Measurement of Emissions from the Main Propulsion Engine (MAN B&W 11K90MC-C) on a Panamax Class Container Ship

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Emissions from the Main Propulsion Engine on a Pamamax Class Ship

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Acknowledgements

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Executive Summary

The California Air Resources Board (CARB), the University of California, Riverside (UCR) and a shipping company partnered to measure the gaseous and particulate matter (PM) emissions from a Panamax[1] Class container ship while at sea. During the testing the engine was operated at: 1) the approximate loads specified in the International Standards Organization (ISO) 8178 E-3 certification testing; and 2) at the speed specified in the voluntary Vessel Speed Reduction (VSR) program. For VSR operations, the speed of the vessel is reduced to 12 knots for a distance of 20 nautical miles from the Port of Los Angeles/Port of Long Beach (POLA/POLB). Exhaust sampling of the main engine was conducted over the one day (24 hour) voyage from Los Angeles to Oakland California during the month of September 2006.

Continuous measurements were made of the concentrations of carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO_2) and carbon dioxide (CO_2). In addition, particulate matter (PM) samples were taken that were subsequently analyzed for total mass, elemental/organic carbon and sulfate. The data are presented in the body of the report.

Emission factors determined from testing for the main engine, a 50,270 kW MAN B&W 11K90MC-C engine operating on a 2.05 wt. % sulfur heavy fuel oil (HFO) are presented in Table ES-1.

Table ES-1: Emission Factors of Criteria Pollutants for Main Engine

Load(%)	CO_2	SO_2	CO	NO_x	PM
	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
8% (VSR)	660	8.60	1.78	20.96	1.66
27%	588	7.66	1.81	15.84	1.08
52%	613	7.99	0.87	16.40	1.41
63%	643	8.37	0.81	17.85	1.69
70%	658	8.57	0.77	18.89	1.78

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[1] Ships classified as Panamax are of the maximum dimensions that will fit through the locks of the Panama Canal, with a typical displacement of 65,000 tons. Many ocean going vessels are built to this specification. For Detailed specifications, refer to Appendix B

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1   Introduction

Businesses at ports throughout the world are working with regulatory and community agencies to increase economic throughputs without increasing environmental impacts. Environmental impacts come mainly from port activity and many ports are projecting substantial increases in activity. Increased port activity without controls will increase emissions in the communities near ports and the environmental impacts. An example of the projected emissions and their sources can be seen from the following figures for the Los Angeles area[2]. From these figures it is it is clear that the ships are the key contributors to the emission inventory in the future. However, little is known about the emissions from these sources, especially the actual in-use emissions.
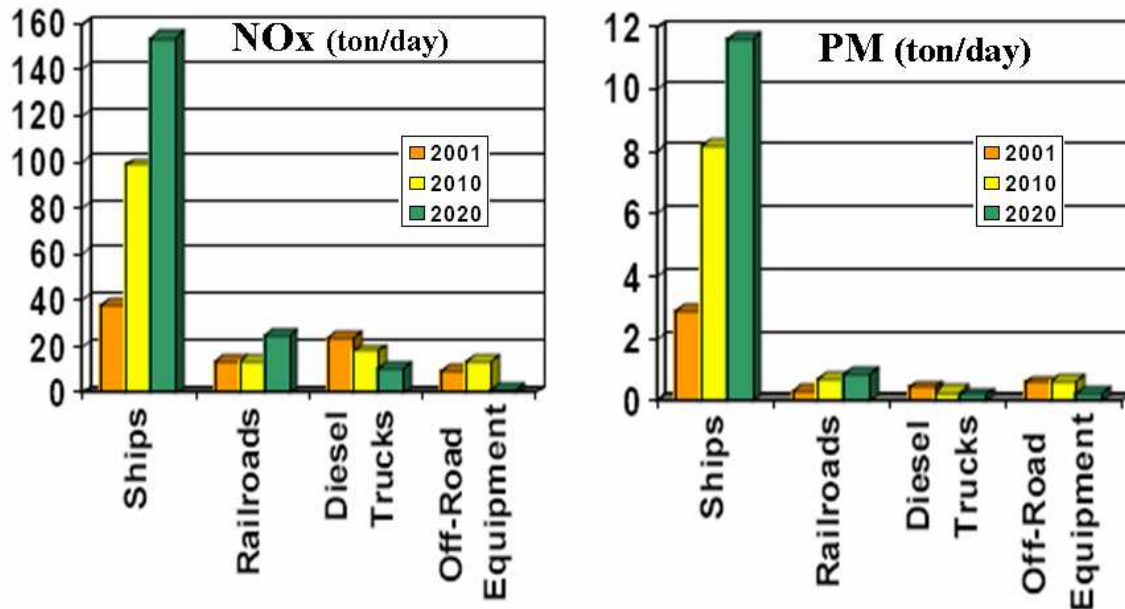
Figure 1-1 Trends for Various Port-Related Emissions (tons/day)

As ocean going vessels are one of the largest uncontrolled sources of pollutants and as emissions data from those sources is very limited, the California Air Resources Board, shipping company, and UCR worked together on a project to measure emissions from the main engine on the vessel during the ISO 8178 E-3 certification test cycles for the engine and during VSR operations. The ISO 8178 E-3 certification conditions are defined later in the report. Vessel Speed Reduction (VSR) operations represent those times when ocean going vessels (OGVs) voluntarily reduce their speed to 12 knots at a distance of 20 nautical miles from the POLA/POLB. More detail on the VSR program is found on the ARB web site[3].

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[2] Ref: *Goods Movement Action Plan* Phase I: Foundations (Sept 2005)
[3] See: http://www.arb.ca.gov/ports/marinevess/vsr/vsr.htm

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1.1 Project Objective

The goal of the project was to measure the criteria gas and PM emissions from the main engine of a Panamax Class container vessel. Criteria pollutants measured include carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM). CO_2 was also measured. Measurements were made while the main engine operated at approximately the loads specified for the ISO 8178 E-3 engine certification cycle and while the vessel followed the VSR program. Values from this study should be helpful in developing emission models and inventory calculations.

2 Test Plan

The test plan was designed to measure CO, NO_x, SO_2, PM, and CO_2 from the main propulsion engine while the container ship operated at or close to the loads specified in ISO 8178 E-3 cycle for engine certification and during operation in the VSR zone. In addition, the test plan included collection of PM filter samples that subsequently could be analyzed for PM mass, and the PM mass was subsequently fractionated into elemental carbon, organic carbon and sulfate. Since the main propulsion engine only operates while at sea, the emissions monitoring was conducted during a sea voyage from the Port of Los Angeles to the Port of Oakland. In the following sections, information on the test engine, test fuels, and test cycles and conditions are provided. Additional details on the test procedures are provided in Appendix A.

2.1.1 Test Engine

The ship tested is equipped with one main engine; a MAN B&W Model 11K90MC-C. This is a large two-stroke, low-speed engine of the MC generation. The engine was manufactured in 1995 and is rated at 50,270 kW. Further details on the engine are provided in Appendix B. The fuel injectors were of the mini-sac design.

Figure 2-1 Picture of the Fuel Injectors on an Engine from the 11K90MC-C Series

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According to the MAN web site[4] all MC engines "comply with the IMO speed dependent NO_x emission limitations, measured according to the ISO 8178 test cycles E2/E3 for Heavy Duty Diesel Engines."

2.2 Test Fuels

The main engine burned heavy fuel oil (HFO) meeting ISO 8217 specifications. Fuel was typical of normal supply. A fuel sample was obtained during the course of the emissions testing. The one liter fuel sample was drawn from the main engine final filter drain, immediately upstream of the injector rail. This sample was subsequently analyzed for a number of fuel properties. In addition, bunker delivery notes were collected that include independent analyses of the HFO fuel properties.

2.3 Test Cycle and Conditions

Normally, the emissions from diesel engines are measured for certification while the engine is in a laboratory and mounted on an engine dynamometer. Test Conditions for the purpose of engine certification are shown in Appendix A. For this project, the emission testing was carried out "in-use," with the engine operating on a vessel during an actual sea voyage. This approach adds complexity to the project, as it is often difficult to match "in-use" engine operating conditions with the modes specified in the ISO 8178 E-3 test cycle. The achievable load points are determined at the time of testing and depend on several factors including, operational constraints, sea current, wave pattern, wind speed/direction, and cargo load. Efforts were made to conduct the emissions measurements on the ship at loads as close as possible to those specified in ISO 8178 E-3.

A detailed plan and schedule for testing was developed with the Chief Engineer. The schedule for the testing is shown in **Table 2-1**.

Main Engine		
Condition	Date	Time
VSR	9/25/2006	21:41
ISO 50%	9/26/2006	5:31
ISO 50%	9/26/2006	6:32
ISO 60%	9/26/2006	8:18
ISO 60%	9/26/2006	8:50
ISO 70%	9/26/2006	10:50
ISO 70%	9/26/2006	11:40
ISO 25%	9/26/2006	12:39
ISO 25%	9/26/2006	13:11

Table 2-1 Main Engine Test Schedule

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[4] http://www.manbw.com/web/viewers/news/articleViewer.aspx?id=484

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2.3.1 Operating Conditions for Measuring Emissions from the Main Engine

At the time of measuring the emissions, the engine speed was set to appropriate the ISO E-3 loads of the vessels was operating at 12 knots, within the VSR zone. The engine operated at each test point for a period of 10-15 minutes to stabilize the gaseous emissions. Subsequently, emissions were measured for about one hour at each operating mode.

In general, the operational and testing protocol for each mode was as follows:

- Upon achieving a new engine set point, the gaseous emissions were monitored until they were stable for a minimum of five (5) minutes
- Continuous and integrated gaseous and PM measurements were acquired over three (3) consecutive test runs at each mode point. The sample time was determined such that a measurable filter mass would be obtained.
- Engine RPM, boost pressure and intake manifold temperature were monitored and recorded at each test mode in order to calculate the mass flow rate of the exhaust.
- Emission factors for each pollutant were calculated from the measured concentration data and calculated mass flow rates.

An important factor is the actual loads when testing an engine on a vessel may differ from the ISO protocol due to practical considerations. For example, the main propulsion engine was not tested at 100% load as specified in the ISO protocol because company policy precluded operating the engine above 91% load.

2.3.2 Calculation of Emission Factor

The emission factor at each mode is calculated from the measured gaseous and PM concentration, the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO E-3 protocol and summing them. The equation used for the overall emission factor is as follows:

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

Where:

A_{WM} = Weighted mass emission level (HC, CO, CO_2, PM, or NO_x) in g/kW-hr
g_i = Mass flow in grams per hour,
P_i = Power measured during each mode, including auxiliary loads, and
WF_i = Effective weighing factor.

2.3.3 Calculation of the Exhaust Flow Rate

Clearly the calculated emission factor is strongly dependent on the mass flow of the exhaust. Appendix A of ISO 8178-1 describes two methods for calculating the exhaust gas mass flow and/or the combustion air consumption. There are approaches other than those described in Appendix A of ISO-8178-1 and these are described below.

2.3.3.1 Methods described in Appendix A of ISO 8178 -1

Two methods are described in Appendix A of ISO-8178-1. Both methods are based on measuring the exhaust gas concentrations and on the knowledge of the fuel consumption.

