# Determination of Emissions from a Very Large Crude Carrier Using Two Different Fuels

**FINAL REPORT**

**ARB contract #12-425**

**Prepared for:**

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# Disclaimer

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# Table of Contents

## Table of Tables

## Table of Figures

# Abstract

Beginning in July 2009, a California regulation has required ocean-going vessels (OGVs) to use marine distillate fuels with progressively lower fuel sulfur contents when within 24 nm of the California coastline (including the islands) and while in port. Since January 2014, OGVs are required to use marine distillate fuels with a fuel sulfur content of 0.1% or less by weight. The North American Emission Control Area (ECA) began implementation in August of 2012 and also established fuel sulfur requirements. In January 2015, the ECA fuel sulfur limit was lowered to ≤ 0.1% by weight consistent with the California regulation. However, the ECA does not specify the use of marine distillate fuels and OGVs may use non-distillate fuels, such as a low sulfur heavy fuel oil to comply with the ECA requirements.

This work presents the in-use criteria pollutant emissions and ultrafine particles from a modern very large crude oil carrier (VLCC) while operating on two different fuels: a marine gas oil (MGO) with less than 0.1% sulfur fuel and a novel low sulfur heavy fuel oil (HFO) that has a fuel sulfur level less than 0.1%. Measurements in this study followed the International Organization for Standardization (ISO) 8178 sampling procedures and protocol for in-use emissions testing and sample analysis. The overall plan focused on the measurement of the gaseous and particulate emissions, including: carbon oxides (CO, CO2,), oxides of nitrogen (NOx) and particulate matter (PM2.5), while the chosen engine operated at steady-state conditions specified in ISO 8178 with either California/ECA-compliant marine gas oil (MGO) or the new, low sulfur HFO that can be used to meet the ECA requirements.

# Executive Summary

## Background

OGVs are significant contributors to California statewide emissions of diesel particulate matter (PM), diesel PM with aerodynamic diameters less than 2.5 micrometers ($PM_{2.5}$), nitrogen oxides (NOx), and sulfur oxides (SOx). In response to growing concerns regarding the emissions of OGVs, California enacted a regulation in 2008 to require the use of lower sulfur marine distillate fuels. This regulation, the OGV Clean Fuel Regulation,[1] requires vessel operators within 24 nautical miles (nm) of the California coastline and islands to use cleaner low sulfur distillate fuels (either marine diesel oil or marine gas oil) in their main engine, auxiliary engines, and auxiliary boilers. The fuel standards are implemented in two phases. Beginning January 1, 2014, the fuel sulfur limit was ≤ 0.1% sulfur by weight.

On March 26, 2010, the International Maritime Organization (IMO) officially designated waters of the United States and Canadian coastlines as an Emission Control Area (ECA) pursuant to Annex VI of the MARPOL Convention. Within the ECA boundary which extends 200 nm offshore, vessels are required to use lower sulfur fuels. Unlike the California OGV Clean Fuel Regulation, the ECA does not specify what type of fuel; rather it establishes a limit only on the fuel sulfur level. The ECA began implementation in August 2012, with a 1 percent sulfur limit that then dropped to a ≤ 0.1% sulfur limit on January 1, 2015. While it was expected that most vessel operators would use low sulfur marine distillate fuels such as MGO or marine diesel oil (MDO) to comply with the ECA, a new low sulfur heavy fuel oil (HFO) has been marketed and made commercially available that can meet the ECA fuel sulfur requirements. The California Air Resources Board is interested in assessing the emissions impacts of switching to this new low sulfur HFO.

## Approach

The overall objective for this evaluation was to determine and compare emissions from four-stroke diesel electric marine engines operating on a ≤ 0.1% sulfur by weight HFO and a ≤ 0.1% sulfur by weight MGO. The study required a vessel for the test platform and a shipping company provided a vessel representative of the very large crude carriers (VLCC) that operate throughout the world. Testing took place as the VLCC travelled from the Port of Los Angeles to Port Angeles, WA. Sampling of the actual in-use emissions of gases ($CO_2$, CO, and $NO_x$) and particulate matter ($PM_{2.5}$) mass from each of two main generator engines was in compliance with the ISO 8178-2 protocol while the engine operating conditions followed the ISO 8178-4 D2 certification test cycle.

## Results

Overall nitrogen oxide (NOx) emission factors were 10.2±0.08 g/kWh and 10.7±0.03 g/kWh for HFO and MGO respectively, which are both well below the Tier 1 NOx standard of 12.9 g/kWh for a medium speed, 512 rpm engine. Additionally, the NOx emission factors measured in this study are well below the 18.7 g/kWh and 18.1 g/kWh emission factors specified by Lloyds services data and the US EPA/ARB for main engine OGVs.

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[1] Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline. title13, California Code of Regulations (CCR) §2299.2 and title 17, CCR §93118.2.

The $PM_{2.5}$ emission factors were 0.62±0.01 g/kWh for HFO and 0.20±0.02 g/kWh for MGO which are well below those listed by Lloyds service data (1.23 g/kWh), US EPA (1.08 g/kWh) and CARB (1.5 g/kWh) due to the very low sulfur content of HFO used in this study. PM was composed mainly of organic carbon (OC) for both fuels with very little elemental carbon (EC) present. Real-time soot measurements with the AVL micro-soot sensor (MSS) and EC analyzed by NIOSH method agreed very well with R2 values of 0.99 while real-time PM with the PPS-M sensor were 40% and 57% lower than gravimetric PM2.5 for HFO and MGO. Differences in these measurements are attributed to semi-volatile and volatile components which contribute to positive filter sorption artifact that are not measured with the heated PPS-M sensor. PM mass measured by the SMPS was much lower than gravimetric PM2.5 mass due to evaporation effects at high measurement dilution ratios. Size distributions showed unimodal peaks for both HFO (30-50 nm) and MGO (20-30 nm) where size increased with decreasing load. Overall, particle number (PN) emissions were 28% and 17% higher with the Pegasor Particle Sensor (PPS-M) compared to the Scanning Mobility Particle Spectrometer (SMPS) for the HFO and MGO, respectively.

## Conclusions

This research characterized the emissions from a VLCC transiting from the Port of Long Beach, CA to Port Angeles, WA using two fuels: a low sulfur MGO and low sulfur HFO. It provides the first in-use testing of a novel low sulfur HFO fuel that provides an alternative to using low sulfur marine distillate fuels as a compliance option under the ECA. Overall, data showed that $NO_x$ emissions were slightly higher with MGO compared to HFO. The $PM_{2.5}$ mass measurements showed approximately 70% higher emissions with HFO compared to MGO. PM emissions resulted in the highest emissions at the 10% load point due to being off optimized load. PM emissions from the SMPS as a function of load showed peak number concentrations ranging from 30 to 50 nm with HFO and 20 to 30 nm with MGO.

Real-time black carbon measured with the AVL MSS and off-line analysis of EC by the NIOSH method compare very well with $R^2>0.99$ and slopes of approximately 1. Real-time PM from the PPS-M sensor is well below the $PM_{2.5}$ measured gravimetrically. This is attributed due to differences in methodology as the PPS-M sensor measures a fraction of the volatiles measured gravimetrically from Teflo filters. Additionally, differences between PM mass from the SMPS and $PM_{2.5}$ measured gravimetrically can be attributed to evaporation of the smaller particles.

# 1 Introduction

OGVs are significant contributors to California statewide emissions of diesel particulate matter (PM), diesel PM with aerodynamic diameters less than 2.5 micrometers (PM2.5), nitrogen oxides (NOx), and sulfur oxides (SOx). In response to growing concerns regarding the emissions of OGVs, California enacted a regulation in 2008 to require the use of lower sulfur marine distillate fuels. This regulation, the OGV Clean Fuel Regulation, requires vessel operators within 24 nautical miles (nm) of the California coastline and islands (California Regulated Waters) to use cleaner low sulfur distillate fuels (either marine diesel oil or marine gas oil) in their main engine, auxiliary engines, and auxiliary boilers. The fuel standards are implemented in two phases beginning in July 2009. Since January 1, 2014, the fuel sulfur limit was ≤ 0.1% sulfur by weight.

On March 26, 2010, the International Maritime Organization (IMO) officially designated waters of the United States and Canadian coastlines as an Emission Control Area (ECA) pursuant to Annex VI of the MARPOL Convention. Within the ECA boundary which extends 200 nm offshore, vessels are required to use lower sulfur fuels. Unlike the California OGV Clean Fuel Regulation, the ECA does not specify what type of fuel; rather it establishes a limit only on the fuel sulfur level. The ECA began implementation in August 2012, with a 1 percent sulfur limit that then dropped to ≤ 0.1% sulfur on January 1, 2015. While it was expected that most vessel operators will use low sulfur marine distillate fuels to comply with the ECA, a new low sulfur heavy fuel oil (HFO) has been developed that can meet the ECA fuel sulfur requirements.

The California OGV Clean Fuel Regulation includes a sunset provision which states that the requirements of the California OGV Fuel Regulation will cease to apply if the United States adopts and enforces requirements that will achieve equivalent emissions reductions to the California OGV Fuel Regulation within Regulated California Waters. To help with the assessment of the emissions impacts of the ECA, the California Air Resources Board is interested in assessing the emissions impacts of switching to this new low sulfur HFO.

To evaluate the emissions impacts of using the low sulfur HFO, emission testing was done to determine and compare emissions from four-stroke diesel electric marine engines operating on ≤ 0.1% sulfur by weight HFO and a ≤ 0.1% sulfur by weight marine gas oil (MGO). The vessel selected for testing was representative of the very large crude carriers (VLCC) that operate throughout the world. Emission testing took place as the VLCC travelled from the Port of Long Beach, CA to Port Angeles, WA.

# 2 Approach

## 1.1 Overview

To evaluate the exhaust emissions of the VLCC, the measurement of the gaseous and particulate emissions, including: carbon oxides (CO, $CO_2$,), oxides of nitrogen ($NO_x$) and particulate matter ($PM_{2.5}$), while the chosen engine operated at steady-state conditions specified in ISO 8178 with either MGO or the new, low sulfur HFO each having fuel sulfur contents of less than 0.1% sulfur by weight was conducted. Measurement methods were IMO and ISO compliant for both the gases and PM. The following sections provide detailed information.

## 1.2 In-use Emission Measurements Using IMO and ISO Methods

Simultaneous measurement of $NO_x$, CO, $CO_2$ from the main marine generator engine exhausts where conducted using the in-use Simplified Measurement Methods (SMM) system that is compliant with the International Maritime Organization (IMO) $NO_x$ Technical Code. ISO methods were used to measure $PM_{2.5}$ mass.

### *1.2.1 Test Vessel, Engine and Fuels*[2]

The vessel selected for the test program was a VLCC. The vessel is powered by four MAN B&W 6L48/60 medium speed diesel engines, each rated at 6.3MW, giving a total installed power of 25.2 MW. Operating data for one of the four MAN B&W 6L48/60 engines is included in Appendix C. Appendix C points out that a number of components, settings and operating values can influence the NOx emissions. One important feature of the engines was the variable injection timing (VIT) and other tools to lower NOx are listed in Appendix B. Note the engines operate a constant speed of 512 rpm so testing follows the ISO 8178 E2 cycle rather than the ISO 8178 E3 propeller curve.

The emissions in this study were characterized for two fuels: a low sulfur MGO (0.005% sulfur by weight) and a low-sulfur HFO (0.011% sulfur by weight) that is commercially available and provides ship operators with the potential of using either marine distillate or HFO to meet the required sulfur limits within the ECA. Both fuels have very little sulfur, ash and vanadium. The main differences in the fuel properties are the viscosity, pour point and micro carbon residue (MCR).

### *1.2.2 Operating Conditions of the Engine while Measuring Emissions*

The MAN B&W 6L48/60 engines on this vessel drive generators to power the electric motors which propel the vessel. Therefore the appropriate test procedure for these engines is with the engine operating according to the 5-modes of the ISO-8178-4 D2 cycle shown in Table 2-1.

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[2] Descriptions and Figures taken from U.S. Department of Transportation Maritime Administration (MARAD) Alternative Fuel for Marine Application Test Plan, 8/23/11 Revised DRAFT

**Table 2-1: Standard Cycle for Testing Marine Propulsion Engines**

| Mode | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Speed | Rated Speed | | | |
| Load | 100% | 75% | 50% | 25% |
| Weighting Factor | 0.20 | 0.50 | 0.15 | 0.15 |

For the ISO cycles, the engine is run for about 30 minutes at rated speed and the highest power possible to warm the engine and stabilize emissions. A plot or map of the peak power at each engine RPM is determined starting with the rated speed. If CE-CERT suspects the 100% load point at rated speed is unattainable, then we select the highest possible load on the engine as Mode 1.

The emissions are measured while the engine operates according to the requirements of ISO-8178-D2. For a diesel engine the highest power mode is run first and then each mode is run in sequence The minimum time for samples is 5 minutes and if necessary, the time is extended to collect sufficient particulate sample mass or to achieve stabilization with large engines. The gaseous exhaust emission concentration values are measured and recorded for the last 3 minutes of the mode.

Engine speed, displacement, boost pressure, and intake manifold temperature are measured to calculate the gaseous flow rate. Emissions factors are calculated in terms of grams per kilowatt hour for each of the operating modes and fuels tested, allowing for emissions comparisons of each fuel relative to the baseline fuel.

The achievable load points were determined at the time of testing and depended on several factors; including constraints by current, wave pattern, and wind speed/direction. Efforts were made to conduct the emissions measurements for each engine at loads as close as possible to those specified in ISO 8178 D2.

### *1.2.3 Engine Performance Measurements during Testing*

Chapter 6 of the $NO_x$ Technical Code[3], "Procedures for demonstrating compliance with $NO_x$ emission limits on board" provides detailed instructions for the required measurements for on-board testing. Some of the engine performance parameters measured or calculated for each mode during the emissions testing are shown in Table 2-2.

