_2	12:28:00	65.0%	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10/24/2019	MGO	1_3	13:44:00	65.0%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00



The figure at the left shows the SO_2 emissions for a previous study where there was a fuel switch. The SO_2 emissions should vary around 7 for the 0.05 S fuel and around 14 ppm for the 0.1 S fuel. For unknown reason there is no response to SO_2 in the analyzer, suggesting something is wrong with the analyzer or the sample collection system for SO_2.

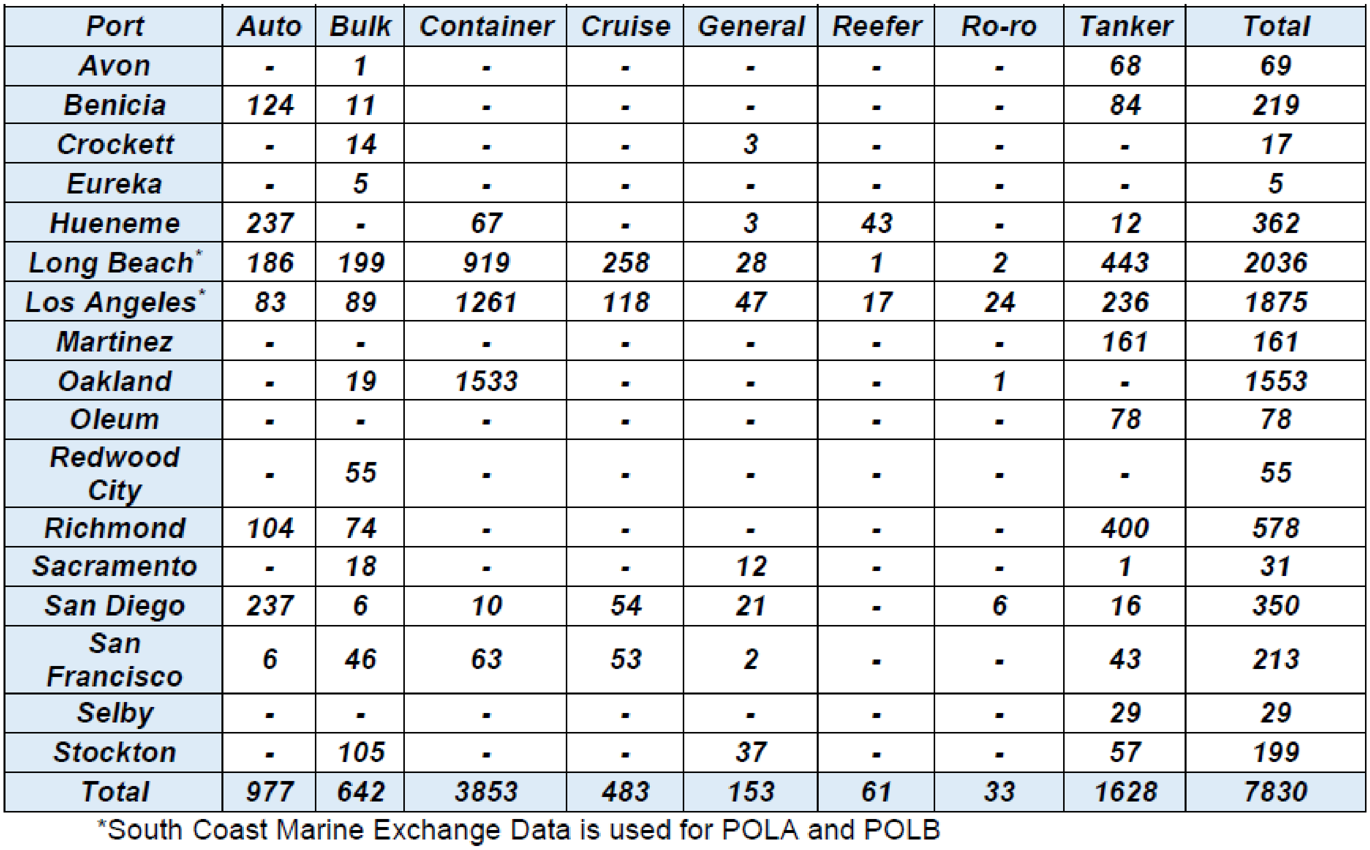
Additional investigation suggests the sample dryer was faulty and the SO2 was being removed by water in the sample line. A new sample drying method is being incorporated for future testing.