Method 1, Carbon Balance, calculates the exhaust mass flow based on the measurement of fuel consumption and the exhaust gas concentrations with regard to the fuel characteristics (carbon balance method). The method given is only valid for fuels without oxygen and nitrogen content, based on procedures used for EPA and ECE calculations.

Method 2, 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.

The carbon balance methods may be used to calculate exhaust flow rate when the fuel consumption is measurable and when the fuel consumption and the concentrations of the exhaust components are known. In these methods, flow rate is determined by balancing carbon content in the fuel to the measured carbon dioxide in the exhaust. This method was not used for this testing as the fuel consumption data were not available.

2.3.3.2 Proprietary programs for calculating the exhaust flow rate

Various engine manufacture companies, like MAN B&W, have developed proprietary programs to calculate exhaust flow rates based on a number of operating parameters and experience during the testing of their designs. The results of both stoichiometric calculations for carbon and oxygen calculations give the total exhaust composition and the exhaust mass flow including the water content. The formulae in the program are mainly based on wet exhaust. We did not have access to those programs.

2.3.3.3 Exhaust flow rate assuming the engine as an air pump

This method has been widely used for calculating exhaust flow rate in diesel engine, especially stationary sources of diesel engines. This method assumes engine is an air pump, and the flow rate is determined from displacement of the cylinder, recorded rpm, and is corrected for temperature and pressure of the inlet air. This method was used by UCR for calculating exhaust flow rate from the marine engine in this project.

3   Results

3.1 Fuel Properties

For comparison, selected fuel properties from the certificate of analysis (COA) for the bunker oil and the analysis of the UCR fuel sample (acquired during testing) are presented in **Table 3-1**.

Table 3-1 Selected Properties of the Fuel Used on the Vessel

Fuel Property	Units	Bunker Delivery COA Result	UCR Sample COA Result
Density @ 15 ^{o}C	g/ml	0.9908	0.9911
Sulfur Content	wt. %	2.05	2.03
Ash Content	wt. %	0.072	0.072
Micro Carbon Residue (10% Btms)	wt. %	14.5	14.71
Heat of Combustion	MJ/kg	40.21	40.24

As seen in the Table, the analyses from the bunker delivery note compares very well with the independent fuel analyses of the UCR sample during testing. For details of the fuel analyses, please refer to Appendix C.

3.2 Sampling Ports

As explained in Appendix A, a partial dilution system was connected directly to the exhaust and no transfer line was used. While the ISO 8178 allows a transfer line of up to 5 meters, the UCR protocol eliminates the transfer line (wherever possible) to minimize potential PM losses. Accordingly, measurements in this campaign were made without a transfer line between the partial dilution system and the raw exhaust.

The sample port was located just below (upstream of) the waste heat boiler on the vessel. Sample probe access into the exhaust stream was gained by temporarily removing an existing thermopile that monitored the temperature of the exhaust. The sampling probe extended over 30 cm into the raw exhaust stack; away from any conditions found near the stack wall boundary.
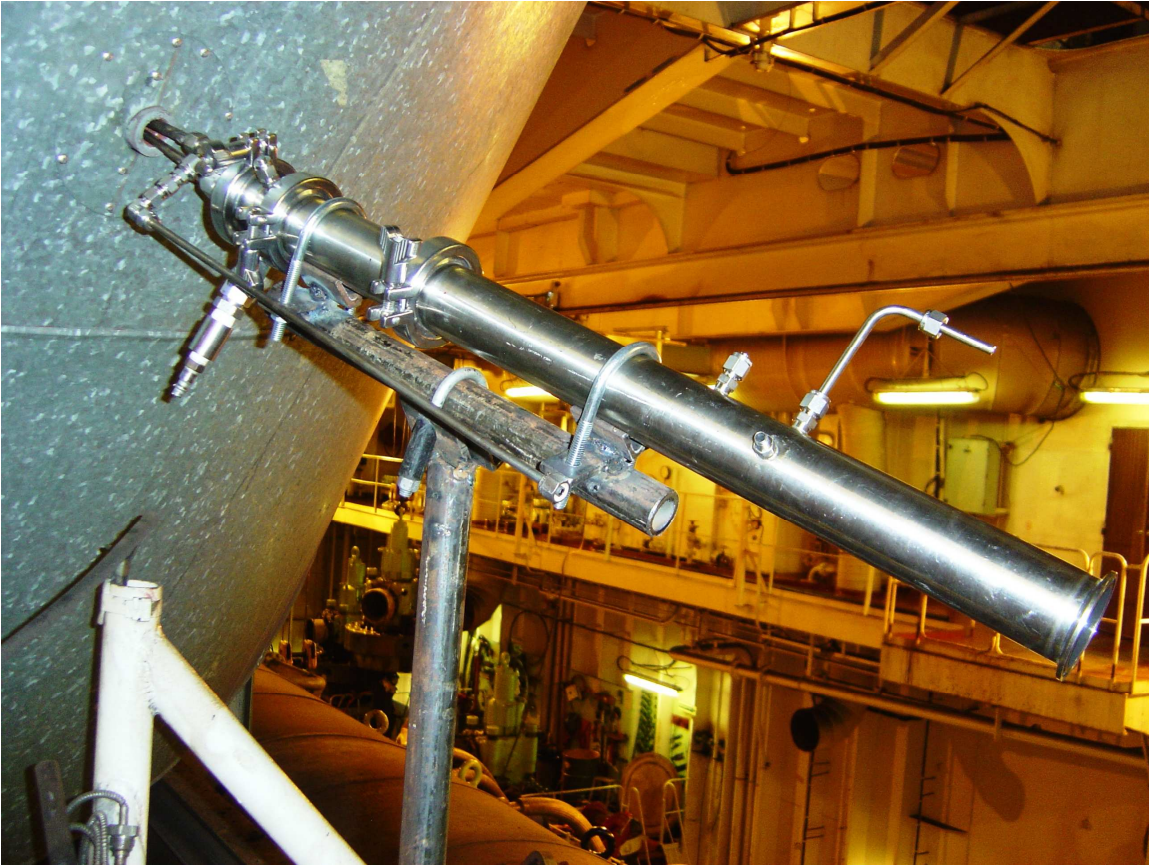
Figure 3-1 Picture of the Partial Dilution Tunnel Direct Connection with the Main Exhaust

3.3 Primary Gaseous Emissions

The major gaseous emissions of interest in the exhaust gas were: CO_2, CO, SO_2 and NO_x. All of the gaseous emissions were measured using instruments specified in the ISO protocol, except for SO_2. ISO 8178-1 Chapter 7.4.3.7 *Sulfur dioxide (SO,) analysis* specifies: "The SO, concentration shall be calculated from the sulfur content of the fuel used, since experience has shown that using the direct measurement method for SO, does not give more precise results." The ISO approach for SO_2 is logical given most (>95%) of the fuel sulfur is converted to SO_2 in the combustion process. Gaseous and PM measurements were conducted in triplicate (consecutive) and the results are presented in following sections.

3.3.1 Main Engine Gaseous Emissions

Gaseous emissions for all diesel engines are dominated by CO_2. Emissions of CO were low as expected for diesel engines. The results of gaseous emissions factors for CO_2, CO, NO_x and SO_2 (calculated based on fuel sulfur content) in terms of g/kW-hr are presented in **Table 3-2** and **Figure 3-2**. Triplicate measurements were made for each set of load conditions and the error bars on the figure represent the confidence limits for the

data collected and analyzed. Calculated values of the coefficient of variation (CV) show the average for the NO_x and CO_2 was about 3%, a very good value for field studies.

Table 3-2 Emission Factor of Different Gases for Main Engine

Load (%)	CO_2	SO_2	CO	NO_x
	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
8% (VSR)	660	8.60	1.78	20.96
27%	588	7.66	1.81	15.84
52%	613	7.99	0.87	16.40
63%	643	8.37	0.81	17.85
70%	658	8.57	0.77	18.89
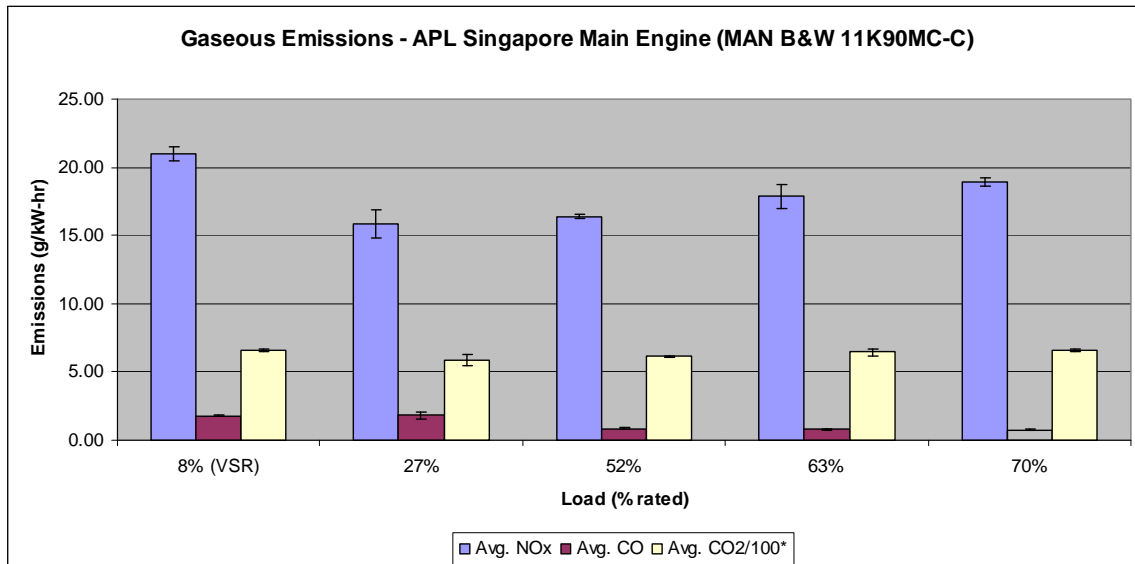
Figure 3-2 Emission Factor (g/kW-hr) for Different Gases from the Main Engine as a Function of Load * Note CO_2 scale

3.4 Particulate Matter (PM) Emissions

3.4.1 PM Mass Emissions

In addition to the gaseous emissions, the test program determined load-specific particulate matter (PM) mass emissions while following the engine certification test cycle. Generally speaking, particulate emissions originate mainly from the condensation of aerosols due to the incomplete combustion of fuel and lubricating oil, elemental or black carbon, and for fuels with high sulfur content, the condensation of hydrated sulfate. Secondary sources of PM include the trace chemical elements in the fuel and lubricating oil; for example, vanadium in bunker fuel and calcium in the lubricating oil.

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As described in Appendix A, the PM mass was sampled from the main stream with a partial dilution method and collected on filter media. Subsequent analyses allowed us to report the PM mass as well as the mass fractions of sulfate, organic carbon (OC) and elemental carbon (EC). The PM mass emissions for the main engine are presented in
Table 3-3 and **Figure 3-3.3**. Triplicate measurements were made and error bars are presented in Figure 5, providing an indication of the confidence limits. A metric of the confidence limits is listed in
Table 3-3 below as the coefficient of determination (C of D). The average coefficient for PM was about 5%; an excellent value for field studies.