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[3] International Maritime Organization, Marine Environment Protection Committee: *Prevention Of Air Pollution From Ships; Report of the Working Group on Annex VI and the NOx Technical Code* (MEPC 57/Wp.7/Add.2 3) April 2008

**Table 2-2: Engine Parameters Measured and Recorded**

| Parameter | Units |
|---|---|
| Load | kW |
| Engine Speed | RPM |
| Generator Output | Amps |
| Fuel supply | Gph |
| Fuel return | Gph |
| Air intake pressure | Psi |
| Air intake temperature | °F |

### *1.2.4 Measurement of Gaseous and Particulate Matter Emissions*

The emission measurements were performed using a partial dilution system that was developed based on the ISO 8178-1 protocol and detailed information is provided in Appendix B, "Measuring Gaseous & Particulate Emissions".

In measuring the gaseous and particulate emissions, CE-CERT followed ISO 8178-2 and Chapter 5 of the $NO_x$ Technical Code as they provide the general requirements for onboard measurements. 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. 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. Environmental Protection Agency Environmental Technology Verification (EPA ETV) program. The signal output of the instrument is interfaced directly with a data acquisition system through an RS-232C interface to record measured values continuously.

The engine parameters noted in Table 2-2 were obtained on the engine control room monitors from screen shots taken by the crew during each mode of operation. Since all measurements are made under steady state operating conditions, periodic screen shots were sufficient.

Emissions were measured while the engine operated at the test modes specified in ISO 8178-4, Table 2-1. The measuring equipment and calibration frequencies met IMO Standards. The details of the CE-CERT equipment are provided in Appendix B, "Measuring Gaseous & Particulate Emissions."

In addition to measuring criteria emissions, additional measurements were made to further characterize the PM emissions. Real-time particulate matter measurements included an AVL MSS, which employs a photo-acoustic method to measure the solid soot fraction of PM. A Pegasor PPS-M sensor was used to characterize both the solid and condensable fractions of total particulate matter mass and number. The PPS-M sensor uses an "escaping current" method where clean air is ionized and mixed with the sample stream thereby charging the particles. The escaping current from the sample is then measured at a fixed flowrate by a faraday cup. A default trap voltage of 400V was used for the PPS-M sensor. Real-time particle size distributions were measured with a Scanning Mobility Particle Spectrometer (SMPS) comprised of a TSI model 3080 classifier, 3081 differential mobility analyzer (DMA) and TSI 3776 condensation particle counter (CPC). A secondary ejector dilution system was added for additional dilution for the SMPS.

# 3 Data Analysis

After returning from the on-board measurement testing, the instrument calibration and raw test data was placed in an Excel file. The calibration and raw test data was then post processed in this file to produce QC summaries and final results summaries for review by the Project Manager.

**Calculation of Emission Factors**

The emission factors at each mode are calculated from the measured gaseous 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 8178 E2 requirements 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 (CO, $CO_2$, $PM_{2.5}$, or $NO_x$) in g/kW-hr
$g_i$ = Mass flow in grams per hour at the $i^{th}$ mode,
$P_i$ = Power measured during each mode, and
$WF_i$ = Effective weighing factor.

## 3.1 Calculation of the Exhaust Flow

Clearly the calculated emission factor is strongly dependent on the mass flow of the exhaust. Two methods for calculating the exhaust gas mass flow are suggested where one uses the carbon balance approach as per ISO 8178[4] and by a speed-density approach, see Appendix A for details. Both methods are based on the measured exhaust gas concentrations and fuel usage rate. The two ISO methods are described below.

### *3.1.1 Carbon balance*

The carbon balance method, calculates the exhaust mass flow based on the measurement of fuel usage and the exhaust gas concentrations with regard to the fuel characteristics (carbon balance method). The carbon balance methods may be used to calculate exhaust flow rate when the fuel usage is measured 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 can only be used when the fuel usage data are available.

### *1.2.5 Speed-density (engine as an air pump)*

This method has been widely used for calculating exhaust flow rate in diesel engines, especially stationary diesel engines. This method assumes the engine is an air pump, and the flow rate is

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[4] *International Standards Organization, IS0 8178-1,* Reciprocating internal combustion engines - Exhaust emission measurement -Part 2: Measurement of gaseous particulate exhaust emissions at site, *First edition 1996-08-l5*

determined from displacement of the cylinder, recorded rpm, with corrections for the temperature and pressure of the inlet air. This method assumes the combustion air flow equals the total exhaust flow. However, for low-speed, two stroke engines, there could be scavenger air flow while the piston is expanding and the exhaust valve is still open. This scavenger air would not be included in the air pump calculation leading to under predicting the total exhaust flow and the emission factors. The method works best for four stroke engines or for two-stroke engines where the scavenger air flow is much smaller than the combustion air.

### *3.1.2 Calculation used*

Given the difficulty in obtaining accurate fuel usage data from large ocean going vessels the carbon balance method is commonly not reliable. As such, UCR performs both methods and determines the most reasonable during reporting. For this testing, the fuel flow rate was not reliable and the exhaust flow was estimated based on using the speed-density approach described above.

# 4 Emission Results

This section presents the results and analysis of the measured emissions of pollutants as a function of fuel type and engine load.

## 4.1 Test Fuels

The properties of the ECA-compliant MGO and the low sulfur HFO are presented in Table 4-1.

**Table 4-1: Fuel Properties**

| fuel | units | Certificate of Analysis (COA) | |
|---|---|---|---|
| | | HFO | MGO |
| density @ 15 $^0$C | kg/m$^3$ | 845.2 | 850.9 |
| viscosity @ 40 $^0$C | cSt | 12.07 | 3 |
| pour point | $^0$C | 18 | -24 |
| MCR | % m/m | 0.047 | 0.02 |
| sulfur | % m/m | 0.011 | 0.005 |
| ash | % m/m | 0 | 0 |
| vanadium | mg/kg | 0 | 0 |

## 4.2 Analysis of Emissions Factors

A key element of the test program was to measure emissions from each of the engines; one running on MGO and the other on low sulfur HFO. The following analysis presents the average emission factors at the average of the measured loads for the MGO and HFO.

### 4.2.1 *Actual test operating modes*

During the emission measurements, the engine was operated at load points close to those specified in ISO 8178 E2 with both fuels. The actual loads in Table 4-2 are typical of the type of deviation from the specified loads when trying to hit the set points while operating at sea.

**Table 4-2: Load Points (Nominal vs. Tested)**

| | ISO-8178 E2 | mode 1 | mode 2 | mode 3 | mode 4 |
|---|---|---|---|---|---|
| fuel | ISO Load | 100 | 75 | 50 | 25 |
| MGO | % | 98% | 73% | 51% | 24% |
| | MW | 6.0 | 4.5 | 3.1 | 1.5 |
| HFO | % | 99% | 73% | 50% | 23% |
| | MW | 6.0 | 4.4 | 3.0 | 1.4 |

Table Notes: MW = mega watt

### *4.2.2 Gaseous Emissions*

**Carbon Dioxide Emissions:** Carbon dioxide ($CO_2$) emissions are checked first as these values provide insight into the accuracy and representativeness of the data. Specifically, the data are reviewed to determine if the numbers are representative of certification values and when compared with similar types of engines.

Figure 4-1 presents the average emission factors at the average engine loads and includes the overall average weighted emission factor. The individual $CO_2$ emission factors are provided in Figure 4-3. Values obtained during this project, ~ 620 g/kW-hr, are about the expected values for a medium speed diesel engine. The higher $CO_2$ emission factors when using MGO are also expected due to the lower energy density of MGO comparted with HFO. Notice that the emissions factor increase significantly as the power decreases from the 25% load point. An increase in brake-specific fuel consumption when the engine is run below 20% load is expected due to decreased engine efficiency at low loads.

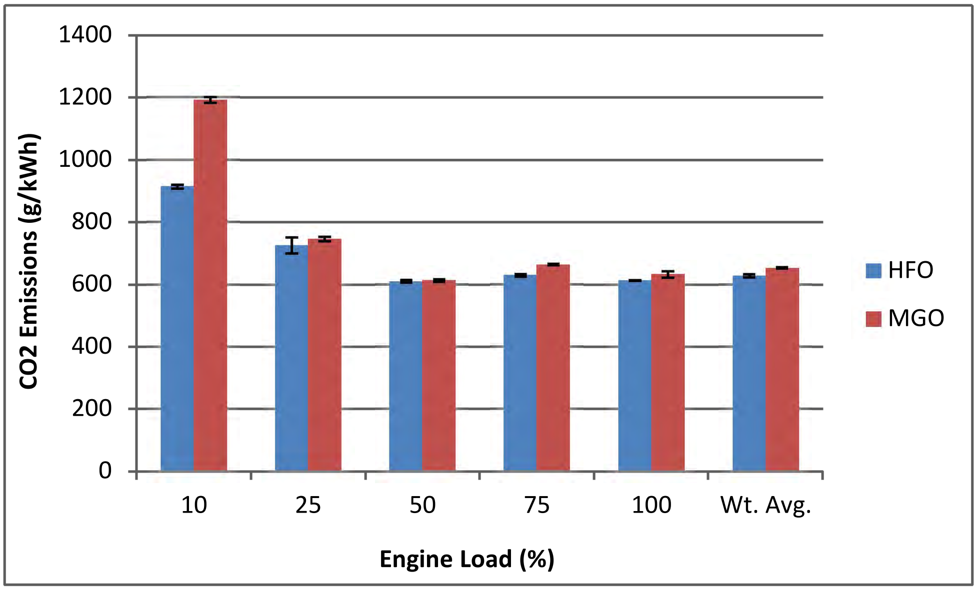

**Figure 4-1: Modal $CO_2$ Emission Factors and Overall Weighted Average**

**NOx Emissions:** The gaseous emission factors for $NO_x$ are presented in g/kW-hr in Figure 4-2. $NO_x$ emission for MGO generally exceeded those for HFO for all loads (except 75%) resulting in a ~5% statistically significant increase in the weighted average (MGO: 10.7±0.03 g/kWh, HFO: 10.2±0.03 g/kWh). These differences are partially accounted for by the fuel density as fuel injection is a volumetric process. MGO has a slightly higher density at 850.9 kg/$m^3$ compared to 845.2 kg/$m^3$ for HFO. Higher density fuels have more mass injection per unit volume compared to lower density fuels resulting in higher combustion temperatures and higher thermal $NO_x$ emissions.

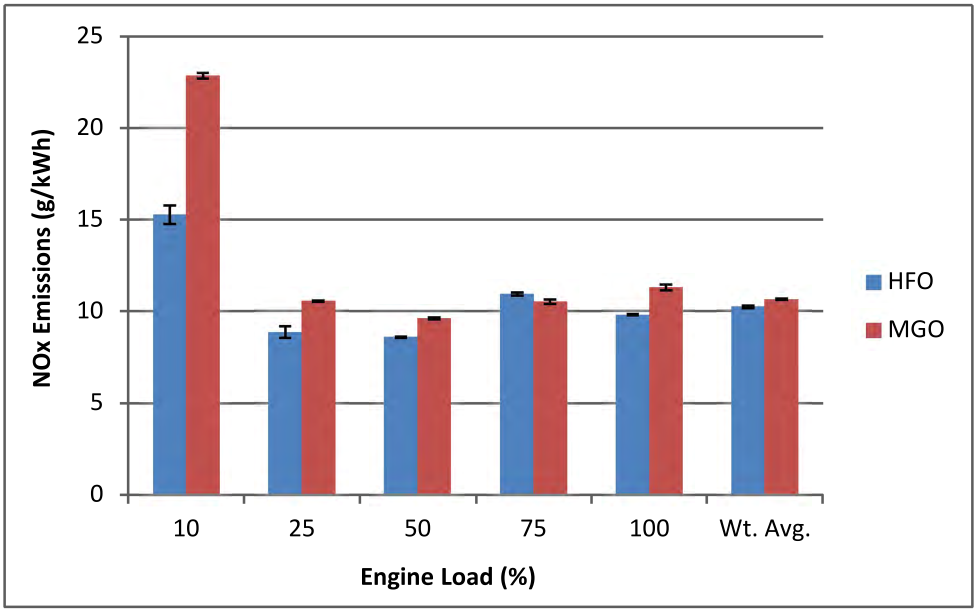

**Figure 4-2: Modal NOx Emission Factors and Overall Weighted Average**

**CO Emissions:** CO emission rates and factors are presented in g/kW-hr in Figure 4-3. CO emissions were low across all load points, which is typical of diesel engines. Statistically significantly higher CO emissions for HFO than MGO were noted at all loads except the 100% load point attributable to increased combustion efficiency at higher temperature due to fuel density.