Figure F-1 Measured SO2 soot and NO_x emissions for the ME MGO and ULSFO

Appendix G –Inventory Summaries

The fraction of tankers compared to other vessels can be calculated from the data in Table G-1. The total number of tankers visiting all ports is 7,830 where 1,628 are tankers which suggests 20.8% of the OGV entering CA ports are tankers. Of the total 1,628 tankers, 1079 tankers are from POLB, POLA, and Richmond (66% of the total count for CA), see Table G-1.

Table G-1 Vessel list for the state of California ports in 2016 [13]



Port	Auto	Bulk	Container	Cruise	General	Reefer	Ro-ro	Tanker	Total
Avon	-	1	-	-	-	-	-	68	69
Benicia	124	11	-	-	-	-	-	84	219
Crockett	-	14	-	-	3	-	-	-	17
Eureka	-	5	-	-	-	-	-	-	5
Hueneme	237	-	67	-	3	43	-	12	362
Long Beach*	186	199	919	258	28	1	2	443	2036
Los Angeles*	83	89	1261	118	47	17	24	236	1875
Martinez	-	-	-	-	-	-	-	161	161
Oakland	-	19	1533	-	-	-	1	-	1553
Oleum	-	-	-	-	-	-	-	78	78
Redwood City	-	55	-	-	-	-	-	-	55
Richmond	104	74	-	-	-	-	-	400	578
Sacramento	-	18	-	-	12	-	-	1	31
San Diego	237	6	10	54	21	-	6	16	350
San Francisco	6	46	63	53	2	-	-	43	213
Selby	-	-	-	-	-	-	-	29	29
Stockton	-	105	-	-	37	-	-	57	199
Total	977	642	3853	483	153	61	33	1628	7830

*South Coast Marine Exchange Data is used for POLA and POLB

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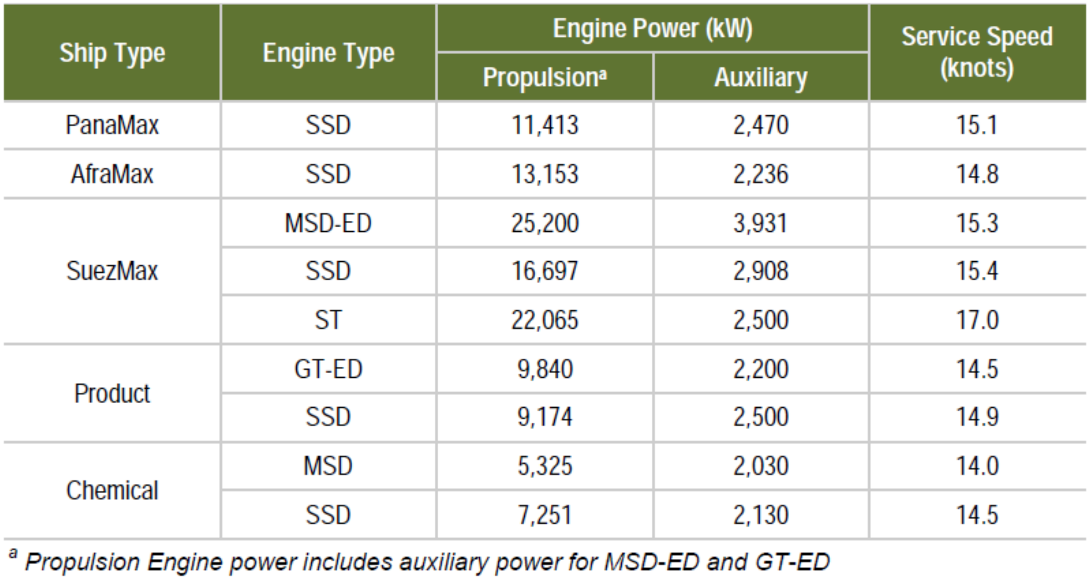
[13] https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessel-fuel-regulation