Table 3-3 Numeric PM Emission Factors in g/kW-hr & Statistics

Load (% rated)	PM (g/kW-hr)	SD	C of D
8%	1.66	0.07	4.4%
27%	1.08	0.08	7.6%
52%	1.41	0.03	1.8%
63%	1.69	0.11	6.3%
70%	1.78	0.06	3.6%
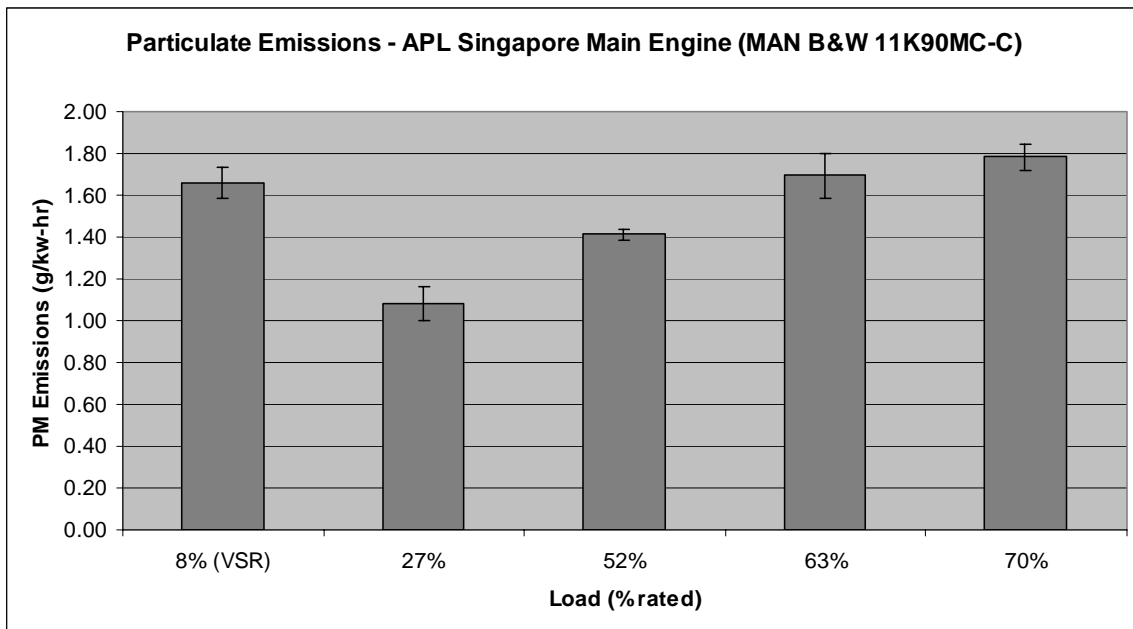
Figure 3-3 Emission Factor (g/kW-hr) for Particulate Matter from the Main Engine as a Function of Load

3.5 Composite Particulate Matter Emissions

3.5.1 Elemental and Organic Carbon

There are very few data from marine engines where the PM mass is fractionated into its major constituent groups: sulfate, organic and elemental carbon. As shown below, for the fuel with a high sulfur (2.05 wt.% S) content, the main fraction of PM mass consists of hydrated sulfate followed by organic carbon and finally, elemental (black) carbon. The remaining PM mass includes chemical constituents in the fuel that are found in the parts-per-million range, like vanadium, in fuel that forms ash during the combustion process and contributes a minor amount to the PM mass.

The emissions of elemental and organic carbon (OC/EC) for main engine are reported in **Figure 3-4**. Note for the main propulsion engine (ME) the OC levels are >10*EC levels and the amount increases significantly at the lowest power. As an internal quality check, UCR was primarily interested in showing the mass on the Teflon filter was equal to the sum of the mass fractions of hydrated sulfate plus organic carbon plus elemental carbon. The comparative mass balance is developed in the next section. One important point is the measured values for OC and EC and their calculated emission factors are important for researchers using these markers in their source apportionment research. Measurement methods for OC and EC are described in the appendix.
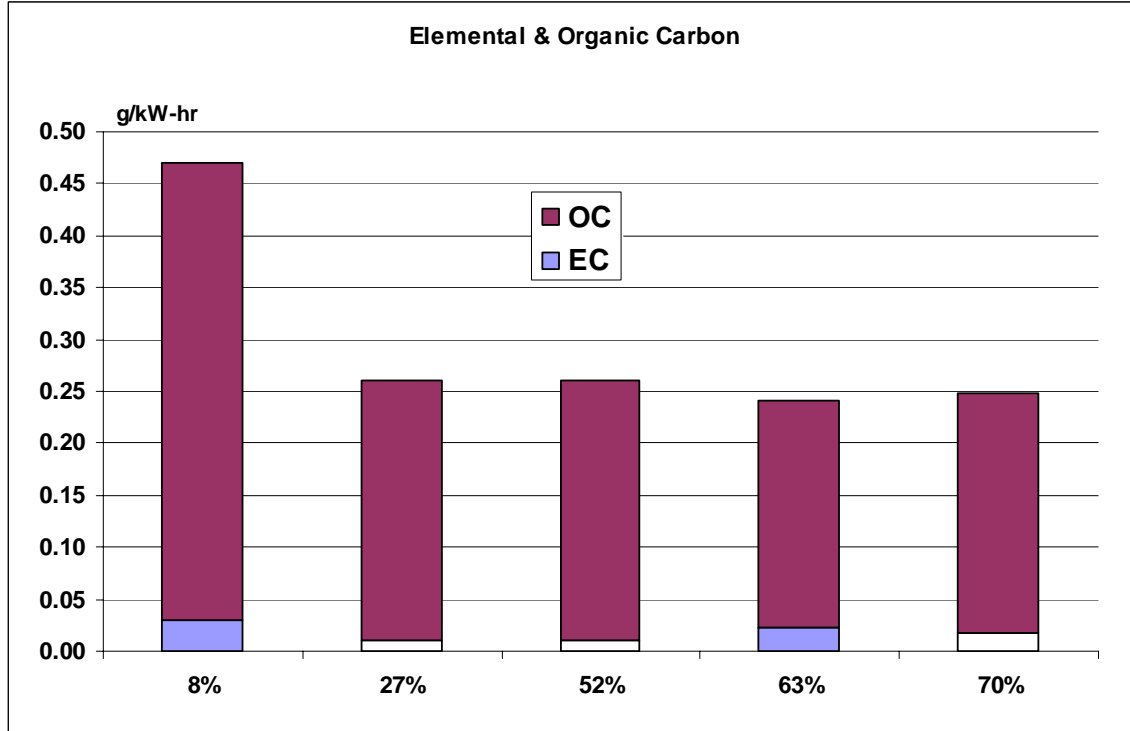
Figure 3-4 Emission Factors in g/kW-hr for the Elemental & Organic Carbon PM fractions

3.5.2 Emissions of Sulfate

Sulfate was extracted from the Teflon filter as described in Appendix A and the extract analyzed for sulfate ions with an ion chromatograph. The sulfate analyses are shown in **Table 3-4** and relate to the level of sulfur in the fuel. The bunker fuel sulfur content was 2.05%. Results show that about 3.7 to 5.0% of the fuel sulfur was converted to sulfate for the main engine.
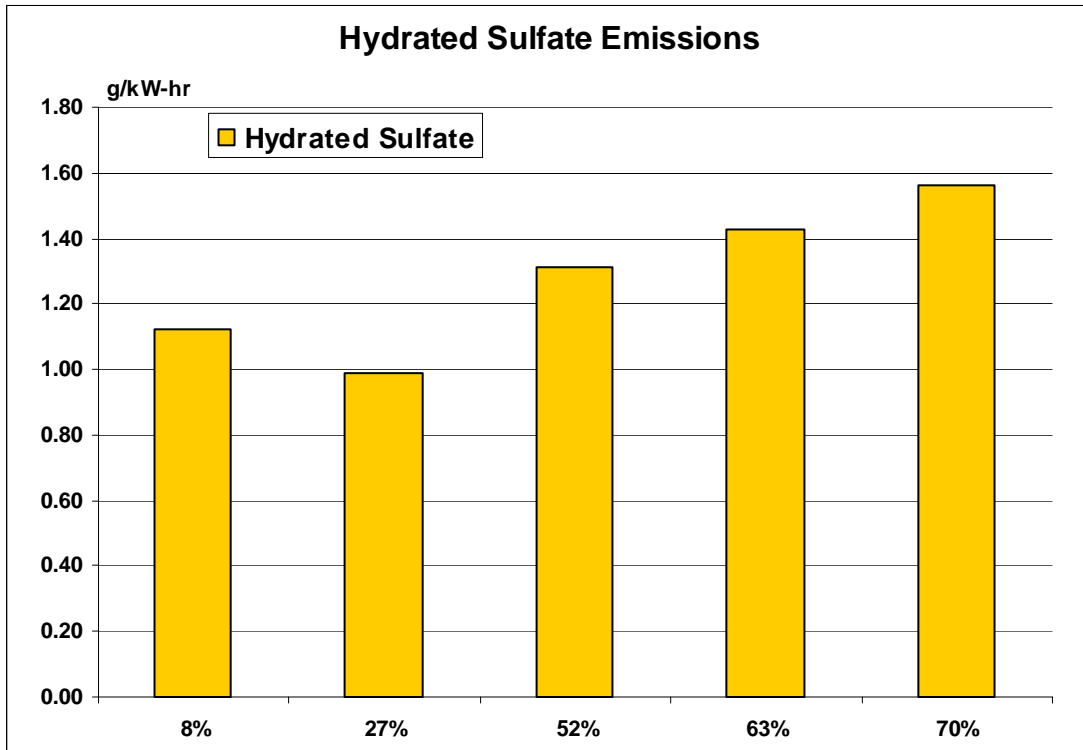
Figure 3-5 Figure of the Sulfate Emissions vs. Engine Load

Engine Type	Load	Unit	Hydrated Sulfate
Main Engine	8% (VSR)	g/kW-hr	1.12
Main Engine	27%	g/kW-hr	0.99
Main Engine	52%	g/kW-hr	1.31
Main Engine	63%	g/kW-hr	1.43
Main Engine	70%	g/kW-hr	1.56

Table 3-4 Sulfate Emissions (g/kW-hr) for the Main Engine

3.5.3 Quality Check for Conservation of PM Mass Emissions

An important element in UCR's analysis approach is the QA/QC check that total mass is conserved for the various PM methods. Specifically, we compare the total PM mass collected on the Teflon filter with the sum of the masses independently measured as sulfate, organic and elemental carbon. The results of the QA/QC for main engine are

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presented in **Table 3-5**. With the exceptions of the 27% and 52% load point samples, the comparison of results between the two methods shows very good agreement (within 5%). The 27% and 52% load point composite results were 16% and 11% higher than the average Teflon mass reference samples. This is still good agreement in light of the fact that composite results for the 27% load were determined from one sample, and those for the 52% were determined from only two samples. This is in contrast to the average reference (Teflon filter) results, which were determined from four samples at each load point (and showed smaller coefficients of deviation). Thus, it can be concluded that the composite results for the main engine emissions tests validate the PM emission factors determined from the Teflon filters.