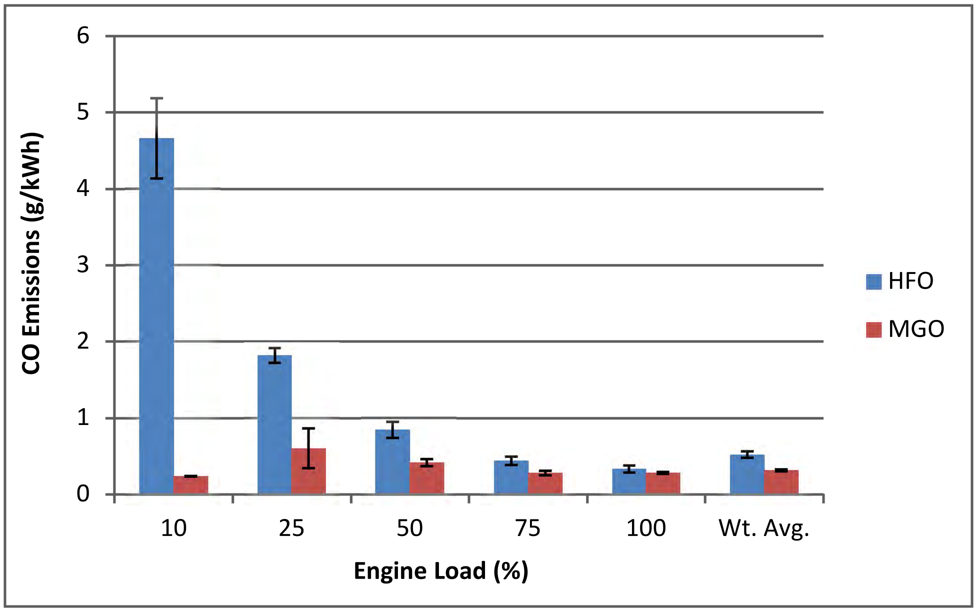

**Figure 4-3: Modal CO Emission Factors Overall Weighted Averages**

### *4.2.3 $PM_{2.5}$ Emissions*

In addition to the gaseous emissions, the test program measured emissions of $PM_{2.5}$ mass. Total $PM_{2.5}$ mass emissions from both fuels are plotted in Figure 4-4. The highest emission factors were observed at the 10% load point for HFO (3.7±0.13 g/kWh) and MGO (1.2±0.12 g/kWh) and decreased with increasing load. Weighted $PM_{2.5}$ mass emissions were approximately a factor of three lower for MGO (0.20±0.02 g/kWh) compared to HFO (0.62±0.01 g/kWh). These differences may be partially attributed to the higher viscosity and MCR of the fuel. Higher viscosity is more difficult to atomize into the piston leading to larger fuel droplets and less complete combustion leading to the observed higher PM and CO emissions for HFO.[5,6]

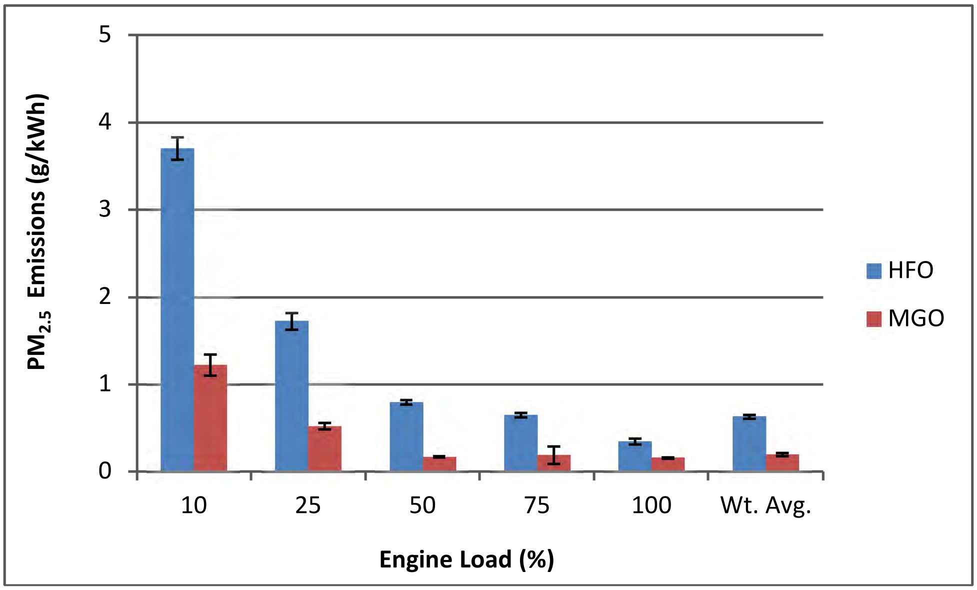

**Figure 4-4: Modal PM Emission Factors and Overall Weighted Averages**

### *4.2.4 PM Composition*

The PM mass was fractioned into elemental plus organic carbon to determine the composition of the mass. In this second measurement approach, a quartz filter captured the PM emissions from the same sample line used for the Teflon PM mass determination. The quartz filter was post processed into elemental carbon (EC) and an organic fraction (OC) of the PM.

An important element of CE-CERT's field program and analysis is the QA/QC check with independent methods. For example, the total $PM_{2.5}$ mass collected on the Teflo® filter should agree with the sum of the masses independently measured as elemental carbon and organic

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[5] . W. F. Northrop, P. V.Madathil, S. V. Bohac, and D. N. Assanis, "Condensational growth of particulate matter from partially premixed low temperature combustion of biodiesel in a compression ignition engine," *Aerosol Science and Technology*, vol. 45, no. 1, pp. 26–36, 2011.

[6] M. Deqing, Q. Junnan, S. Ping, M. Yan, Z. Shuang, and C. Yongjun, "Study on the combustion process and emissions of a turbocharged diesel engine with EGR," *Journal of Combustion*, vol. 2012, Article ID Article ID 932724, 9 pages, 2012.

carbon. To account for hydrogen and oxygen in the organic carbon, the organic carbon is multiplied by a factor of 1.2[7]. Observed EC/OC ratios were very low ranging from 0.02 to 0.05 for HFO and 0.03 to 0.14 for MGO which was consistent with those measured in past studies with similar fuels.[8,9,10] The EC plus organic matter (OM) $PM_{2.5}$ measured by EC and OC analysis by the NIOSH method can be compared to the total $PM_{2.5}$ measured gravimetrically on Teflo filters. This comparison is possible as there is little sulfur, ash and metals in both fuels, limiting their overall contribution to non-carbon $PM_{2.5}$. Linear regressions for both fuels show good correlations with $R^2$ values >0.99.

The plot showing the parity and the cumulative mass is provided below as Figure 4-5. Both lines are linear, showing very good agreement between the independent methods for measuring PM.

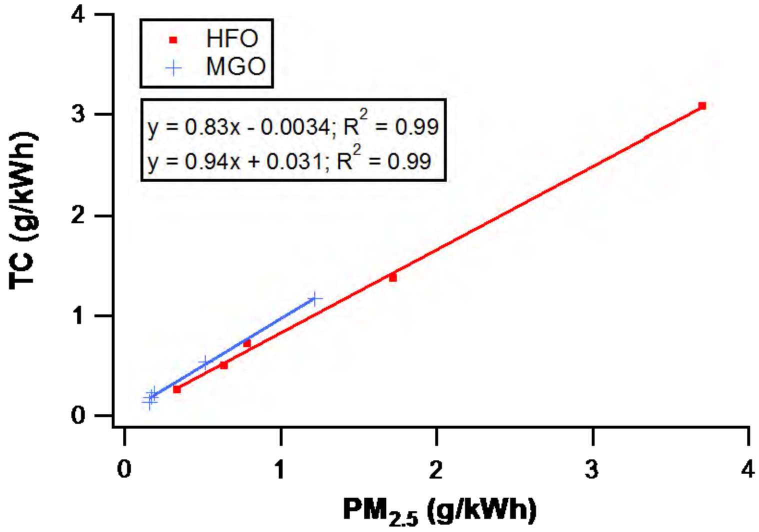

**Figure 4-5: Comparison of Teflon PM Mass with Cumulative Quartz Mass (EC + OC)**

### *4.2.5 Real-Time PM*

The correlation between EC collected on quartz filters and analyzed by the NIOSH method and soot measured in real-time by the photo-acoustic method AVL MSS are shown in Figure 4-6. For both HFO and MGO fuels, the resulting linear regressions show good agreement ($slope=1.01^{HFO}$ and $slope=1.03^{MGO}$) with excellent $R^2$ values >0.99.

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[7] Shah, S.D., Cocker, D.R., Miller, J.W., Norbeck, J.M. Emission rates of particulate matter and elemental and organic carbon from in-use diesel engines. *Environ. Sci. & Technology*, **2004**, 38 (9), pp 2544-2550.

[8] Agrawal, H., et al., *In-use gaseous and particulate matter emissions from a modern ocean going container vessel.* Atmospheric Environment, 2008. **42**(21): p. 5504-5510.

[9] Agrawal, H., et al., *Emissions from main propulsion engine on container ship at sea.* Journal of Geophysical Research-Atmospheres, 2010. **115**.

[10] Agrawal, H., et al., *Emission measurements from a crude oil tanker at sea.* Environmental Science & Technology, 2008. **42**(19): p. 7098-7103.

Kamboures et al.[11] previously measured an $R^2$ of 0.86 for AVL MSS versus EC determined by the IMPROVE_A method, while Khan et al.[12] previously measured an $R^2$ of 0.88 for PM measured by the AVL MSS.

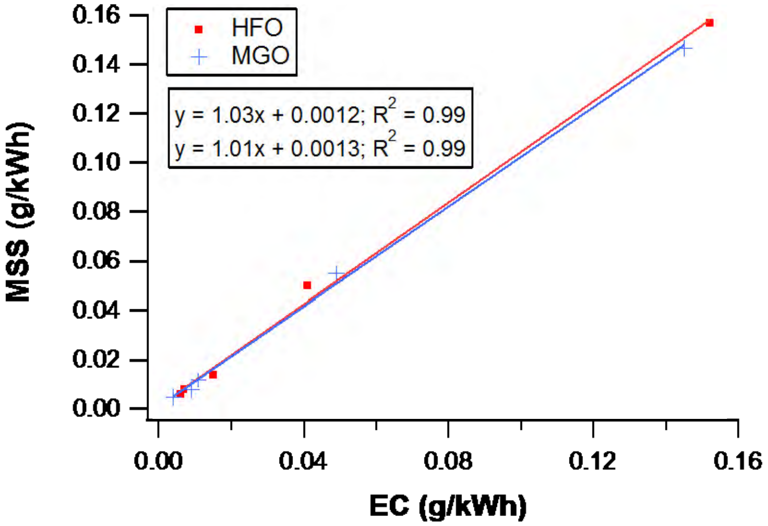

**Figure 4-6: Comparison of Photo-Acoustic Method vs. NIOSH Elemental Carbon**

Linear regressions in Figure 4-7 between the PPS-M sensor and $PM_{2.5}$ measured gravimetrically showed good agreement with $R^2$ >0.99 for both fuels. PPS-M sensor data was corrected using size distribution measured from the SMPS in this study as default calibration is based on size distributions with an average size of 50 nm.[11] The weighted emission factors show that real-time PM mass measured by the PPS-M sensor is approximately 39% lower than $PM_{2.5}$ teflon mass for HFO and 57% lower with MGO. Previous studies[11] have shown the PPS-M sensor to exhibit lower PM mass compared to filter based methods. These differences may be attributed to differences in measurement methods. PM filter collection followed ISO-8178 sampling protocol where the diluted sample stream is maintained at a temperature of <52 ºC before the filters. Species collected on these filters include solid and semi-volatiles. The PPS-M Sensor measures PM at 200 ºC while only measuring the solid and some of the volatile species. At these higher temperatures, the same volatile species collected on the Teflon filters will not be measured by the PPS-M sensor. Amanatidis et al.[11,13] stated from Giechaskiel et al. that heating the PPS-M sensor to 200ºC only partially removes the semi-volatile and volatile species. It was concluded that the PPS-M sensor should lie between the AVL MSS and the PM measured gravimetrically.

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[11] Kamboures, M.A.; Shishan, H., You, Y.; Sandoval, J.; Rieger, P.; Hugan, S-M, H; Zhang, S.; Dzhema, I.; Huo, D.; Ayala, A.; Oliver Change, M.C.; Black carbon emissions in gasoline vehicle exhaust: A measurement and instrument comparison. J. Air & Waste Management. **2013**, 63, 886-901.

[12] Amanatidis, S., Ntziachristos, L., Samaras, Z., Janka, K. et al., "Applicability of the Pegasor Particle Sensor to Measure Particle Number, Mass and PM Emissions," SAE Technical Paper 2013-24-0167, 2013, doi:10.4271/2013-24-0167.

[13] Giechaskiel, B.,& Drossinos,Y.(2010). Theoretical Investigation of Volatile Removal Efficiency of Particle Number Measurement Systems. SAE Technical Paper 2010-01-1304.

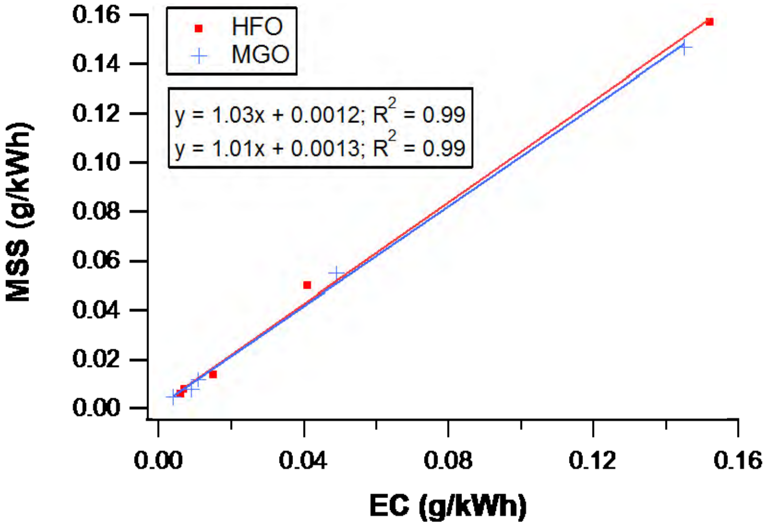

Figure 4-7: Comparison of PPS-M Method vs. Gravimetric $PM_{2.5}$

Figure 4-8 shows the correlation of the PM mass measured from the SMPS versus the $PM_{2.5}$ gravimetric mass. Both methods show good agreement as a function of fuel type with $R^2$>0.99. For the weighted emission factors, PM mass measured by the SMPS is approximately 46% lower than gravimetric $PM_{2.5}$ for HFO and 74% lower with MGO. This can be attributed to evaporation due to the high dilution ratios with the SMPS. The sample was diluted at approximately 73:1 before entering the SMPS. The sheath air within the unit further dilutes the sample at 10:1 for a total dilution ratio of 730:1.