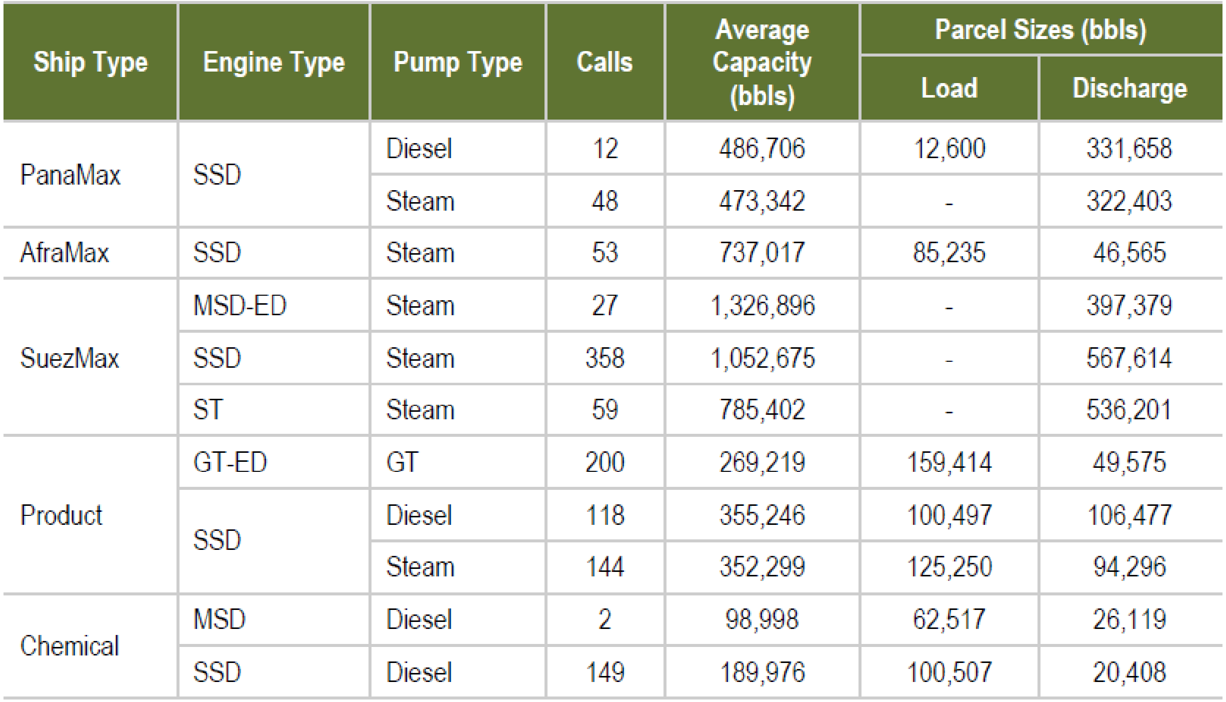
Table G-2 Average ship characteristics (ICF 2014) [14]



Ship Type	Engine Type	Engine Power (kW)		Service Speed (knots)
		Propulsion[a]	Auxiliary	
PanaMax	SSD	11,413	2,470	15.1
AfraMax	SSD	13,153	2,236	14.8
SuezMax	MSD-ED	25,200	3,931	15.3
	SSD	16,697	2,908	15.4
	ST	22,065	2,500	17.0
Product	GT-ED	9,840	2,200	14.5
	SSD	9,174	2,500	14.9
Chemical	MSD	5,325	2,030	14.0
	SSD	7,251	2,130	14.5

[a] Propulsion Engine power includes auxiliary power for MSD-ED and GT-ED

Table G-3 Calls and Average Ship Capacities and Parcel Sizes (2008 – 2010) (ICF 2014) [13]



Ship Type	Engine Type	Pump Type	Calls	Average Capacity (bbls)	Parcel Sizes (bbls)	
					Load	Discharge
PanaMax	SSD	Diesel	12	486,706	12,600	331,658
		Steam	48	473,342	-	322,403
AfraMax	SSD	Steam	53	737,017	85,235	46,565
SuezMax	MSD-ED	Steam	27	1,326,896	-	397,379
	SSD	Steam	358	1,052,675	-	567,614
	ST	Steam	59	785,402	-	536,201
Product	GT-ED	GT	200	269,219	159,414	49,575
	SSD	Diesel	118	355,246	100,497	106,477
		Steam	144	352,299	125,250	94,296
Chemical	MSD	Diesel	2	98,998	62,517	26,119
	SSD	Diesel	149	189,976	100,507	20,408

[1] For this work UCR summed up the calls for each vessel type and then divided by the number of months to get a monthly rate, then estimated.

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[14] ICF International Chevron Richmond Long Wharf Shipping Emissions Model, Final Report February 7, 2014. Prepared by ICF for Chevron Products Company.

Table G-4 Total tanker OGV activities for the Port of LA (Startcrest 2017)

Vessel Type	Berth		Anchorage	
				Count
Panamax	47.8	112	51.9	75
Suezmax	173.3	1	16.0	1