As shown in **Table 3-5,** the sulfate fraction represents from 68 to 93% of the PM emissions for the main engine when operating on HFO with 2.05 wt% sulfur.

| Load% | Emissions Factors (g/kW-hr) | | | |
	PM mass	H2SO4*7H20	EC	OC
8%	1.66	1.12	0.03	0.44
27%	1.08	0.99	0.01	0.25
52%	1.41	1.31	0.01	0.25
63%	1.69	1.43	0.02	0.22
70%	1.78	1.56	0.02	0.23

Table 3-5 Comparison of PM Emission Factors with EC+OC+ Hydrated Sulfate Emission Factors for Main Engine

Another perspective is shown in **Figure 3-6** where the total PM from Teflon is compared with the sum of the fractions, expressed as sulfate, elemental and organic carbon.

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Figure 3-6 Comparative Plots of Total PM Emissions with Composite PM Emissions

4   Findings and Recommendations

4.1   Findings

Ocean going vessels are the primary transport unit for goods entering and leaving the California ports, yet little is known about their emissions. This work was designed to measure the emissions and emission factors for the main propulsion engine on a Panamax Class container ship as it entered and operated in and near California waters.

The approach to developing the needed information was to rely on the ISO 8178 E-3 test cycle used to certify the engine and the ISO emission measurement methods, including the use of a partial dilution tunnel for measuring PM. We also measured the emissions while the vessel followed the 12knots voluntary speed reduction program (VSR). Results showed it was possible to make these measurements while the vessel was at sea.

Table 4-1 Emission Factors of Criteria Pollutants for Main Engine

Load(%)	CO_2	SO_2	CO	NO_x	PM
	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
8% (VSR)	660	8.60	1.78	20.96	1.66
27%	588	7.66	1.81	15.84	1.08
52%	613	7.99	0.87	16.40	1.41
63%	643	8.37	0.81	17.85	1.69
70%	658	8.57	0.77	18.89	1.78

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In addition to measuring the criteria pollutants (CO, NO_x, SO_2 and PM), UCR also fractioned the PM mass into its major constituents: hydrated sulfate, organic carbon and elemental carbon. Results showed that (65+%) of the mass was hydrated sulfate and most of the remainder was organic carbon. Elemental carbon and ash contents were a minor fraction of the total mass.

4.2 Recommendations

Given the scarcity of emission data from ocean going vessels, it is recommended that more measurements be made. One area of concern is the calculated mass flow since it is a significant factor in the calculated emission factor. Consequently we suggest that a pitot tube or like mass measuring device be implemented during the next test in order to provide confidence in the calculated mass flow method used in this report.

Appendix A

A.1 Certification Emission Test Protocol for Main Engines

In 2003, the US EPA[5] published the compliance limits, the test protocols and measurement methods for large marine engines in the Code of Federal Regulations. EPA recognized the duty cycle used in determination of compliance with emission standards was critical and specified a duty cycle intended to simulate in-use operation. Testing consisted of exercising the engine over a prescribed duty cycle of speeds and loads. To address operational differences between engines, EPA adopted two different duty cycles. One for engines that operate on a fixed-pitch propeller curve (E3) and the other for propulsion engines that operates at a constant speed (E2). These are the same duty cycles specified by International Organization for Standardization[6] (ISO) and IMO Annex VI and shown in **Table A-0-1** below.

Table A-0-1 ISO Test Cycles type "E" for Marine Applications

Mode number (cycle B)	1	2	3	4	5	6	7	8	9	10	11
Mode number (cycle E1)	1	2					3	4			5
Speed	Rated speed					Intermediate speed					Low-idle speed
Torque [1], %	100	75					75	50			0
Weighting factor	0,08	0,11					0,19	0,32			0,3
Mode number (cycle E2)	1	2	3	4							
Speed	Rated speed					Intermediate speed					Low-idle speed
Torque [1], %	100	75	50	25							
Weighting factor	0,2	0,5	0,15	0,15							
Mode number (cycle E3)	1					2		3		4	
Speed [1], %	100					91		80		63	
Power, %	100					75		50		25	
Weighting factor	0,2					0,5		0,15		0,15	

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[5] US Environmental Protection Agency, 40 CFR Parts 9 and 94 *Control of Emissions From New Marine Compression-Ignition Engines at or Above 30 Liters Per Cylinder*; Final Rule, February 28, 2003

[6] International Standards Organization, IS0 8178-4 First edition, 1996-08-l 5, *Reciprocating Internal Combustion Engines - Exhaust Emission Measurement -Part 4: Test Cycles for Different Engine Applications* Reference number IS0 8178-4:1996(E)

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For this vessel, UCR followed the E3 cycle as closely as practical. Usually the engine is not operated at 100% power so UCR measured the vessel at the highest power possible. Measurements were also made at the speed of 12 knots required for the Voluntary Speed Reduction (VSR) program.

A.2 Measuring Gaseous and PM Emissions from Marine Diesel Engines

UCR selected methods for sampling and analysis of the gases and particulate matter (PM) to conform to the requirements of ISO 8178-1[7]. The approach involved the use of a partial flow dilution system with single Venturi as shown in Figure A-1. Raw exhaust gas was transferred from the exhaust pipe (EP) to the dilution tunnel (DT) through the sampling probe (SP) due to the negative pressure created by the Venturi (VN) in DT.
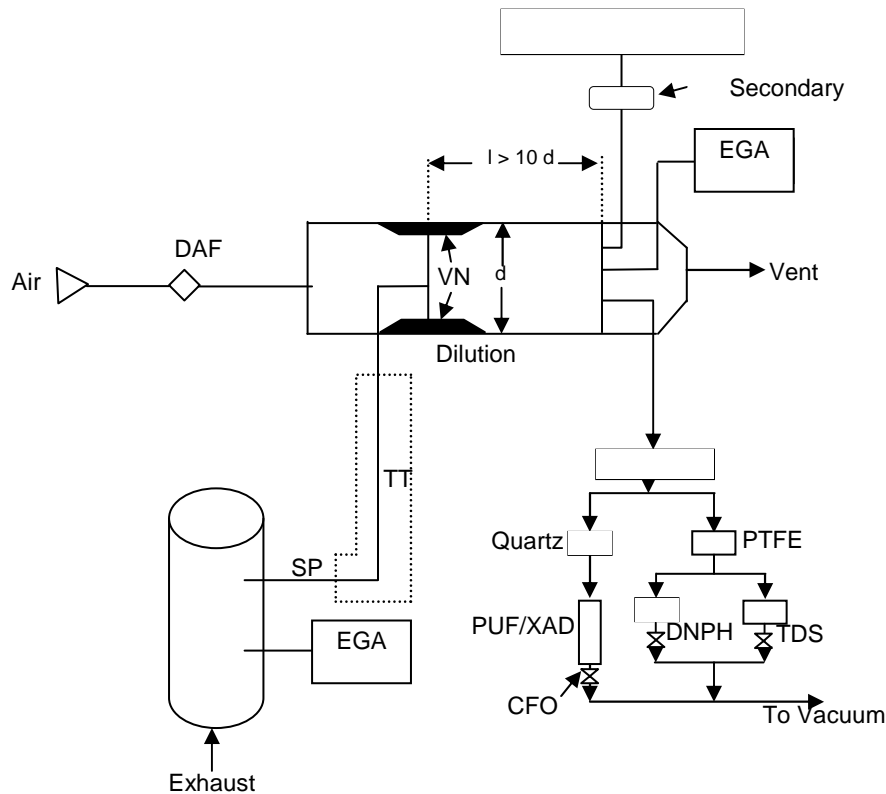
Figure A-0-1 Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

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[7] *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*

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The gas flow rate through SP depends on the momentum exchange at the Venturi zone and is therefore affected by the absolute temperature of the gas at the exit of tube in the Venturi. 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. The tracer gas concentrations (CO_2 or NO_x) are measured in the raw exhaust gas, the diluted exhaust gas and the dilution air using the exhaust gas analyzer (EGA), and the dilution ratio is calculated from the measured values.

In order to apply the ISO approach in the field, UCR designed a portable set of equipment that is field deployable. The equipment fits into several metal cases with an interior of foam molding to allow sensitive equipment, like computers, to be easily transported or even be lifted and dropped into cargo areas on a vessel without harm to the contents. For practical purposes, the design includes pieces of equipment that allow the use of a range of common electrical (120/240V, 50/60Hz) and supply air utilities. For example, while UCR tries to obtain instrument grade pressurized air for dilution air, we further process any supply air through a field processing unit to assure the quality of the dilution air. The processing air takes the supply air through a number of steps including reducing the pressure to about 30psig as that allows a dilution ratio of about 5/1 in the geometry of our system. The next stages, in sequence, for conditioning the supply air included: 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-0-2** below shows the unit for processing the dilution air.

Figure A-0-2 Field Processing Unit for Purifying Dilution Air in Transport Case

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

A.2.1 Measuring the Gaseous Emissions

The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 can simultaneously measure up to five separate gas components using the measurement methods recommended by the EPA. The signal output of the instrument was interfaced directly with a laptop computer through an RS-232C interface to record measured values continuously (Figure A-3). Major features of the PG-250 include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA ETV program.
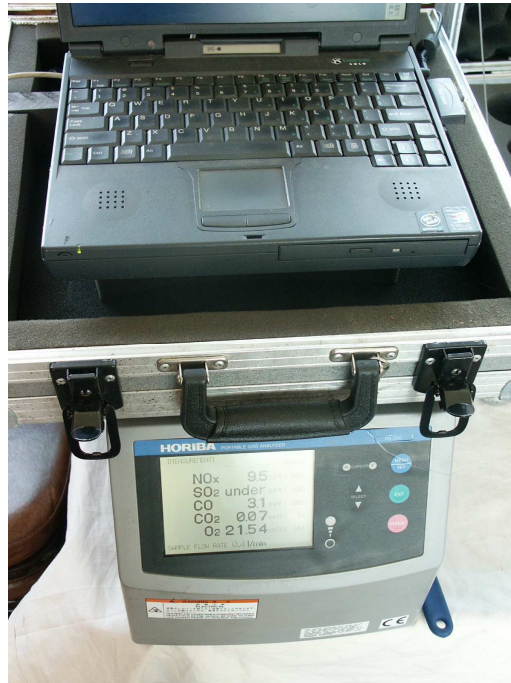
Figure A-0-3 In-field Illustration of Continuous Gas Analyzer and Computer for Data Logging

Details of the gases and the ranges for the Horiba instrument are shown in **Table A-0-2**. Note that the Horiba instrument measured sulfur oxides (SO_2); however, the ISO reference reports: "The SO, concentration shall be calculated from the sulfur content of the fuel used, since experience has shown that using the direct measurement method for SO_2, does not give more precise results."

Table A-0-2 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)	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)	0-200, 500, 1000, & 3000 ppmv
Oxygen	Zirconium oxide sensor	0-10, & 25 vol%

For quality control, UCR carried 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 by Praxair (Los Angeles, CA). Drift was determined to be within manufacturer specifications of $\pm 1\%$ full scale per day, except for SO_2 set at $\pm 2\%$ F.S./day. Other specifications of the instruments are provided in **Table A-0-3** below.