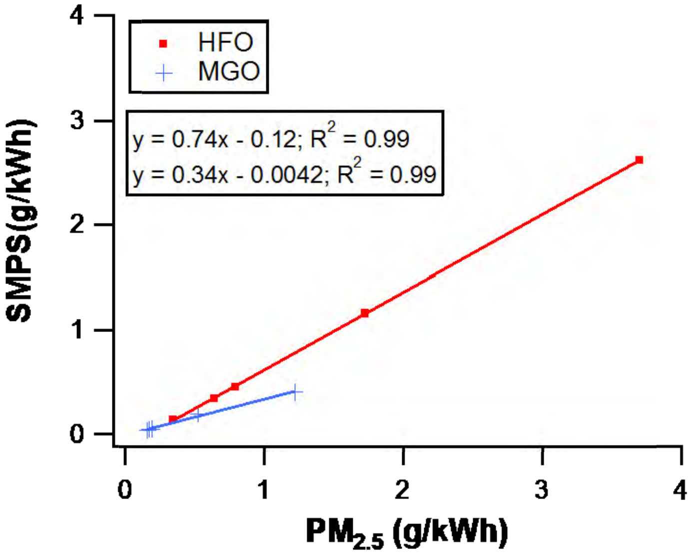

Figure 4-8: Comparison of SMPS Method vs. Gravimetric $PM_{2.5}$

The ratio of PM mass calculated from the SMPS and measured gravimetrically for both fuels was compared (Figure 5). This ratio known as the "density correction factor" is the density needed for the SMPS PM mass to equate to the gravimetric PM mass. As the peak mass diameter from the SMPS decreases from HFO to MGO, the density correction factor increases. At smaller diameters (MGO), more evaporation occurs with higher dilution ratios.

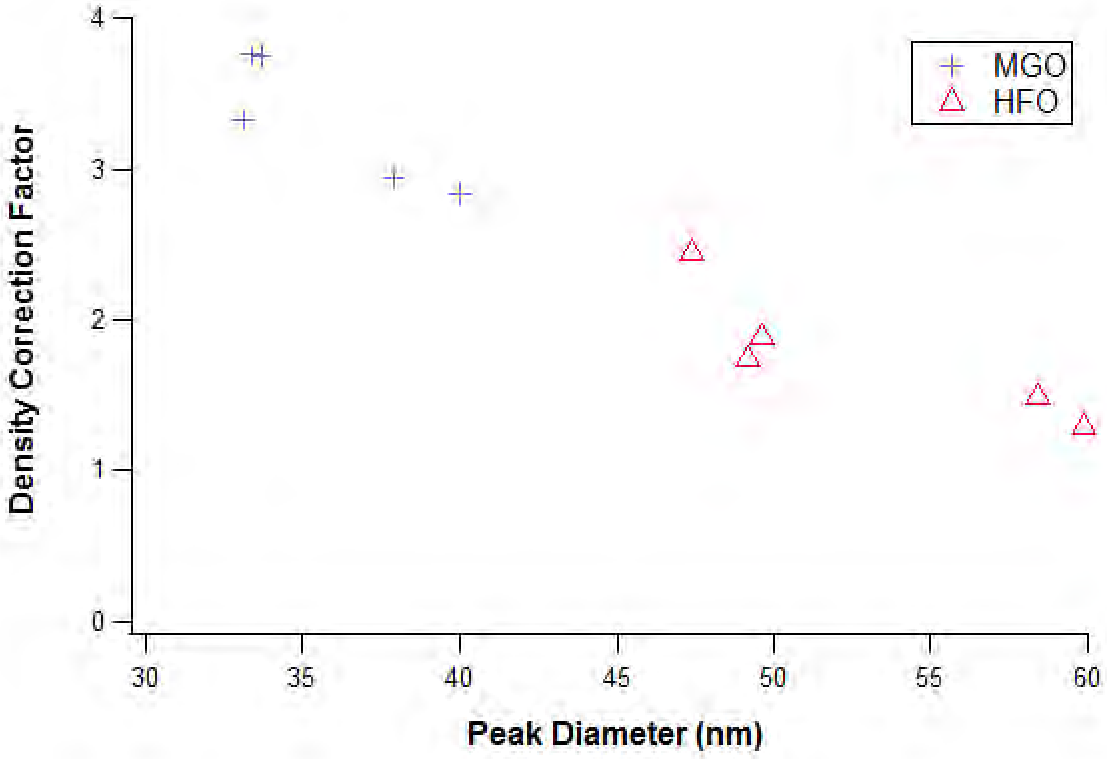

**Figure 4-9: Density Correction Factors for HFO and MGO**

### *4.2.6 Particle Size and Number*

The particle size distributions measured by the SMPS for HFO show peak number concentrations at diameters ranging from 30 to 50 nm, compared to 20 to 30 nm with MGO (Figure 4-10). Error bars denote the standard deviation from the average of the triplicate load point repeats. At each repeat, the SMPS produced four scans. Previous research conducted by Kasper et al. [32], showed size distributions for MGO from approximately 40 nm at 100% load to 25 nm at 10% load. For HFO they found that at 10% load, HFO showed larger mean particle diameters than MGO, while MGO showed larger mean particle diameters than HFO. Lyyränen et al. [33] found peak number concentrations for HFO at approximately 40 to 45 nm independent of the load.

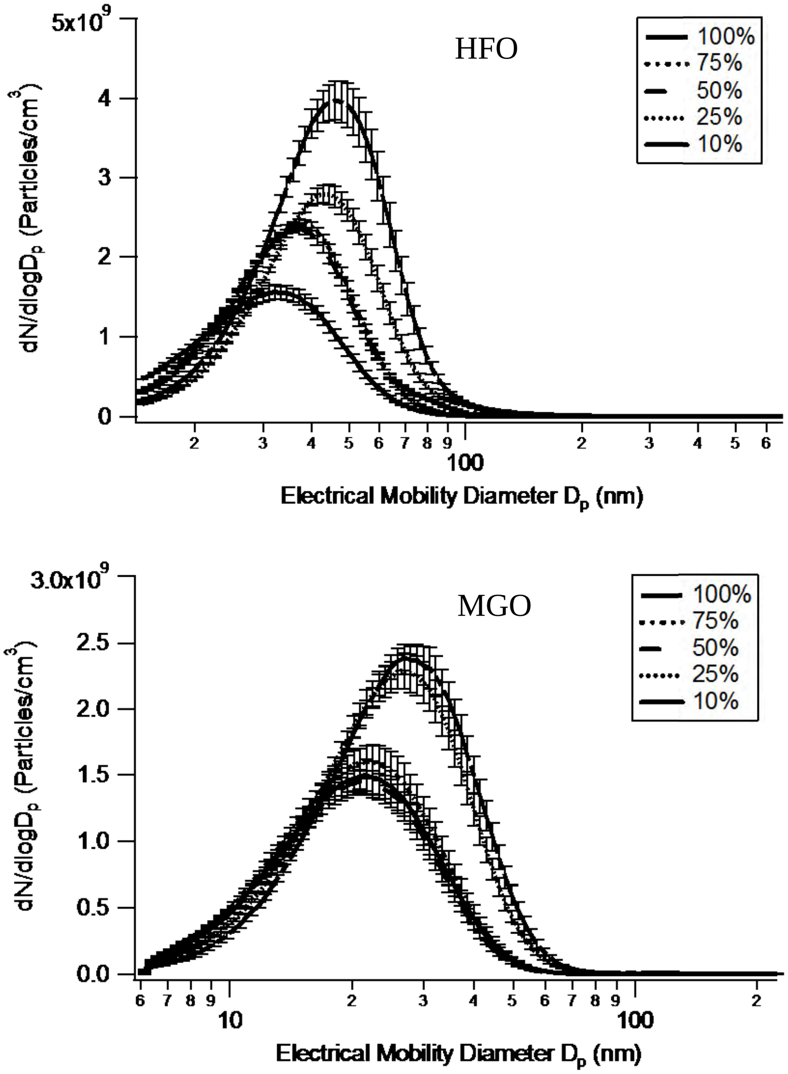

**Figure 4-10: Particle Number Size Distributions as a Function of Load**

Figure 4-11 shows the particle mass concentrations by size corrected for dilution ratio as a function of load point and fuel type. For HFO, the 10% and 25% load points showed the largest peak mass concentrations followed by the 50% to 100% load points. For MGO, both 10% and 25% modes show similar concentratins at 30 nm compared to similar concentrations at 20 nm for the 50% to 100% load points. The increase in PM mass concentrations with decreasing load points for MGO and HFO in Figure 4-11 are consistent with the PM mass results in Figure 4-4. For MGO, peak mass concentrations ranged from 41nm and 39nm with 10% and 25% load points compared to 33nm with the 50%, 75% and 100% load points. As the mass is proportional to the $D_p^3$, the 10% and 25% load points have the highest PM mass followed by the 50% to 100% load points, agreeing well with the $PM_{2.5}$ gravimetric mass in Figure 4-4. For HFO, the peak mass diameters occur at 62nm and 57nm for 10% and 25% load points followed by 50nm for the 50% and 75% load points and 46nm with the 100% load point. Similar to MGO, these trends follow the gravimetric $PM_{2.5}$ in Figure 4-4.

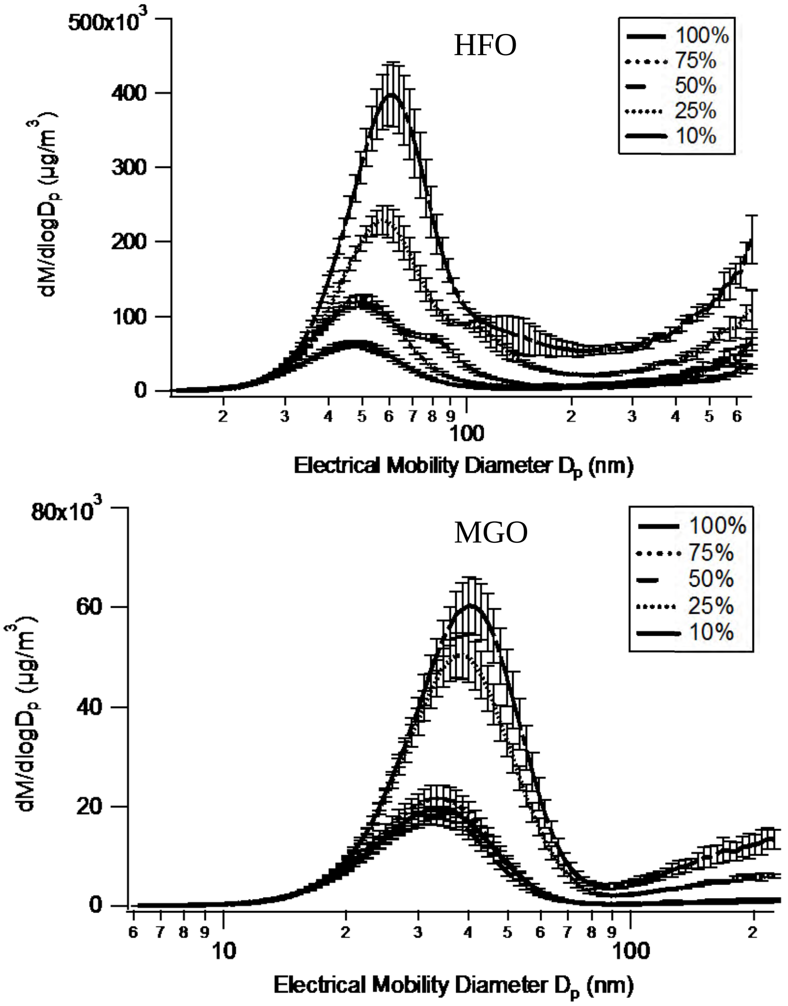

**Figure 4-11: Particle Mass Size Distributions as a Function of Load**

Total particle number emissions for both the SMPS and the PPS-M sensor are shown in Figure 4-12 below. The total particle number from the SMPS was determined by integrating the number concentration from the size distributions. Overall, the particle number for the PPS-M sensor compared to the integrated SMPS number is 28% higher with HFO and 17% higher with MGO. Dilution ratios for the PPS-M sensor and SMPS were on average 11.6:1 and 72.9:1 respectively.