Table A-0-3 Quality Specifications for the Horiba PG-250

Repeatability	±0.5% F.S.(NOx : ≦100ppm range CO : ≦1000ppm range)
	±1.0% F.S.
Linearity	±2.0% F.S.
Drifft	±1.0% F.S./day(SO₂：±2.0%F.S./day)

A.2.2 Measuring the Particulate Matter (PM) Emissions

A raw particulate sampling probe was fitted close to and upstream of the raw gaseous sample probe in the exhaust. In order to measure PM, a sampling probe was inserted into the end of the dilution tunnel (>10 diameters downstream) and directed to a PM sample splitter that allowed up to three samples to be collected. For the particulate samples, we used one of the PM lines and directed it to a cyclone separator, sized to remove particles

>2.5um. From the separator, we added two lines with 47 Gelman filter holders, one for collecting PM on a Teflon filter and the other for collecting PM on a quartz filter. Thus the flow in the dilution tunnel was split into two fractions, a smaller flow for measuring PM mass and PM properties and a much larger flow that was vented outside the vessel. Note with the partial dilution approach for measuring gases and PM that it is critical for the dilution ratio be determined very accurately.

UCR collected simultaneous Teflon and quartz filters at each operating mode and analyzed them according to standard procedures. The simultaneous collection of quartz and Teflon filters allows an internal quality check of the PM mass. Teflon (Teflo) filters used to acquire PM mass were weighted following the procedure of the Code of Federal Regulations (CFR) (40 CFR Part 86). Briefly, total PM were collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, $T = 25\,^{\circ}C$) and weighed daily until two consecutive weight measurements were within 3 µg. Finally, the filters were extracted with HPLC grade water and isopropyl alcohol and analyzed for the sulfate ions using a Dionex DX-120 ion chromatograph.

PM samples were collected in parallel on 2500 QAT-UP Tissuquartz Pall (Ann Arbor, MI) 47 mm filters that were preconditioned at 600°C for 5 h. A 1.5 cm^2 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 (NIOSH 1996). All PM filters were sealed in containers immediately after sampling, and kept chilled until analyzed.

A.3 Quality Control/Quality Assurance (QC/QA)

Each of the laboratory methods for PM mass and chemical analysis has a standard operating procedure including the frequency of running the standards and the repeatability that is expected when the standard is run. Additionally the data for the standards are plotted to ensure that the values fall within the upper and lower control limits for the method and that there is no obvious trends or bias in the results for the reference materials. As an additional quality check, results from independent methods are compared and values from this work are compared with previously published values, like the manufacturer data base.

- For the ISO cycles, run the engine at rated speed and the highest power possible to warm the engine and stabilize emissions for about 30 minutes.
- Determine a plot or map of the peak power at each engine RPM, starting with rated speed. UCR suspected the 100% load point at rated speed was unattainable with propeller torque so Mode 1 would represent the highest attainable RPM/load.
- Emissions were measured while the engine operates according to the requirements of ISO-8178-E3. For the main engine first run was made for 50% load which was also the mode running on the 12 knots speed for Vehicle Speed Reduction (VSR), The minimum time for main engine samples were 5 minutes and if necessary, the

       time was extended to collect sufficient particulate sample mass or to achieve stabilization with large engines.

- The gaseous exhaust emission concentration values were measured and recorded for the last 3 min of the mode.
- Engine speed, displacement, boost pressure, and intake manifold temperature were measured in order to calculate the gaseous flow rate.
- Emissions factors are calculated in terms of grams per kilowatt hour for each of the operating modes.

Appendix B

B.1 Detailed specifications for the Panamax Class Vessel

Ships classified as **Panamax**[8] are of the maximum dimensions that will fit through the locks of the Panama Canal. This size is determined by the dimensions of the lock chambers, and the depth of the water in the canal. A Panamax cargo ship would typically have a displacement of around 65,000 tons. Panamax is a significant factor in the design of cargo ships, with many ships being built to exactly the maximum allowable size.

Panamax is determined principally by the dimensions of the canal's lock chambers, each of which is 33.53 <u>meters</u> (110 <u>ft</u>) wide by 320.0 meters (1050 ft) long, and 25.9 meters (85 ft) deep. The usable length of each lock chamber is 304.8 meters (1000 ft). The available water depth in the lock chambers varies, but the shallowest depth is at the southsill of the Pedro Miguel Locks and is 12.55 meters (41.2 ft) at a Miraflores Lake level of 16.61 meters (54 feet 6 in). The height of the Bridge of the Americas at Balboa is the limiting factor on a vessel's overall height. The maximum dimensions allowed for a ship transiting the canal are:

- Length: 294.1 meters (965 ft)
- Beam (width): 32.3 meters (106 ft)
- Draft: 12.0 meters (39.5 ft) in tropical fresh water (the salinity and temperature of water affect its density, and hence how deeply a ship will sit in the water)
- Height: 57.91 meters (190 ft) measured from the waterline to the vessel's highest point.

B.2 Detailed specifications for the K90MC Engines

According to the MAN web site[9] all MC engines: "comply with the IMO speed dependent NO_x emission limitations, measured according to the ISO 8178 test cycles E2/E3 for Heavy Duty Diesel Engines. Specific Fuel Oil Consumption (SFOC) and NO_x are interrelated parameters, so an engine offered without fulfilling the IMO NO_x limitations is subject to a tolerance of only 3% of the SFOC.

The figures for SFOC represent values obtained when the engine and turbocharger are matched at the lowest possible SFOC values and when fulfilling the IMO NO_x emission limitations. The SFOC figures are given in g/kWh with a tolerance of 5% and are based on use of a fuel with a lower calorific value of 42,700 kJ/kg (10,200 kcal/kg) at ISO conditions"

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[8] From Wikipedia internet encyclopedia, see http://en.wikipedia.org/wiki/Panamax

[9] http://www.manbw.com/web/viewers/news/articleViewer.aspx?id=484

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

K90MC-C6

Bore: 900 mm, Stroke: 2300 mm

Layout points		L_1	L_2	L_3	L_4
Speed	r/min	104	104	89	89
mep	bar	18.0	14.4	18.0	14.4
		kW	kW	kW	kW
11K90MC-C6		50270	40150	43010	34430

Specific Fuel Oil Consumption (SFOC)

g/kWh		171	164	171	164

Lubricating and Cylinder Oil Consumption

Lubricating oil	0.15 g/kWh
Cylinder oil	0.7 g/kWh

Main dimensions & weights

Cyl. No	11
L_{min} mm	21662
H_1 mm	12800
H_2 mm	12600
H_3 mm	12375
A mm	1699
B mm	4286
E mm	1602
Dry Mass t*	1686

*The mass can vary up to 10% depending on the design and options chosen.
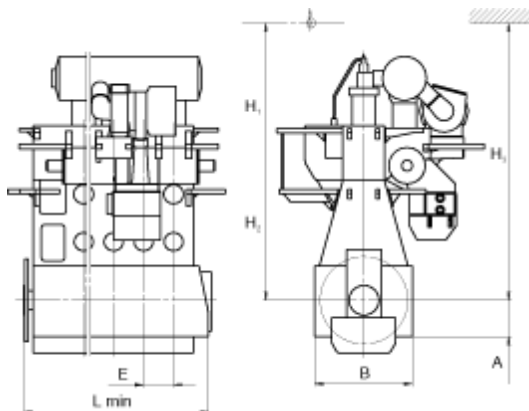
Appendix C – Test Data and Calculations

C.1 Detailed Engine Operational Results

Test ID	Date	Time	Load%	Load KW	Speed rpm	Manifold Pres. bar	Intake Temp. °C	Displacement liter	Std Correction (Pa*Tstd)/(Pstd*Ta)	Calc. Exh. Flow scfm
MEISO8-1	09/25/2006	22:01:00	8.03%	4036	49.2	0.28	44	16095.2	1.180	32989
MEISO8-2	09/25/2006	22:13:00	8.03%	4035	49.3	0.29	44	16095.2	1.189	33312
MEISO8-3	09/25/2006	22:27:00	7.55%	3796	48.6	0.29	44	16095.2	1.189	32839
MEISO8-4	09/25/2006	22:43:00	7.85%	3948	49.6	0.29	44	16095.2	1.189	33515
MEISO50-1	09/26/2006	5:50:00	51.66%	25970	90.8	1.4	38	16095.2	2.244	115810
MEISO50-2	09/26/2006	6:03:00	51.60%	25940	90.1	1.45	38	16095.2	2.291	117299
MEISO50-3	09/26/2006	6:27:00	51.58%	25930	89.8	1.43	38	16095.2	2.272	115959
MEISO50-4	09/26/2006	6:41:00	51.46%	25870	89.7	1.4	38	16095.2	2.244	114408
MEISO60-1	09/26/2006	9:06:00	60.57%	30450	97.9	1.93	42	16095.2	2.702	150359
MEISO60-2	09/26/2006	9:22:00	61.73%	31030	97.8	1.94	42	16095.2	2.712	150716
MEISO60-3	09/26/2006	9:38:00	64.75%	32550	97.8	1.94	42	16095.2	2.712	150716
MEISO70-1	09/26/2006	11:05:00	69.13%	34750	101.3	2.21	44	16095.2	2.941	169309
MEISO70-2	09/26/2006	11:19:00	69.78%	35080	101.4	2.15	44	16095.2	2.886	166321
MEISO70-3	09/26/2006	11:38:00	71.45%	35920	101.5	2.15	44	16095.2	2.886	166485
MEISO70-4	09/26/2006	11:56:00	71.59%	35990	101.8	2.22	44	16095.2	2.950	170672
MEISO25-1	09/26/2006	12:54:00	28.80%	14480	73.2	0.62	42	16095.2	1.500	62381
MEISO25-2	09/26/2006	13:08:00	27.73%	13940	73.1	0.62	43	16095.2	1.495	62099
MEISO25-3	09/26/2006	13:24:00	27.15%	13650	73	0.61	42	16095.2	1.490	61830
MEISO25-4	09/26/2006	13:45:00	26.14%	13140	73.5	0.69	43	16095.2	1.559	65115

C.2 Emissions Sampling System Dilution Ratios

Measured Raw vs Dilute Concentration			
			Dilution Ratio
Condition	Date	Time	by CO_2
VSR	09/25/2006	21:41	4.750
ISO 50%	09/26/2006	5:31	5.221
ISO 50%	09/26/2006	6:32	5.378
ISO 60%	09/26/2006	8:18	5.390
ISO 60%	09/26/2006	8:50	5.224
ISO 70%	09/26/2006	10:50	5.531
ISO 70%	09/26/2006	11:40	5.756
ISO 25%	09/26/2006	12:39	6.619
ISO 25%	09/26/2006	13:11	6.967

C.3 ISO Correction Factors for Temperature and Humidity

ISO
NOx $KHDIES = 1/(1-0.012*(Ha-10.71)-0.00275*(Ta-298)+0.00285*(Tsc-Tscref))$

    where   Tsc = intercooled air temp K
                    Tscref = intercooled reference air temp K
                    Ha = 6.22*Ra*pa/(pb-pa*Ra*10e-02)
                    Ra = relative humidity of intake air (%)
                    pa = saturation vapor pressure of intake air kPa
                    pb = barometric pressure kPa

	Ra %	pa kPa	pb kPa	Ha	Ta K	Tsc K	Tscref K	KHDIES
MEISO8	87	1.9602	101.53	12.55669	290.35	317.15	317.2883	1.001519
MEISO50	83	1.5863	101.68	9.252163	287.05	311.15	301.0387	0.929002
MEISO60	82	1.5966	101.78	9.181975	287.15	315.15	302.2574	0.921729
MEISO70	70	1.9602	101.98	9.670118	290.35	317.15	304.548	0.935076
MEISO25	68	2.3358	101.78	11.50162	293.15	316.15	301.0387	0.955196

ISO
PM $Kp = 1/(1+0.0133*(Ha-10.71))$

	Ha	Kp
MEISO8	12.55669	0.976028
MEISO50	9.252163	1.019773
MEISO60	9.181975	1.020744
MEISO70	9.670118	1.014024
MEISO25	11.50162	0.989581

C.4 Gaseous Emissions Data and Calculations

Test	Date	Time	Average Measured Dilute Concentrations						Average Corrected Raw Concentrations (corrected for calibration factors and dilution ratio)				
			NO	NOx (ppm)	CO (ppm)	CO2 (ppm)	O2 (ppm)	SO2 (ppm)	NO	NOx (ppm)	CO (ppm)	CO2 (%)	SO2 (ppm)
MEISO8-1	09/25/2006	22:01		150.4	23.5	5296.8	206923	54.3		777.1	107.0	2.53	258.0
MEISO8-2	09/25/2006	22:13		147.2	23.5	5277.4	206935	44.1		760.4	107.0	2.52	209.5
MEISO8-3	09/25/2006	22:27		137.0	22.3	4960.0	207357	36.3		708.0	101.4	2.37	172.3
MEISO8-4	09/25/2006	22:43		148.2	23.4	5238.7	206952	44.2		765.6	106.4	2.50	210.0
MEISO50-1	09/26/2006	5:50		210.8	19.2	8180.6	203558	81.2		1185.6	94.4	4.30	424.1
MEISO50-2	09/26/2006	6:03		208.5	19.2	8129.0	203610	80.7		1172.6	94.4	4.27	421.5
MEISO50-3	09/26/2006	6:27		207.3	18.8	8035.5	203735	79.0		1201.0	95.2	4.35	425.0
MEISO50-4	09/26/2006	6:41		208.8	19.9	8129.0	203639	72.0		1209.6	100.5	4.40	387.3
MEISO60-1	09/26/2006	9:06		219.4	17.5	8119.4	203742	81.0		1235.0	86.0	4.27	423.3
MEISO60-2	09/26/2006	9:22		216.5	17.0	8025.8	203855	79.3		1218.2	83.6	4.22	414.0
MEISO60-3	09/26/2006	9:38		211.7	16.7	7935.5	203971	78.9		1191.6	82.2	4.17	412.2
MEISO70-1	09/26/2006	11:05		214.8	15.6	7829.0	204048	77.0		1279.9	81.1	4.36	425.8
MEISO70-2	09/26/2006	11:19	199.4	213.0	15.1	7752.4	204133	77.1	1188.2	1269.1	78.5	4.32	426.3
MEISO70-3	09/26/2006	11:38		210.1	15.0	7680.6	204223	76.2		1302.9	81.0	4.45	438.7
MEISO70-4	09/26/2006	11:56		207.0	15.0	7538.7	204387	75.2		1284.0	81.0	4.37	432.8
MEISO25-1	09/26/2006	12:54		151.6	27.6	5916.1	206506	69.0		1081.0	171.4	3.94	456.6
MEISO25-2	09/26/2006	13:08		147.1	29.8	5893.5	206529	68.5		1103.8	194.8	4.13	477.2
MEISO25-3	09/26/2006	13:24	141.5	147.8	31.8	5890.3	206494	68.2	1062.3	1109.3	208.0	4.13	475.0
MEISO25-4	09/26/2006	13:45		145.5	32.0	5800.0	206552	66.7		1092.3	209.6	4.07	465.0

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

Test	Date	Time	Exhaust Flow Rate dscfm[1]	Mass Emission Rates						Load kW	Load-Specific Emission Factors				calc
				g/hr NO	g/hr NOx	g/hr CO	g/hr CO2	g/hr SO2[2]			g/kW-hr NOx	ISO Corr. g/kW-hr NOx	g/kW-hr CO	g/kW-hr CO2	g/kW-hr SO2[2]
MEISO8-1	09/25/2006	22:01	32989		84962	7118	2648237	34485		4036	21.1	21.1	1.76	656	8.5
MEISO8-2	09/25/2006	22:13	33312		83948	7188	2664371	34695		4035	20.8	20.8	1.78	660	8.6
MEISO8-3	09/25/2006	22:27	32839		77055	6717	2468563	32145		3796	20.3	20.3	1.77	650	8.5
MEISO8-4	09/25/2006	22:43	33515		85038	7195	2660922	34650		3948	21.5	21.6	1.82	674	8.8
MEISO50-1	09/26/2006	5:50	115810		455087	22046	15781988	205510		25970	17.5	16.3	0.85	608	7.9
MEISO50-2	09/26/2006	6:03	117299		455857	22330	15883969	206838		25940	17.6	16.3	0.86	612	8.0
MEISO50-3	09/26/2006	6:27	115959		461561	22262	15988940	208205		25930	17.8	16.5	0.86	617	8.0
MEISO50-4	09/26/2006	6:41	114408		458674	23206	15958661	207810		25870	17.7	16.5	0.90	617	8.0
MEISO60-1	09/26/2006	9:06	150359		615434	26076	20346706	264951		30450	20.2	18.6	0.86	668	8.7
MEISO60-2	09/26/2006	9:22	150716		608488	25406	20160004	262520		31030	19.6	18.1	0.82	650	8.5
MEISO60-3	09/26/2006	9:38	150716		595212	24982	19933123	259565		32550	18.3	16.9	0.77	612	8.0
MEISO70-1	09/26/2006	11:05	169309		718194	27693	23391551	304600		34750	20.7	19.3	0.80	673	8.8
MEISO70-2	09/26/2006	11:19	166321	654968	699593	26335	22753774	296295		35080	19.9	18.6	0.75	649	8.4
MEISO70-3	09/26/2006	11:38	166485		718921	27216	23485665	305826		35920	20.0	18.7	0.76	654	8.5
MEISO70-4	09/26/2006	11:56	170672		726331	27900	23631453	307724		35990	20.2	18.9	0.78	657	8.6
MEISO25-1	09/26/2006	12:54	62381		223490	21575	7794101	101493		14480	15.4	14.7	1.49	538	7.0
MEISO25-2	09/26/2006	13:08	62099		227176	24410	8135143	105934		13940	16.3	15.6	1.75	584	7.6
MEISO25-3	09/26/2006	13:24	61830	217689	227323	25949	8095452	105417		13650	16.7	15.9	1.90	593	7.7
MEISO25-4	09/26/2006	13:45	65115		235739	27533	8394885	109316		13140	17.9	17.1	2.10	639	8.3

[1] Exhaust flow calculated from engine rpm, intake press./temp and displacement

[2] Per ISO 8178, SO2 mass emissions calculated from fuel S% and BSFC

C.5 Particulate Matter Emissions Data and Calculations

Test	Date	Time	Load % of Max	Sample ID Teflon	Sample ID Quartz	Volume Sampled Teflon liters/min	Volume Sampled Quartz liters/min	Time Sampled Teflon min	Time Sampled Quartz min	Teflon PM Mass mg/filter	Sulfate ppm	Sulfate mg/filter	EC ug/filter	OC ug/filter
MEISO8-1	09/25/2006	22:01	8.03%	SS060343		4.862	27.00	10.0	10.0	1.266				
MEISO8-2	09/25/2006	22:13	8.03%	SS060344	SSQTX609014	4.862	27.00	10.0	12.0	1.203			91.1	1850.3
MEISO8-3	09/25/2006	22:27	7.55%	SS060345	SSQTX609015	4.862	27.00	9.8	12.0	1.15	39.322	0.3146	108.8	2408.4
MEISO8-4	09/25/2006	22:43	7.85%	SS060348	SSQTX609016	4.862	27.00	10.0	12.0	1.294	44.906	0.3592	170.1	2035.1
MEISO50-1	09/26/2006	5:50	51.66%	SS060349	SSQTX609017	4.862	27.00	10.0	12.0	1.682			113.8	2590.8
MEISO50-2	09/26/2006	6:03	51.60%	SS060350	SSQTX609019	4.862	27.00	10.0	12.0	1.704			109.1	1885.9
MEISO50-3	09/26/2006	6:27	51.58%	SS060351	SSQTX609018	4.862	27.00	10.0	12.0	1.702	89.316	0.7145	105.9	1932.3
MEISO50-4	09/26/2006	6:41	51.46%	SS060352	SSQTX609020	4.862	27.00	10.0	12.0	1.689	80.413	0.6433	148.1	1659.7
MEISO60-1	09/26/2006	9:06	60.57%	SS060380	SSQTX609022	4.862	27.00	10.0	12.0	1.904			137.7	1646.6
MEISO60-2	09/26/2006	9:22	61.73%	SS060381	SSQTX609023	4.862	27.00	10.0	12.0	1.859			139.7	1603.1
MEISO60-3	09/26/2006	9:38	64.75%	SS060382	SSQTX609024	4.862	27.00	10.0	13.0	1.851	91.520	0.7322	133.2	1947.7
MEISO70-1	09/26/2006	11:05	69.13%	SS060394	SSQTX609027	4.862	27.00	10.0	12.0	1.987			85.4	1600.6
MEISO70-2	09/26/2006	11:19	69.78%	SS060395	SSQTX609028	4.862	27.00	10.0	12.0	1.89			141.9	1731.9
MEISO70-3	09/26/2006	11:38	71.45%	SS060396	SSQTX609029	4.862	27.00	10.0	12.0	1.873	97.138	0.7771	124.5	1591.7
MEISO70-4	09/26/2006	11:56	71.59%	SS060397	SSQTX609030	4.862	27.00	10.0	12.0	1.843	81.952	0.6556	88.5	1651.5
MEISO25-1	09/26/2006	12:54	28.80%	SS060398	SSQTX609031	4.862	27.00	10.0	12.0	1.027			77.4	1557.2
MEISO25-2	09/26/2006	13:08	27.73%	SS060399	SSQTX609032	4.862	27.00	10.0	12.0	1.02			100.4	1662.3
MEISO25-3	09/26/2006	13:24	27.15%	SS060410	SSQTX609033	4.862	27.00	10.0	12.0	1.022	52.153	0.4172	95.3	1654.3
MEISO25-4	09/26/2006	13:45	26.14%	SS060411		4.862	27.00	10.0	12.0	1.003	40.842	0.3267		