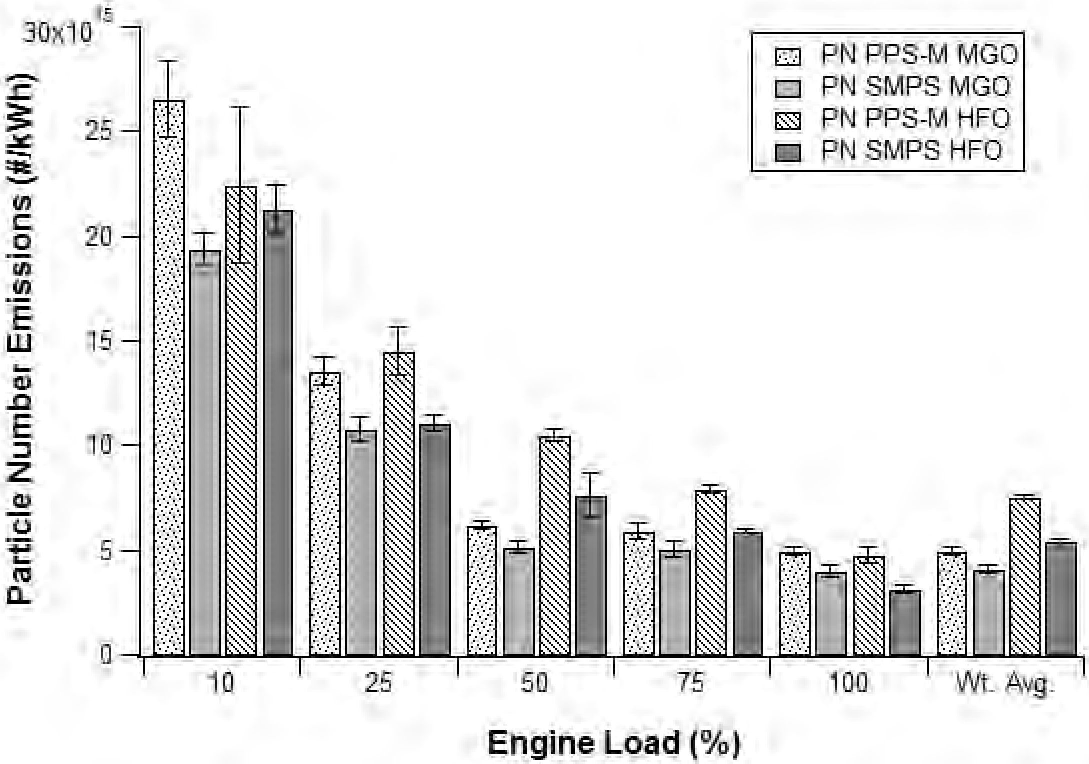

**Figure 4-12: Particle Number Emissions for HFO and MGO Fuels**

Khalek et al.[14] has shown that diesel particulate in the nanoparticle (<50nm) size range is very sensitive to changes in dilution ratio. With high OC/EC ratios in this study, gas to particle conversions will be the dominate mode of growth. Higher dilution ratios will suppress particle growth as there will be less species available for heterogeneous nucleation.[15] Differences in particle number between the PPS-M sensor and the SMPS are statistically significant for both fuels except for HFO at the 10% load point. Previous studies[11] with the PPS-M sensor have shown higher PN emissions compared to a TSI model 3010 D CPC and a TSI model 3776 CPC. Higher PN emissions with the PPS-M sensor can be partially attributed to its low cut point of a few nm compared to the SMPS. For the SMPS, a wider size range was used for HFO compared to MGO as larger particle sizes were seen with HFO. The lower limit of the size range used for HFO was 15 nm compared to 6 nm with MGO. As the cut points for both instruments are more similar for MGO than HFO, this may be why there is only a 17% difference with MGO compared to the 28% difference with HFO between the PPS-M sensor and SMPS. The remaining deviations can be attributed to differences in measurement methodology as the PPS-M sensor is based on an escaping current method while the SMPS uses a CPC to grow the particles to an optically detectable size.

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[14] Khalek, I.A., Kittelson, D., Brear, F. "The Influence of Dilution Conditions in Diesel Exhaust Particle Size Distribution Measurements," SAE International 1999-01-1142.

[15] Kittelson, D. B. Engines and nanoparticles: a review. J. Aerosol Sci 1998, 29 (5-6), 575–588.

# 5 Discussion and Conclusions

This research characterized the emissions from a VLCC transiting from the Port of Long Beach, CA to Port Angeles, WA while using two fuels: a low sulfur MGO and low sulfur HFO. It provides the first in-use testing of a novel low sulfur HFO fuel that provides an alternative to using low sulfur marine distillate fuels as a compliance option under the ECA. Overall, data showed that $NO_x$ emissions were slightly higher with MGO compared to HFO. The $PM_{2.5}$ mass measurements showed approximately 70% higher emissions with HFO compared to MGO. $PM_{2.5}$ emissions resulted in the highest emissions at the 10% load point due to being off optimized load. PM emissions from the SMPS as a function of load showed peak number concentrations ranging from 30 to 50 nm with HFO and 20 to 30 nm with MGO.

Real-time black carbon measured with the AVL MSS and off-line analysis of EC by the NIOSH method compare very well with R2>0.99 and slopes of approximately 1. Real-time PM from the PPS-M sensor is well below the PM2.5 measured gravimetrically. This is attributed due to differences in methodology as the PPS-M sensor measures a fraction of the volatiles measured gravimetrically from Teflo filters. Additionally, differences between PM mass from the SMPS and $PM_{2.5}$ measured gravimetrically can be attributed to evaporation of the smaller particles. $NO_x$ and PM emission factors (g/kWh) for main engine, medium speed OGVs from this study are compared against previous studies in Table 5-1 below.

| Main Engines (MSD) | Fuel | Sulfur (%) | $NO_x$ | CO | PM | $SO_2$ |
|---|---|---|---|---|---|---|
| | | | g/kWh | | | |
| Measured (Weighted) | MGO | 0.005 | 10.7 ± 0.03 | 0.31 ± 0.01 | 0.2 ± 0.02 | -- |
| | HFO | 0.06 | 10.2 ± 0.03 | 0.5 ± 0.04 | 0.62 ± 0.02 | -- |
| Lloyds Services data | HFO | -- | 13.7 | 1.59 | 1.25 | -- |
| US EPA | MGO | 0.5 | 13.2 | 0.47 | 0.29 | 1.98 |
| | MGO | 0.1 | 13.2 | 0.31 | 0.17 | 0.4 |
| CARB | MGO | 0.1 | 13.2 | 1.1 | 0.25 | 0.4 |
| | MGO | 0.1 | 13.2 | 1.1 | 0.38 | 2.08 |
| | HFO | -- | 14.0 | 1.1 | 1.5 | 11.5 |

**Table 5-1: Comparison of Measured vs. Published Emission Factors**

$NO_x$ emissions for both HFO and MGO calculated in this study show are well below those of the Lloyds services data [36], US EPA [10] and CARB [11]. $PM_{2.5}$ emissions were 0.20±0.02 g/kWh for MGO compared to a range of 0.17 to 0.38 g/kWh for Lloyds services data [36], US EPA [10] and CARB [11]. For HFO, PM emissions were significantly less at 0.62±0.01 g/kWh compared to a range of 1.3 to 1.5 g/kWh directly attributable to the sulfur content in the fuels.

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# Appendix A Test Cycles and Fuels for Different Engine Applications

## Introduction

Engines for off-road use are made in a much wider range of power output and used in more applications than engines for on-road use. The objective of IS0 8178-4[16] is to provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. IS0 8178-4 specifies the test cycles while measuring the gaseous and particulate exhaust emissions from reciprocating internal combustion (RIC) engines coupled to a dynamometer or at the site. The tests are carried out under steady-state operation using test cycles representative of given applications. Table A-1 gives definitions used throughout ISO 8178.

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

**Table A-1: Definitions Used Throughout ISO 8178**

## Constant speed

For engines designed to operate at a constant speed, such as generator sets with intermittent load, the torque figures, with the engine operating at rated speed, are percentage values of the torque corresponding to the prime power rating as defined in ISO 8528-1[17].

## Modes and Weighting Factors for Test Cycles

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

[17] International Standards Organization, IS0 8528-1:2005, Reciprocating internal combustion engine driven alternating current generating sets -- Part 1: Application, ratings and performance

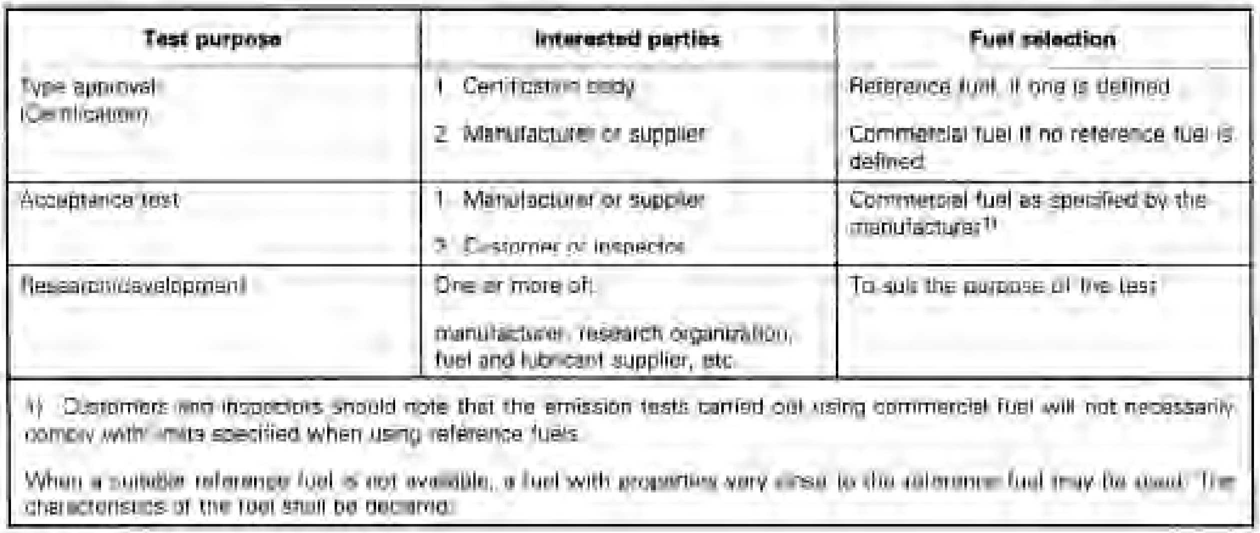
The combined table of modes and weighting factors is shown in Table A-2. Most test cycles were derived from the 13-mode steady state test cycle (UN-ECE R49). Apart from the test modes of cycles E3, E4 and E5, which are calculated from propeller curves, the test modes of the other cycles can be combined into a universal cycle (B) with emissions values calculated using the appropriate weighting factors. Each test shall be performed in the given sequence with a minimum test mode length of 10 minutes or enough to collect sufficient particulate sample mass. The mode length shall be recorded and reported and the gaseous exhaust emission concentration values shall be measured and recorded for the last 3 min of the mode. The completion of particulate sampling ends with the completion of the gaseous emission measurement and shall not commence before engine stabilization, as defined by the manufacturer.

### Test Fuels

Fuel characteristics influence engine emissions so ISO 8178-2 provides guidance on the characteristics of the test fuel. Where fuels designated as reference fuels in IS0 8178-5 are used, the reference code and the analysis of the fuel shall be provided. For all other fuels the characteristics to be recorded are those listed in the appropriate universal data sheets in IS0 8178-5. The fuel temperature shall be in accordance with the manufacturer’s recommendations. The fuel temperature shall be measured at the inlet to the fuel injection pump or as specified by the manufacturer, and the location of measurement recorded. The selection of the fuel for the test depends on the purpose of the test. Unless otherwise agreed by the parties the fuel shall be selected in accordance with Table A-3.

| **B-Type mode number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Torque** | 100 | 75 | 50 | 25 | 10 | 100 | 75 | 50 | 25 | 10 | 0 |
| **Speed** | Rated speed | | | | | Intermediate speed | | | | | Low idle |
| **Off-road vehicles** | | | | | | | | | | | |
| Cycle C1 | 0,15 | 0,15 | 0,15 | | 0,1 | 0,1 | 0,1 | 0,1 | | | 0,15 |
| Cycle C2 | | | | 0,06 | | 0,02 | 0,05 | 0,32 | 0,3 | 0,1 | 0,15 |
| **Constant speed** | | | | | | | | | | | |
| Cycle D1 | 0,3 | 0,5 | 0,2 | | | | | | | | |
| Cycle D2 | 0,05 | 0,25 | 0,3 | 0,3 | 0,1 | | | | | | |
| **Locomotives** | | | | | | | | | | | |
| Cycle F | 0,25 | | | | | | | 0,15 | | | 0,6 |
| **Utility, lawn and garden** | | | | | | | | | | | |
| Cycle G1 | | | | | | 0,09 | 0,2 | 0,29 | 0,3 | 0,07 | 0,05 |
| Cycle G2 | 0,09 | 0,2 | 0,29 | 0,3 | 0,07 | | | | | | 0,05 |
| Cycle G3 | 0,9 | | | | | | | | | | 0,1 |
| **Marine application** | | | | | | | | | | | |
| Cycle E1 | 0,08 | 0,11 | | | | | 0,19 | 0,32 | | | 0,3 |
| Cycle E2 | 0,2 | 0,5 | 0,15 | 0,15 | | | | | | | |
| **Marine application propeller law** | | | | | | | | | | | |
| **Mode number E3** | **1** | | | | | **2** | | **3** | **4** | | |
| **Power** (%) | 100 | | | | | 75 | | 50 | 25 | | |
| **Speed** (%) | 100 | | | | | 91 | | 80 | 63 | | |
| **Weighting factor** | 0,2 | | | | | 0,5 | | 0,15 | 0,15 | | |
| **Mode number E4** | **1** | | | | | **2** | | **3** | **4** | | **5** |
| **Speed** (%) | 100 | | | | | 80 | | 60 | 40 | | Idle |
| **Torque** (%) | 100 | | | | | 71,6 | | 46,5 | 25,3 | | 0 |
| **Weighting factor** | 0,06 | | | | | 0,14 | | 0,15 | 0,25 | | 0,4 |
| **Mode number E5** | **1** | | | | | **2** | | **3** | **4** | | **5** |
| **Power** (%) | 100 | | | | | 75 | | 50 | 25 | | 0 |
| **Speed** (%) | 100 | | | | | 91 | | 80 | 63 | | Idle |
| **Weighting factor** | 0,08 | | | | | 0,13 | | 0,17 | 0,32 | | 0,3 |

**Table A-2: Combined Table of Modes and Weighting Factors**



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

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

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

**Table A-3:** **Fuel Selection Criteria**

## Appendix B Measuring Gaseous & Particulate Emissions

### Scope

ISO 8178-1[18] and ISO 8178-2[19] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in IS0 8178- *Part 4: Test cycles for different engine applications*. The emission results represent the mass rate of emissions per unit of work accomplished. Specific emission factors are based on brake power measured at the crankshaft, the engine being equipped only with the standard auxiliaries necessary for its operation. Per ISO, auxiliary losses are <5 % of the maximum observed power. IMO ship pollution rules and measurement methods are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78[20], 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.

### Sampling System for Measuring 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 CE-CERT chose the partial flow dilution system with single venturi as shown in Figure B-1.