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

| | | | | Load-Specific PM Emission Factors | | | | |
| | | | Load | PM Mass Teflon | ISO Corr. PM Mass | EC Quartz | OC Quartz | Hydrated Sulfate |
Test	Date	Time	kW	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr	g/kW-hr
MEISO8-1	09/25/2006	22:01	4036	1.70	1.66			
MEISO8-2	09/25/2006	22:13	4035	1.63	1.59	0.019	0.376	
MEISO8-3	09/25/2006	22:27	3796	1.67	1.63	0.023	0.513	1.06
MEISO8-4	09/25/2006	22:43	3948	1.80	1.76	0.036	0.426	1.17
MEISO50-1	09/26/2006	5:50	25970	1.35	1.38	0.014	0.313	
MEISO50-2	09/26/2006	6:03	25940	1.39	1.42	0.013	0.231	
MEISO50-3	09/26/2006	6:27	25930	1.41	1.44	0.013	0.241	1.39
MEISO50-4	09/26/2006	6:41	25870	1.39	1.42	0.018	0.205	1.23
MEISO60-1	09/26/2006	9:06	30450	1.75	1.79	0.019	0.227	
MEISO60-2	09/26/2006	9:22	31030	1.68	1.72	0.019	0.218	
MEISO60-3	09/26/2006	9:38	32550	1.55	1.58	0.015	0.225	1.43
MEISO70-1	09/26/2006	11:05	34750	1.85	1.88	0.012	0.224	
MEISO70-2	09/26/2006	11:19	35080	1.71	1.74	0.019	0.235	
MEISO70-3	09/26/2006	11:38	35920	1.73	1.75	0.017	0.220	1.67
MEISO70-4	09/26/2006	11:56	35990	1.74	1.76	0.013	0.234	1.44
MEISO25-1	09/26/2006	12:54	14480	1.01	1.00	0.011	0.230	
MEISO25-2	09/26/2006	13:08	13940	1.04	1.03	0.015	0.254	
MEISO25-3	09/26/2006	13:24	13650	1.11	1.10	0.016	0.271	1.06
MEISO25-4	09/26/2006	13:45	13140	1.20	1.18			0.91

C.6 Criteria Pollutant Summary Results and Statistics

Condition		NOx	ISO Corr. g/kW-hr NOx	g/kW-hr CO	g/kW-hr CO2	calc g/kW-hr SO2	PTFE g/kW-hr PM	ISO PTFE g/kW-hr PM
ME8-1		21.1	21.1	1.76	656	8.5	1.70	1.66
ME8-2		20.8	20.8	1.78	660	8.6	1.63	1.59
ME8-3		20.3	20.3	1.77	650	8.5	1.67	1.63
ME8-4		21.5	21.6	1.82	674	8.8	1.80	1.76
ME8	**AVG**	**20.9**	**21.0**	**1.78**	**660**	**8.6**	**1.70**	**1.66**
	SD	**0.52**	**0.52**	**0.026**	**10.1**	**0.13**	**0.074**	**0.073**
	ERR (%)	**2.5**	**2.5**	**1.48**	**1.5**	**1.5**	**4.38**	**4.38**
ME25-1		15.4	14.7	1.49	538	7.0	1.01	1.00
ME25-2		16.3	15.6	1.75	584	7.6	1.04	1.03
ME25-3		16.7	15.9	1.90	593	7.7	1.11	1.10
ME25-4		17.9	17.1	2.10	639	8.3	1.20	1.18
ME25	**AVG**	**16.6**	**15.8**	**1.81**	**588**	**7.7**	**1.09**	**1.08**
	SD	**1.04**	**0.99**	**0.255**	**41.3**	**0.54**	**0.083**	**0.082**
	ERR (%)	**6.3**	**6.3**	**14.11**	**7.0**	**7.0**	**7.60**	**7.60**
ME50-1		17.5	16.3	0.85	608	7.9	1.35	1.38
ME50-2		17.6	16.3	0.86	612	8.0	1.39	1.42
ME50-3		17.8	16.5	0.86	617	8.0	1.41	1.44
ME50-4		17.7	16.5	0.90	617	8.0	1.39	1.42
ME50	**AVG**	**17.7**	**16.4**	**0.87**	**613.4**	**8.0**	**1.39**	**1.41**
	SD	**0.13**	**0.12**	**0.021**	**4.3**	**0.06**	**0.025**	**0.026**
	ERR (%)	**0.7**	**0.7**	**2.44**	**0.7**	**0.7**	**1.82**	**1.82**
ME60-1		20.2	18.6	0.86	668	8.7	1.75	1.79
ME60-2		19.6	18.1	0.82	650	8.5	1.68	1.72
ME60-3		18.3	16.9	0.77	612	8.0	1.55	1.58
ME60	**AVG**	**19.4**	**17.9**	**0.81**	**643**	**8.4**	**1.66**	**1.69**
	SD	**0.98**	**0.91**	**0.045**	**28.4**	**0.37**	**0.104**	**0.106**
	ERR (%)	**5.1**	**5.1**	**5.48**	**4.4**	**4.4**	**6.25**	**6.25**
ME70-1		20.7	19.3	0.80	673	8.8	1.85	1.88
ME70-2		19.9	18.6	0.75	649	8.4	1.71	1.74
ME70-3		20.0	18.7	0.76	654	8.5	1.73	1.75
ME70-4		20.2	18.9	0.78	657	8.6	1.74	1.76
ME70	**AVG**	**20.2**	**18.9**	**0.77**	**658**	**8.6**	**1.76**	**1.78**
	SD	**0.33**	**0.31**	**0.021**	**10.6**	**0.14**	**0.063**	**0.064**
	ERR (%)	**1.6**	**1.6**	**2.68**	**1.6**	**1.6**	**3.59**	**3.59**

C.7 Fuel Analyses

To: Mr. Kenneth Tan / NOL Technical Services Department
(nol_tsd_spore@nol.com.sg)
From: Los Angeles Bunker Surveyors, Inc. / E-mail:
labunker@worldnet.att.net

LAB Ref No.:   LAB-N3459
Supplier: Chemoil Corporation
Port: Los Angeles, CA
Barge: Olympic L.
Delivery Sample: Seal #210747
Sampling Method: Line drip @ vessel's manifold

Quality		RMG 380
LAB Report No:	082201	
Density, @15 C	990.8	991.0 max
Vis: @50 C, cSt	296.8	380.0 max
Flash Point, C	82	60 min
Water, vol%	0.10	0.50 max
Sulfur, wt%	2.05	4.50 max
Pour Point, C	-5	30 max
Carbon, wt%	14.5	18 max
Ash, wt%	0.072	0.15 max
TSP, wt%	0.02	0.10 max
Aluminum, ppm	11	Al + Si
Silicon, ppm	17	= 80 max
Vanadium, ppm	259	300 max
Sodium, ppm	30.6	----
Zinc, ppm	1	----
Iron, ppm	24	----
Nickel, ppm	26	----
Lead, ppm	<1	----
Calcium, ppm	17	----
Magnesium, ppm	5	----
CCAI	856	----
MJ / KG	40.21	----

Results compared with ISO Specification RMG 380. Based on this sample, the
Specification is met,

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

Intertek Caleb Brett

R E P O R T   O F   A N A L Y S I S

Vessel   : SUBMITTED SAMPLE AND ANALYSIS
   **Port/Terminal**   : U C RIVERSIDE
Customer Reference   : PO# RT10114026
    Our Reference   : 260-0007627
Date Sample Taken   : ---
Date Submitted   : 09/08/07
Date Tested   : 09/11-12/07
Sample Designated As : H.F.O
Drawn By   : AS SUBMITTED
Representing   : # HFO 09-06 TEST
    Lab Reference   : 07-15131

TEST	METHOD	RESULT	UNITS
Density @ 15°C	D 4052	0.9911	g/ml
Density @ 20°C	D 4052	0.9854	g/ml
Viscosity @ 40ºC	D 445	743.4	cSt
Viscosity @ 100ºC	D 445	31.78	cSt
Sulfur Content	D 4294	2.03	Wt%
Ash Content	D 482	0.072	Wt%
Micro Carbon Residue (10%Btms)	D 4530	14.71	Wt%
Water by Distillation	D 95	0.05	Vol%
Heat of Combustion	D 4868	17299	btu/lb
Carbon Content	D 5291	85.87	Wt%
Oxygen Content	D 5291	1.64	Wt%
Hydrogen Content	D 5291	9.63	Wt%
Nitrogen Content	D 5291	0.46	Wt%

Los Angeles Laboratory
941 Freeman Ave, Suite A Signal Hill, Ca 90755

C.8 Gas Analyzer Calibrations

PG-250 CALIBRATION (9/25/06)

PG-250 CALIBRATION (9/25/06)
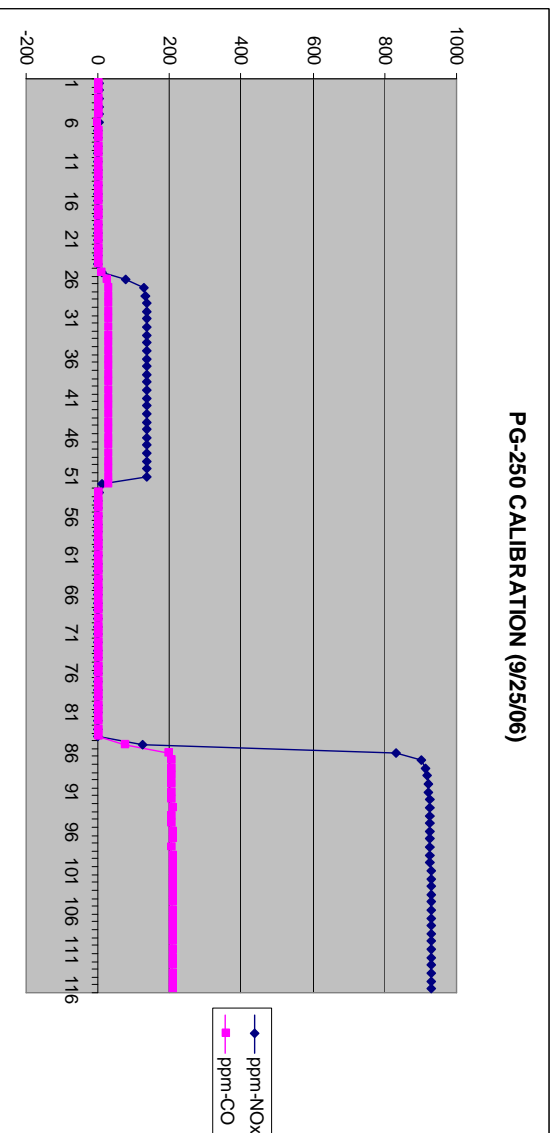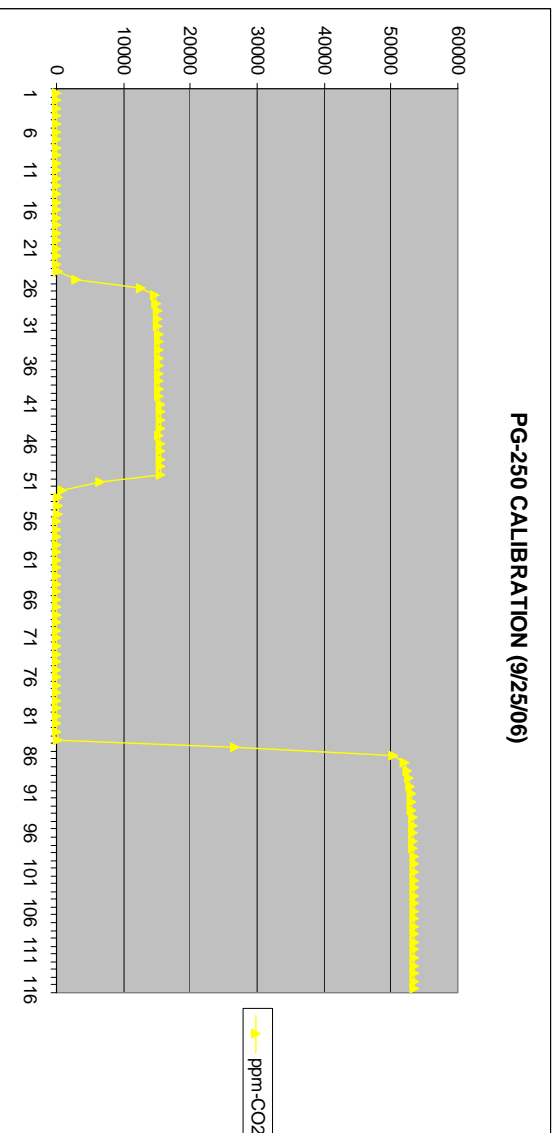
	Low Zero Meas	Low Meas	Low Cert.	High Meas	High Cert.
CO2	0	15500	15600	53600	52000
NOx	0.1	137	149	929	975
CO	-0.3	26.2	25.1	206	203