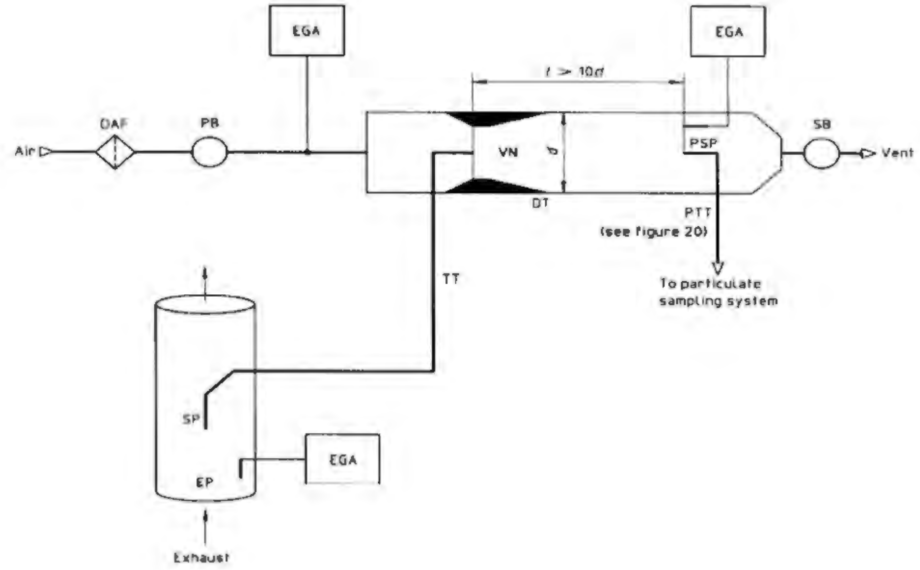


**Figure B-1: Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling**

A partial flow dilution system was selected based on cost and the impossibility of a full flow dilution for "medium and large" engine testing on the test bed and at site. The flow in the dilution system eliminates water condensation in the dilution and sampling systems and

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[18] 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

[19] 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

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

maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions 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 CE-CERT's partial dilution system in Figure B-1 shows that 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 B-1.

### Dilution Air System

A partial flow dilution system requires dilution air and CE-CERT uses compressed air in the field as it is readily available. ISO recommends the dilution air be at 25 ± 5°C, filtered and charcoal scrubbed to eliminate background hydrocarbons. The dilution air may be dehumidified. To ensure the compressed air is of a high quality CE-CERT processes any supplied air through a field processing unit that reduces the pressure to about 30 psig as that level allows a dilution ratio of about 5/1 in the geometry of our system. The next stages, in sequence, include: 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 voyage. Figure B-2 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit

**Figure B-2: Field Processing Unit for Purifying Dilution Air in Carrying Case**

| Section | Selected ISO and IMO Criteria | CE-CERT 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 position is 6 pipe diameters of straight pipe upstream and 3 pipe diameters downstream of the probe. | CE-CERT follows the ISO recommendation, as closely as 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. | CE-CERT uses a stainless steel tube with diameter of 8mm placed near the center line. |
| Transfer Tube (TT) | As short as possible and < 5 m in length;<br>Equal to/greater than probe diameter & < 25 mm diameter;<br>TTs insulated. For TTs > 1m, heat wall temperature to a minimum of 250°C or set for < 5% thermophoretic losses of PM. | CE-CERT no longer uses a transfer tube. |
| Dilution Tunnel (DT) | shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions;<br>shall be at least 75 mm inside diameter (ID) for the fractional sampling type, constructed of stainless steel with a thickness of > 1.5 mm. | CE-CERT 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 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. | CE-CERT uses a 5-gas analyzer meeting IMO/ISO specs |

**Table B-1: Components of a Sampling System: ISO/IMO Criteria & CE-CERT Design**

## 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 CE-CERT uses. The dilution ratio is simply calculated from measured gas concentrations of $CO_2$ and/or $NO_x$ in the raw exhaust gas versus the concentrations in the diluted exhaust gas. CE-CERT 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%. CE-CERT’s experience indicates the independently determined dilution ratios are usually within 5%. Table B-2 presents the % difference for the current data. 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.

| Test Mode | ULSDFM | 50/50 Blend |
|---|---|---|
| 100 | -10.1 | -6.2 |
| 100 | -7.2 | -5.4 |
| 100 | -4.6 | -2.0 |
| 75 | -7.4 | -4.1 |
| 75 | -7.1 | -4.5 |
| 75 | -7.0 | -4.7 |
| 50 | -5.2 | -4.3 |
| 50 | -5.1 | -3.4 |
| 50 | -5.5 | -4.0 |
| 25 | 3.0 | -1.1 |
| 25 | -1.1 | 0.2 |
| 25 | 0.0 | 0.1 |
| 10 | 11.5 | 8.3 |
| 10 | 14.2 | 7.8 |
| 10 | 9.1 | 5.6 |

**Table B-2: % Difference between Dilution Ratio by Carbon Dioxide and Nitrogen Oxides**

## 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. CE-CERT 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 CE-CERT that the flow rate selected should be the lowest rate in the system under test.

## Measuring the Gaseous Emissions: CO, $CO_2$, HC, $NO_x$, $O_2$, $SO_2$

Measurement of the concentration of the main gaseous constituents is one of the key activities in measuring emission factors. This section covers the ISO/IMO protocols and that used by CE-

CERT. For $SO_2$, ISO recommends and CE-CERT concurs that the concentration of $SO_2$ is calculated based on the fact that 95+% of the fuel sulfur is converted to $SO_2$.

Measuring Gaseous Emissions: ISO & IMO Criteria

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

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

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

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

ISO & IMO 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. The efficiency of the converter shall be > 90 %, and >95 % is strongly recommended.

ISO requires measurement of the effects from exhaust gases on the measured values of CO, $CO_2$, $NO_x$, and $0_2$. 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: CE-CERT 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 U.S. EPA. 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 Environmental Technology Verification (ETV)[21] program. Figure B-3 is a photo showing a common setup of this system.

**Figure B-3:** **Setup Showing Gas Analyzer with Computer for Continuous Data Logging**

Details of the gases and the ranges for the Horiba instrument are shown in Table B-3. Note that the Horiba instrument measures sulfur oxides ($SO_2$); however, the CE-CERT follows the protocol in ISO and calculates the $SO_2$ level from the sulfur content of the fuel as the direct measurement for $SO_2$ is less precise than calculation.

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[21] http://www.epa.gov/etv/verificationprocess.html

| 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 | 0-5, 10, & 25 vol% |

**Table B-3: Detector Method and Concentration Ranges for Horiba PG-250**

For quality control, CE-CERT 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 B-4. 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.

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

**Table B-4: Quality Specifications for the Horiba PG-250**

## 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, as measured at a point immediately upstream of the primary filter. The particulate consists of primarily carbon, condensed hydrocarbons and sulfates, and associated water. Measuring particulates requires a dilution system and CE-CERT 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. IMO does not offer a protocol for measuring PM. A comparison of the ISO and CE-CERT practices for sampling PM is shown in Table B-5.

| | ISO | CE-CERT |
|---|---|---|
| Dilution tunnel | Either full or partial flow | Partial flow |
| Tunnel & sampling system | Electrically conductive | Same |
| Pretreatment | None | Cyclone, removes >2.5µm |
| Filter material | Fluorocarbon based | 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 | Multiple |
| 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 |
| Weighing chamber | 22±3°C & RH= 45%± 8 | Same |
| Analytical balance, LDL µg | 10 | 0.5 |
| Flow measurement | Traceable method | Same |
| Flow calibration, months | < 3months | Every voyage |

**Table B-5: Measuring Particulate by ISO and CE-CERT Methods**

**Sulfur content.** According to ISO, particulates measured using IS0 8178 are “conclusively proven” to be effective for fuel sulfur levels up to 0.8%. CE-CERT is often faced with measuring PM for fuels with sulfur content exceeding 0.8% and has extended this method to those fuels as no other method is prescribed for fuels with a higher sulfur content.

## Added Comments about CE-CERT’s Measurement of PM

In the field CE-CERT 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 stream 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 Gellman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. CE-CERT simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes them according to standard procedures.

Briefly, total PM is collected on Pall Gellman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters are conditioned for 24 hours in an environmentally controlled room (RH = 40%, T= 25 °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 Teflon filters provides a comparative check of PM mass measured by two independent methods and serves as an important Quality Check for measuring PM mass.

## Measuring Non-Regulated Gaseous Emissions

Neither ISO nor IMO provide a protocol for sampling and analyzing non-regulated emissions. CE-CERT 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 as shown in Figure B-4.

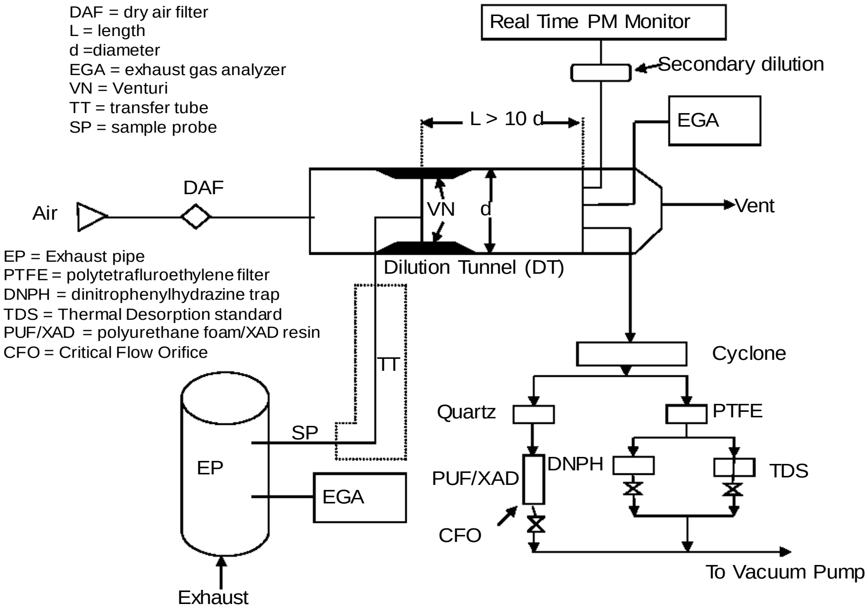


**Figure B-4:** **Partial Flow Dilution System with Added Separation Stages for Sampling both Regulated and Non-regulated Gaseous and PM Emissions**

## Flow Control System

Figure B-4 shows the sampling system and media for sample collection. Critical flow orifices are used to control flow rates through all systems and all flows are operated under choked conditions (outlet pressure << 0.52 * inlet pressure). Thermocouples and absolute pressure gauges are used to correct for pressure and temperature fluctuations in the system. On the $C_4$-$C_{12}$ line (TDS tube line) and DNPH line, flows are also metered as differential pressure through a laminar flow element. Nominal flow rates are 20 liters per minute (lpm) for the quartz and Teflon media, 1 lpm for the DNPH and 0.2 lpm for the TDS line. Each flow rate is pressure and temperature corrected for the sampling conditions encountered during the operating mode.

## Measuring Non-Regulated Particulate Emissions

### *Measuring the Elemental and Organic Carbon Emissions*

CE-CERT collected simultaneous Teflo$^{TM}$ and Quartz filters at each operating mode and analyzed them according to standard procedures. PM samples are 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 are sealed in containers immediately after sampling, and kept chilled until analyzed.

### *Measuring Real-Time Particulate Matter (PM) Emissions-DusTrak*

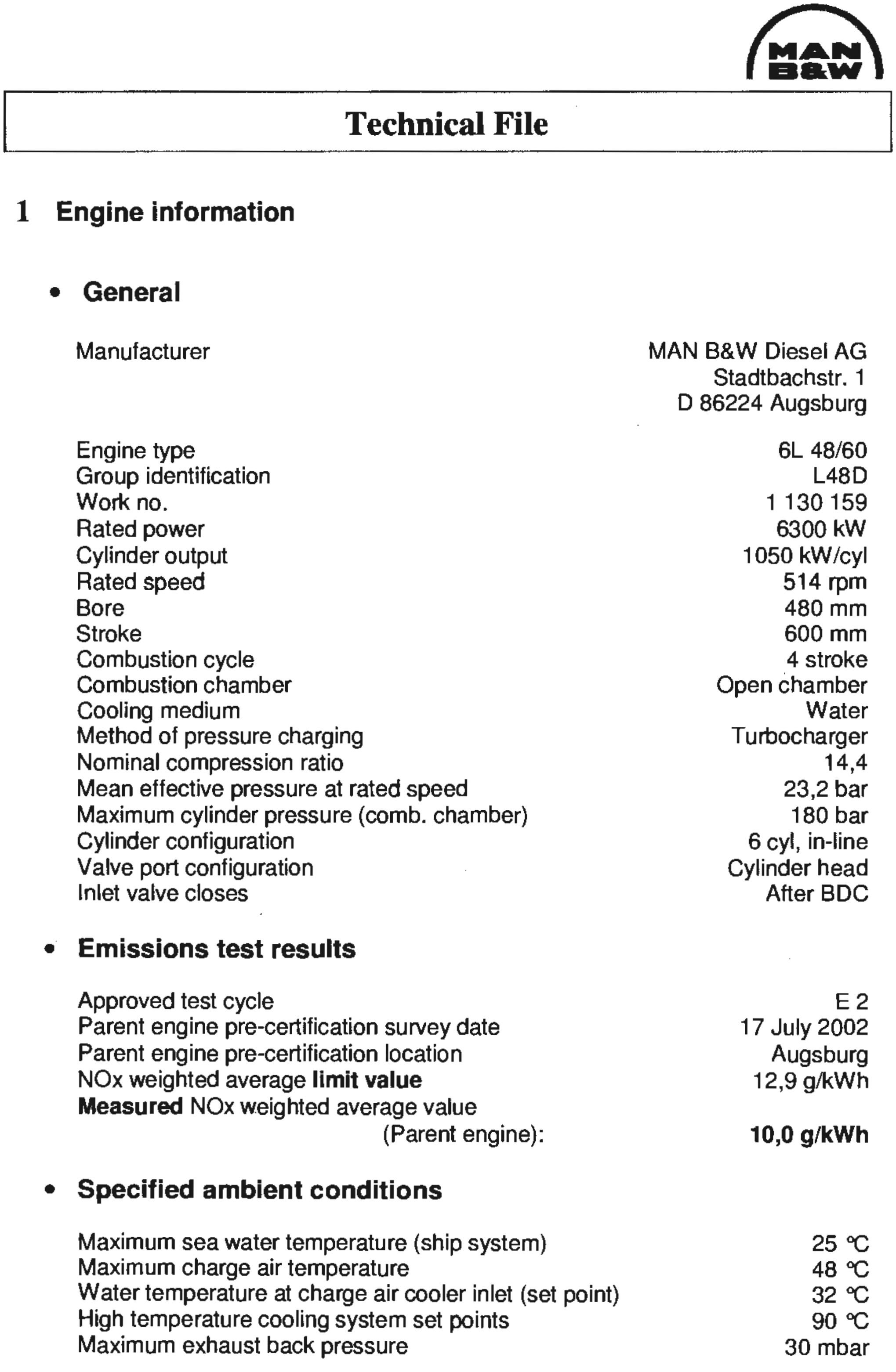
In addition to the filter-based PM mass measurements, CE-CERT takes continuous readings with a Nephelometer (TSI DustTrak 8520, Figure B-5) so as to capture both the steady-state and transient data. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout with the added benefits of a built-in data logger. The DustTrak/nephelometer is fairly simple to use and has excellent sensitivity to untreated diesel exhaust. It measures light scattered by aerosol introduced into a sample chamber and displays the measured mass density in units of $mg/m^3$. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some scientists question the accuracy of PM mass measurements. However, CE-CERT 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 $3m^2/g$. For these projects, a TSI DustTrak 8520 nephelometer measuring 90° light scattering at 780nm (near-infrared) is used.

**Figure B-5: Picture of TSI DustTrak**

***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 with a standard 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.

# Appendix C Engine Specifications



MAN B&W

## Technical File

### 1 Engine information

- **General**

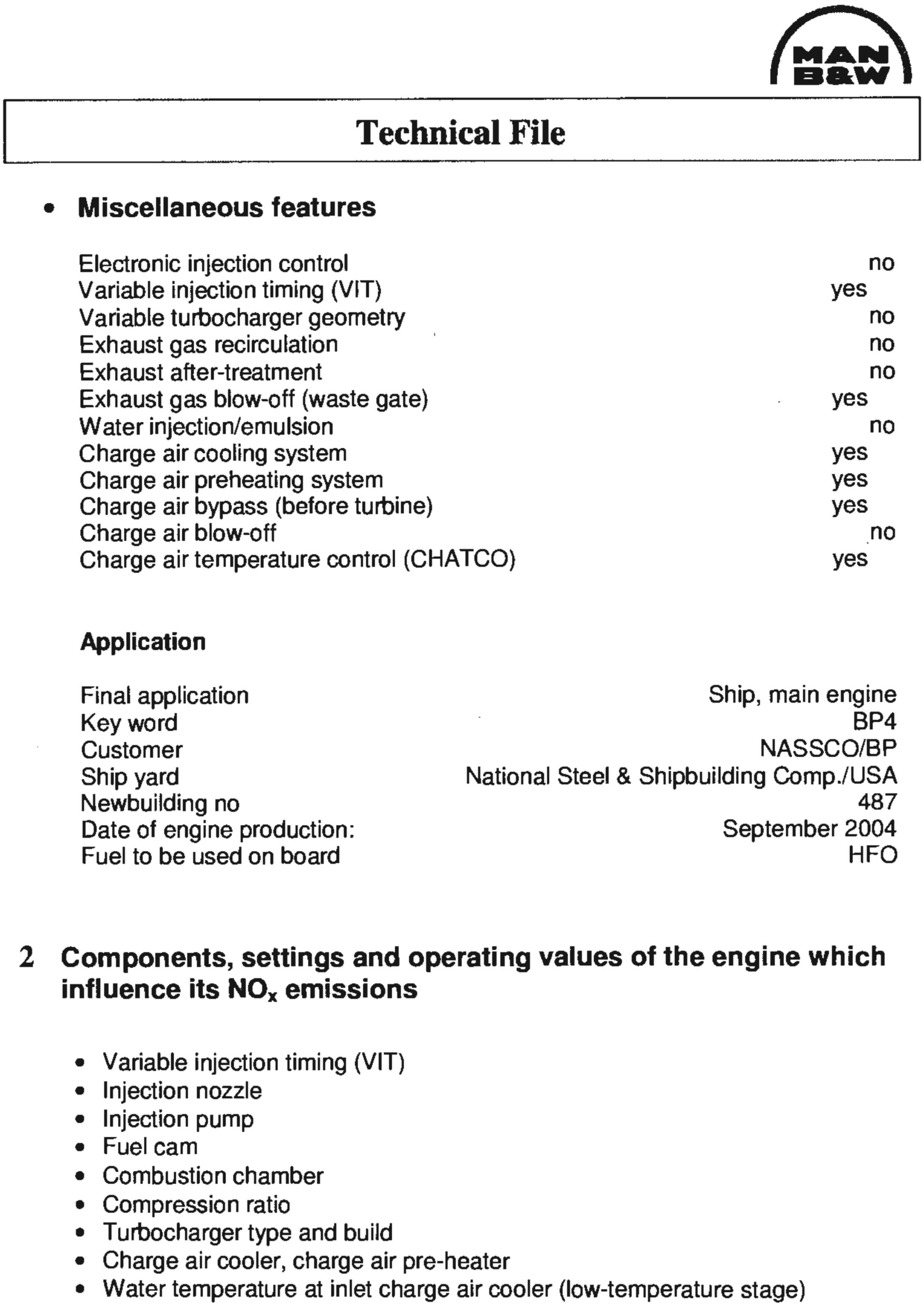
| | |
|---|---|
| Manufacturer | MAN B&W Diesel AG<br>Stadtbachstr. 1<br>D 86224 Augsburg |
| Engine type | 6L 48/60 |
| Group identification | L48D |
| Work no. | 1 130 159 |
| Rated power | 6300 kW |
| Cylinder output | 1050 kW/cyl |
| Rated speed | 514 rpm |
| Bore | 480 mm |
| Stroke | 600 mm |
| Combustion cycle | 4 stroke |
| Combustion chamber | Open chamber |
| Cooling medium | Water |
| Method of pressure charging | Turbocharger |
| Nominal compression ratio | 14,4 |
| Mean effective pressure at rated speed | 23,2 bar |
| Maximum cylinder pressure (comb. chamber) | 180 bar |
| Cylinder configuration | 6 cyl, in-line |
| Valve port configuration | Cylinder head |
| Inlet valve closes | After BDC |

- **Emissions test results**

| | |
|---|---|
| Approved test cycle | E 2 |
| Parent engine pre-certification survey date | 17 July 2002 |
| Parent engine pre-certification location | Augsburg |
| NOx weighted average **limit value** | 12,9 g/kWh |
| **Measured** NOx weighted average value (Parent engine): | **10,0 g/kWh** |

- **Specified ambient conditions**

| | |
|---|---|
| Maximum sea water temperature (ship system) | 25 °C |
| Maximum charge air temperature | 48 °C |
| Water temperature at charge air cooler inlet (set point) | 32 °C |
| High temperature cooling system set points | 90 °C |
| Maximum exhaust back pressure | 30 mbar |



MAN B&W

## Technical File

- **Miscellaneous features**

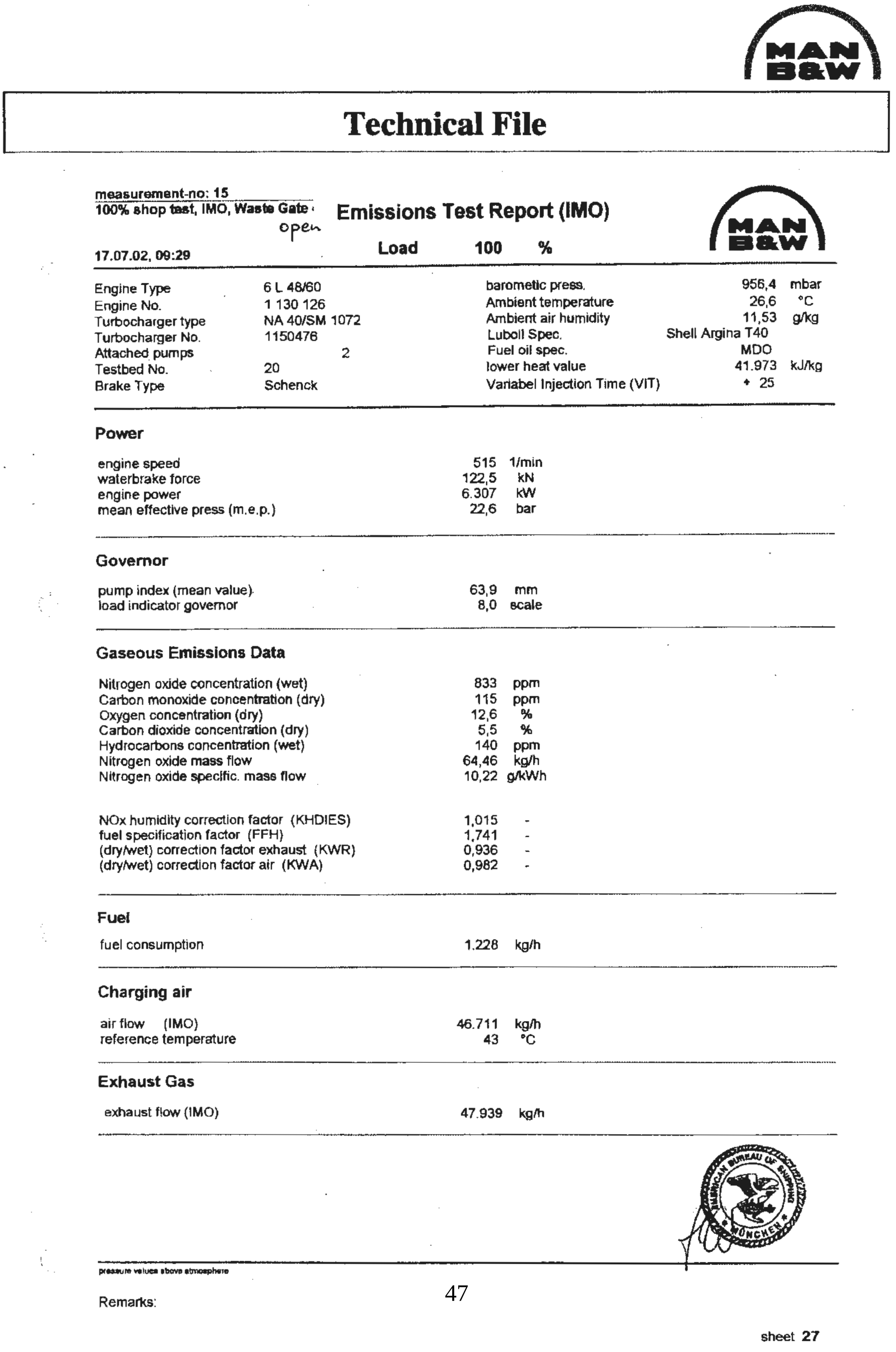
| | |
|---|---|
| Electronic injection control | no |
| Variable injection timing (VIT) | yes |
| Variable turbocharger geometry | no |
| Exhaust gas recirculation | no |
| Exhaust after-treatment | no |
| Exhaust gas blow-off (waste gate) | yes |
| Water injection/emulsion | no |
| Charge air cooling system | yes |
| Charge air preheating system | yes |
| Charge air bypass (before turbine) | yes |
| Charge air blow-off | no |
| Charge air temperature control (CHATCO) | yes |

**Application**

| | |
|---|---|
| Final application | Ship, main engine |
| Key word | BP4 |
| Customer | NASSCO/BP |
| Ship yard | National Steel & Shipbuilding Comp./USA |
| Newbuilding no | 487 |
| Date of engine production: | September 2004 |
| Fuel to be used on board | HFO |

## 2 Components, settings and operating values of the engine which influence its $NO_x$ emissions

- Variable injection timing (VIT)
- Injection nozzle
- Injection pump
- Fuel cam
- Combustion chamber
- Compression ratio
- Turbocharger type and build
- Charge air cooler, charge air pre-heater
- Water temperature at inlet charge air cooler (low-temperature stage)



MAN B&W

## Technical File

**measurement-no: 15**
**100% shop test, IMO, Waste Gate** open

**17.07.02, 09:29**

### Emissions Test Report (IMO)

**Load 100 %**

MAN B&W

| | | | | |
|---|---|---|---|---|
| Engine Type | 6 L 48/60 | barometic press. | 956,4 | mbar |
| Engine No. | 1 130 126 | Ambient temperature | 26,6 | °C |
| Turbocharger type | NA 40/SM 1072 | Ambient air humidity | 11,53 | g/kg |
| Turbocharger No. | 1150476 | Luboil Spec. | Shell Argina T40 | |
| Attached pumps | 2 | Fuel oil spec. | MDO | |
| Testbed No. | 20 | lower heat value | 41.973 | kJ/kg |
| Brake Type | Schenck | Variabel Injection Time (VIT) | + 25 | |

**Power**

| | | |
|---|---|---|
| engine speed | 515 | 1/min |
| waterbrake force | 122,5 | kN |
| engine power | 6.307 | kW |
| mean effective press (m.e.p.) | 22,6 | bar |

**Governor**

| | | |
|---|---|---|
| pump index (mean value) | 63,9 | mm |
| load indicator governor | 8,0 | scale |