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

PG-250 POST-TEST CAL CHECK (9/26/06)

Legend: ppm-CO2

PG-250 POST-TEST CAL CHECK (9/26/06)

Legend: ppm-NOx, ppm-CO

Pre-Test	Low Zero	Low Meas	Low Cert.	High Meas	High Cert.
CO2	0	15500	15600	53600	52000
NOx	0.1	137	149	929	975
CO	-0.3	26.2	25.1	206	203

Post-Test	Low Zero	Low Meas	Low Cert.	High Meas	High Cert.
CO2	0	15500	15600	53600	52000
NOx	0.3	139.6	149	929	975
CO	-0.5	27.2	25.1	206	203

	Corr. Fact.	LOW
CO2	0.9936	
NOx	0.9282	
CO	1.0637	
Span Drift		
CO2		0.0%
NOx		1.0%
CO		0.5%
Zero Drft		
CO2		0.0%
NOx		0.1%
CO		-0.1%

PRAXAIR

Praxair
5700 South Alameda Street
Los Angeles, CA 90058
Telephone: (323) 585-2154
Facsimile: (714) 542-6689

Received at 5/20/06

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

CUSTOMER   UC RIVERSIDE   **P.O NUMBER**

REFERENCE STANDARD

COMPONENT	NIST SRM NO.	CYLINDER NO.	CONCENTRATION
CARBON MONOXIDE GMIS	vs.SRM#2613	CC 50887	24.42 ppm
NITRIC OXIDE GMIS	SRM#1685b	CC 155474	258.2 ppm
CARBON DIOXIDE GMIS	vs.SRM#2626	SA 14765	2.573 %

ANALYZER READINGS

R=REFERENCE STANDARD   Z=ZERO GAS   C=GAS CANDIDATE

1. COMPONENT CARBON MONOXIDE GMIS   **ANALYZER MAKE-MODEL-S/N** Siemens Ultramat 5E S/N A12-729
ANALYTICAL PRINCIPLE NDIR
FIRST ANALYSIS DATE 05/16/06   **LAST CALIBRATION DATE** 05/03/06
                                                SECOND ANALYSIS DATE 05/23/06

Z 0.00	R 24.60	C 25.20	CONC. 25.0	Z 0.00	R 24.55	C 25.30	CONC. 25.2
R 24.65	Z 0.00	C 25.20	CONC. 25.0	R 24.60	Z 0.00	C 25.35	CONC. 25.2
Z 0.00	C 25.15	R 24.60	CONC. 25.0	Z 0.00	C 25.30	R 24.60	CONC. 25.1
U/M ppm		MEAN TEST ASSAY 25.0		U/M ppm		MEAN TEST ASSAY 25.2	

2. COMPONENT NITRIC OXIDE GMIS   **ANALYZER MAKE-MODEL-S/N** Thermo Env. 42H S/N 42H-44979-273
ANALYTICAL PRINCIPLE CHEMILUMINESCENCE
FIRST ANALYSIS DATE 05/16/06   **LAST CALIBRATION DATE** 05/02/06
                                                SECOND ANALYSIS DATE 05/23/06

Z 0	R 254	C 147	CONC. 149	Z 0	R 244	C 142	CONC. 150
R 254	Z 0	C 146	CONC. 148	R 245	Z 0	C 141	CONC. 149
Z 0	C 145	R 253	CONC. 148	Z 0	C 141	R 245	CONC. 149
U/M ppm		MEAN TEST ASSAY 148		U/M ppm		MEAN TEST ASSAY 149	

3. COMPONENT CARBON DIOXIDE GMIS   **ANALYZER MAKE-MODEL-S/N** Siemens Ultramat 5E S/N A12-730
ANALYTICAL PRINCIPLE NDIR
FIRST ANALYSIS DATE 05/16/06   **LAST CALIBRATION DATE** 05/03/06
                                                SECOND ANALYSIS DATE

Z 0.000	R 2.570	C 1.565	CONC. 1.57	Z	R	C	CONC.
R 2.575	Z 0.000	C 1.560	CONC. 1.56	R	Z	C	CONC.
Z 0.000	C 1.555	R 2.570	CONC. 1.56	Z	C	R	CONC.
U/M %		MEAN TEST ASSAY 1.56		U/M %		MEAN TEST ASSAY	

THIS CYLINDER NO. SA 25921   **CERTIFIED CONCENTRATION**
HAS BEEN CERTIFIED ACCORDING TO SECTION
OF TRACEABILITY PROTOCOL NO. EPA-600/R97/121 REV. 9/97

CARBON MONOXIDE	25.1 ppm
NITRIC OXIDE	149 ppm
CARBON DIOXIDE	1.56 %
NITROGEN	BALANCE

PROCEDURE G1
CERTIFIED ACCURACY ± 1 **% NIST TRACEABLE**
CYLINDER PRESSURE 2000 PSIG
CERTIFICATION DATE 05/23/06
EXPIRATION DATE 05/23/08 **TERM** 24 MONTHS

VALUES NOT VALID BELOW 150 PSIG.
NOx=151 ppm FOR REFERENCE USE ONLY.

ANALYZED BY   Henry Koung   **CERTIFIED BY**   Jack Fu

Emissions from the Main Propulsion Engine on a Pamamax Class Ship

PRAXAIR

Praxair
5700 South Alameda Street
Los Angeles, CA 90058
Telephone: (323) 585-2154
Facsimile: (714) 542-6689

CERTIFICATE OF ANALYSIS / EPA PROTOCOL GAS

CUSTOMER UC RIVERSIDE   **P.O NUMBER**

REFERENCE STANDARD

COMPONENT		NIST SRM NO.	CYLINDER NO.	CONCENTRATION
CARBON MONOXIDE	GMIS	SRM#2636a	CC 134908	250.6 ppm
NITRIC OXIDE	GMIS	SRM#1687b	CC 63690	991 ppm
CARBON DIOXIDE	GMIS	SRM#1674b	SA 11563	5.03 %

ANALYZER READINGS

R=REFERENCE STANDARD   **Z=ZERO GAS**   **C=GAS CANDIDATE**

1. COMPONENT CARBON MONOXIDE GMIS   **ANALYZER MAKE-MODEL-S/N** Siemens Ultramat 5E S/N A12-729
ANALYTICAL PRINCIPLE NDIR   **LAST CALIBRATION DATE** 11/01/05
FIRST ANALYSIS DATE 11/09/05   **SECOND ANALYSIS DATE** 11/16/05

Z 0.0	R 250.6	C 203.4	CONC. 203	Z 0.0	R 250.6	C 203.2	CONC. 203
R 250.6	Z 0.0	C 203.2	CONC. 203	R 250.6	Z 0.0	C 203.2	CONC. 203
Z 0.0	C 203.4	R 250.6	CONC. 203	Z 0.0	C 203.4	R 250.6	CONC. 203
U/M ppm		MEAN TEST ASSAY 203 ppm		U/M ppm		MEAN TEST ASSAY 203 ppm	

2. COMPONENT NITRIC OXIDE GMIS   **ANALYZER MAKE-MODEL-S/N** Thermo Env. 42H S/N 42H-44979-273
ANALYTICAL PRINCIPLE Chemiluminescence   **LAST CALIBRATION DATE** 11/01/05
FIRST ANALYSIS DATE 11/09/05   **SECOND ANALYSIS DATE** 11/16/05

Z 0	R 941	C 931	CONC. 980	Z 0	R 990	C 975	CONC. 976
R 941	Z 0	C 925	CONC. 974	R 991	Z 0	C 976	CONC. 976
Z 0	C 924	R 946	CONC. 967	Z 0	C 975	R 991	CONC. 975
U/M ppm		MEAN TEST ASSAY 974 ppm		U/M ppm		MEAN TEST ASSAY 976 ppm	

3. COMPONENT CARBON DIOXIDE GMIS   **ANALYZER MAKE-MODEL-S/N** Siemens Ultramat 5E S/N A12-730
ANALYTICAL PRINCIPLE NDIR   **LAST CALIBRATION DATE** 11/01/05
FIRST ANALYSIS DATE 11/09/05   **SECOND ANALYSIS DATE**

Z 0.00	R 5.03	C 5.19	CONC. 5.19	Z	R	C	CONC.
R 5.02	Z 0.00	C 5.19	CONC. 5.20	R	Z	C	CONC.
Z 0.00	C 5.20	R 5.03	CONC. 5.20	Z	C	R	CONC.
U/M %		MEAN TEST ASSAY 5.20 %		U/M %		MEAN TEST ASSAY	

THIS CYLINDER NO. FF 20592

HAS BEEN CERTIFIED ACCORDING TO SECTION EPA-600/R97/121
OF TRACEABILITY PROTOCOL NO. Rev. 9/97
PROCEDURE G1
CERTIFIED ACCURACY ± 1 **% NIST TRACEABLE**
CYLINDER PRESSURE 2000 **PSIG**
CERTIFICATION DATE 11/16/05
EXPIRATION DATE 11/16/07 **TERM** 24 MONTHS

CERTIFIED CONCENTRATION

CARBON MONOXIDE	203 ppm
NITRIC OXIDE	975 ppm
CARBON DIOXIDE	5.20 %
NITROGEN	BALANCE

NOx= 996ppm(For reference only). Values not valid below 150 psig. NO conc. is corrected for CO2 interfernece.

ANALYZED BY HENRY KOUNG   **CERTIFIED BY** CHRIS VU