**Gaseous Emissions Data**

| | | |
|---|---|---|
| Nitrogen oxide concentration (wet) | 833 | ppm |
| Carbon monoxide concentration (dry) | 115 | ppm |
| Oxygen concentration (dry) | 12,6 | % |
| Carbon dioxide concentration (dry) | 5,5 | % |
| Hydrocarbons concentration (wet) | 140 | ppm |
| Nitrogen oxide mass flow | 64,46 | kg/h |
| Nitrogen oxide specific. mass flow | 10,22 | g/kWh |
| NOx humidity correction factor (KHDIES) | 1,015 | - |
| fuel specification factor (FFH) | 1,741 | - |
| (dry/wet) correction factor exhaust (KWR) | 0,936 | - |
| (dry/wet) correction factor air (KWA) | 0,982 | - |

**Fuel**

| | | |
|---|---|---|
| fuel consumption | 1.228 | kg/h |

**Charging air**

| | | |
|---|---|---|
| air flow (IMO) | 46.711 | kg/h |
| reference temperature | 43 | °C |

**Exhaust Gas**

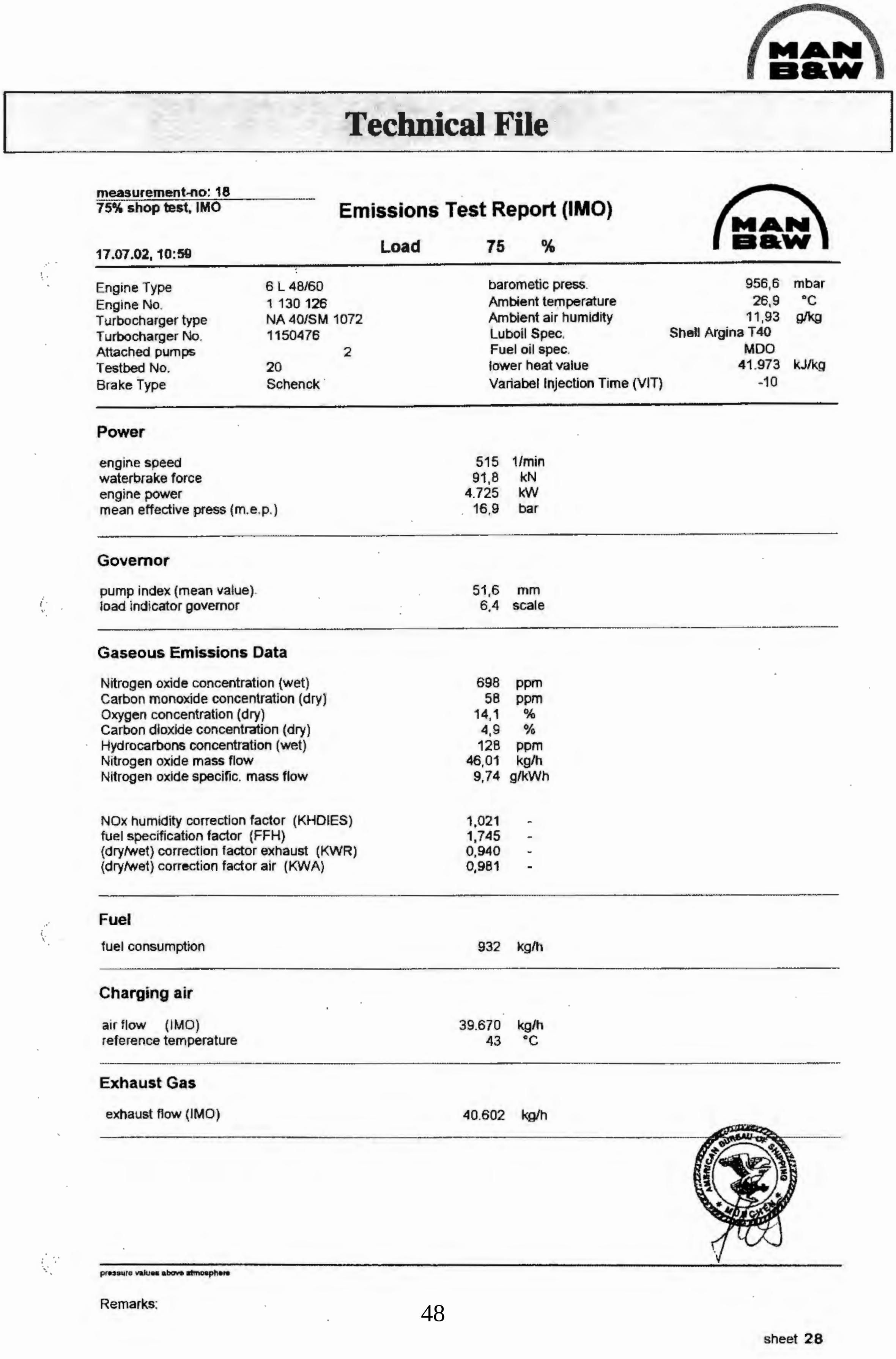
| | | |
|---|---|---|
| exhaust flow (IMO) | 47.939 | kg/h |

AMERICAN BUREAU OF SHIPPING MÜNCHEN

pressure values above atmosphere

Remarks:

sheet **27**



MAN B&W

## Technical File

**measurement-no: 18**
**75% shop test, IMO**

**17.07.02, 10:59**

### Emissions Test Report (IMO)

**Load 75 %**

MAN B&W

| | | | | |
|---|---|---|---|---|
| Engine Type | 6 L 48/60 | barometic press. | 956,6 | mbar |
| Engine No. | 1 130 126 | Ambient temperature | 26,9 | °C |
| Turbocharger type | NA 40/SM 1072 | Ambient air humidity | 11,93 | g/kg |
| Turbocharger No. | 1150476 | Luboil Spec. | Shell Argina T40 | |
| Attached pumps | 2 | Fuel oil spec. | MDO | |
| Testbed No. | 20 | lower heat value | 41.973 | kJ/kg |
| Brake Type | Schenck | Variabel Injection Time (VIT) | -10 | |

**Power**

| | | |
|---|---|---|
| engine speed | 515 | 1/min |
| waterbrake force | 91,8 | kN |
| engine power | 4.725 | kW |
| mean effective press (m.e.p.) | 16,9 | bar |

**Governor**

| | | |
|---|---|---|
| pump index (mean value) | 51,6 | mm |
| load indicator governor | 6,4 | scale |

**Gaseous Emissions Data**

| | | |
|---|---|---|
| Nitrogen oxide concentration (wet) | 698 | ppm |
| Carbon monoxide concentration (dry) | 58 | ppm |
| Oxygen concentration (dry) | 14,1 | % |
| Carbon dioxide concentration (dry) | 4,9 | % |
| Hydrocarbons concentration (wet) | 128 | ppm |
| Nitrogen oxide mass flow | 46,01 | kg/h |
| Nitrogen oxide specific. mass flow | 9,74 | g/kWh |
| NOx humidity correction factor (KHDIES) | 1,021 | - |
| fuel specification factor (FFH) | 1,745 | - |
| (dry/wet) correction factor exhaust (KWR) | 0,940 | - |
| (dry/wet) correction factor air (KWA) | 0,981 | - |

**Fuel**

| | | |
|---|---|---|
| fuel consumption | 932 | kg/h |

**Charging air**

| | | |
|---|---|---|
| air flow (IMO) | 39.670 | kg/h |
| reference temperature | 43 | °C |

**Exhaust Gas**

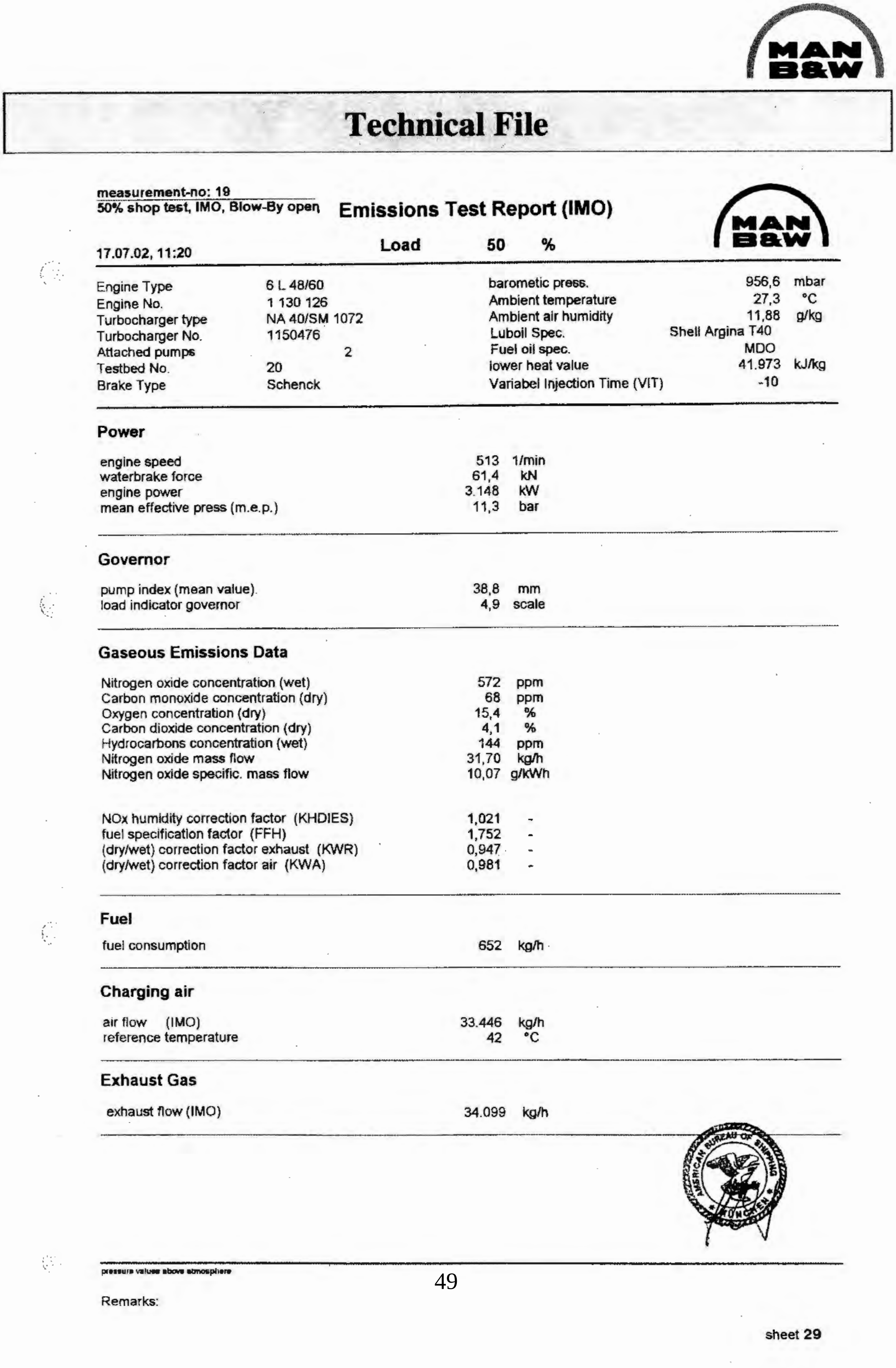
| | | |
|---|---|---|
| exhaust flow (IMO) | 40.602 | kg/h |

American Bureau of Shipping * München

pressure values above atmosphere

Remarks:

sheet **28**



MAN B&W

# Technical File

**measurement-no: 19**
**50% shop test, IMO, Blow-By open**

## Emissions Test Report (IMO)

**Load 50 %**

MAN B&W

**17.07.02, 11:20**

| | | | | |
|---|---|---|---|---|
| Engine Type | 6 L 48/60 | barometic press. | 956,6 | mbar |
| Engine No. | 1 130 126 | Ambient temperature | 27,3 | °C |
| Turbocharger type | NA 40/SM 1072 | Ambient air humidity | 11,88 | g/kg |
| Turbocharger No. | 1150476 | Luboil Spec. | Shell Argina T40 | |
| Attached pumps | 2 | Fuel oil spec. | MDO | |
| Testbed No. | 20 | lower heat value | 41.973 | kJ/kg |
| Brake Type | Schenck | Variabel Injection Time (VIT) | -10 | |

### Power

| | | |
|---|---|---|
| engine speed | 513 | 1/min |
| waterbrake force | 61,4 | kN |
| engine power | 3.148 | kW |
| mean effective press (m.e.p.) | 11,3 | bar |

### Governor

| | | |
|---|---|---|
| pump index (mean value). | 38,8 | mm |
| load indicator governor | 4,9 | scale |

### Gaseous Emissions Data

| | | |
|---|---|---|
| Nitrogen oxide concentration (wet) | 572 | ppm |
| Carbon monoxide concentration (dry) | 68 | ppm |
| Oxygen concentration (dry) | 15,4 | % |
| Carbon dioxide concentration (dry) | 4,1 | % |
| Hydrocarbons concentration (wet) | 144 | ppm |
| Nitrogen oxide mass flow | 31,70 | kg/h |
| Nitrogen oxide specific. mass flow | 10,07 | g/kWh |
| | | |
| NOx humidity correction factor (KHDIES) | 1,021 | - |
| fuel specification factor (FFH) | 1,752 | - |
| (dry/wet) correction factor exhaust (KWR) | 0,947 | - |
| (dry/wet) correction factor air (KWA) | 0,981 | - |

### Fuel

| | | |
|---|---|---|
| fuel consumption | 652 | kg/h |

### Charging air

| | | |
|---|---|---|
| air flow (IMO) | 33.446 | kg/h |
| reference temperature | 42 | °C |

### Exhaust Gas

| | | |
|---|---|---|
| exhaust flow (IMO) | 34.099 | kg/h |

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pressure values above atmosphere

Remarks:

sheet **29**