Derenzo and Associates, Inc.
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EMISSION TEST REPORT

Title	Test report for the verification of NO_X, CO and VOC emission rates from an engine dynamometer test cell
Report Date	December 22, 2014
Test Date(s)	October 22-23, 2014

Facility Information	
Name	Westport Fuel Systems Inc.
Street Address	14900 Galleon Court
City, County	Plymouth Township, Wayne

Facility Permit Information			
State Registration No.:	P0316	PTI No.:	19-12

Testing Contractor	
Company	Derenzo and Associates, Inc.
Mailing Address	39395 Schoolcraft Rd Livonia MI 48150
Phone	(734) 464-3880
Project No.	1410003A

TEST REPORT
FOR VERIFICATION OF
NO_X, CO AND VOC EMISSION RATES
FROM AN
ENGINE DYNAMOMTER TEST CELL

WESTPORT FUELS, INC.

1.0 INTRODUCTION

Westport Fuel Systems, Inc. (Westport Fuels) has received State of Michigan Permit to Install (PTI) No. 19-12 (issued April 4, 2012) from the Michigan Department of Environmental Quality, Air Quality Division (MDEQ-AQD) for the operation of its seven (7) engine dynamometer test cells and one (1) chassis dynamometer (FG-TESTCELLS) located in Plymouth Township, Wayne County, Michigan.

Nitrogen oxide (NOx), carbon monoxide (CO) and volatile organic compounds (VOC) concentrations and emission rates were measured for EU-TESTCELL7 while compressed natural gas (CNG) was used as fuel in the engine.

The compliance testing was performed by Derenzo and Associates, Inc. (Derenzo and Associates) representatives Jason Logan, Anthony Brogowski, and Daniel Wilson on October 22 and 23, 2014. Mr. Mark Dziadosz and Ms. Jill Zimmerman from the MDEQ-AQD were on-site to observe portions of the compliance testing. Process coordination was provided by Mr. Lee Gibson of Westport Fuels.

Questions regarding this emission test report should be directed to:

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Report Certification

This test report was prepared by Derenzo, Associates, Inc. based on field sampling data collected by Derenzo and Associates, Inc. Facility process data were collected and provided by Westport Fuel Systems, Inc. employees or representatives.

I certify that the testing was conducted in accordance with the approved test plan unless otherwise specified in this report. I believe the information provided in this report and its attachments are true, accurate, and complete.

Report Prepared By:

Jason Logan
Environmental Consultant
Derenzo and Associates, Inc.

Reviewed By:

Robert Harvey, P.E.
General Manager
Derenzo and Associates, Inc.

This test report has been reviewed by Westport Fuel Systems, Inc. representatives and approved for submittal to the Michigan Department of Environmental Quality. I certify that the facility operating conditions were in compliance with permit requirements and were at the maximum routine operating conditions for the facility. Based on information and belief formed after reasonable inquiry, the statements and information in this report are true, accurate and complete.

Lee Gibson
Supervisor, Engine Testing
Westport Fuel Systems, Inc.

2.0 SUMMARY OF TEST RESULTS

The exhaust gas from EU-TESTCELL7 was analyzed for NO_x, CO, VOC, oxygen (O_2) and carbon dioxide (CO_2) content using instrumental analyzers. Three (3) sampling periods were performed with the engine exhaust routed to a catalyst and three (3) sampling periods were performed without a catalyst. Additionally, for each scenario, one of the three tests was performed as steady state, while the other two were performed during transient engine cycling.

The results of the emission testing project are summarized in Tables 2.1 and 2.2 below. Data and results for each test period are presented in Section 5.0 of this document and Tables 5.2 and 5.3.

Table 2.1 Summary of measured emissions from EU-TESTCELL7

Test No.	Catalyst Present	Transient or Steady State	NOx Emissions (lb/hr)	CO Emissions (lb/hr)	VOC Emissions (lb/hr)
Test 1	Yes	Steady State	3.60	6.90	0.016
Test 2	Yes	Transient	2.08	4.12	0.013
Test 3	Yes	Transient	1.93	3.95	0.014
Test 4	No	Steady State	3.47	8.03	0.012
Test 5	No	Transient	2.19	3.78	0.012
Test 6	No	Transient	2.29	3.77	0.012

Table 2.2 Summary of emission factors from EU-TESTCELL7

Test No.	Catalyst Present	Transient or Steady State	NOx Emissions (lb/kg fuel)	CO Emissions (lb/kg fuel)	VOC Emissions (lb/kg fuel)
Test 1	Yes	Steady State	0.12	0.24	5.41E-04
Test 2	Yes	Transient	0.11	0.22	6.96E-04
Test 3	Yes	Transient	0.10	0.21	7.09E-04
Test 4	No	Steady State	0.12	0.28	4.21E-04
Test 5	No	Transient	0.12	0.20	6.37E-04
Test 6	No	Transient	0.12	0.20	6.36E-04

3.0 SOURCE DESCRIPTION

3.1 General Process Description

The facility (flexible group FGTESTCELLS) consists of seven (7) engine dynamometer test cells and one (1) chassis dynamometer test cell. EU-TESTCELL7 is an engine dynamometer test cell capable of firing various fuels. The test cell can be operated with or without a control device and are released to the atmosphere through an exhaust stack (SV-07).

3.2 Rated Capacities, Type and Quantity of Raw Materials Used

The CNG engine that was installed and tested in EU-TESTCELL7 has the following capacities:

- Engine Size: 6.8 liters
- Engine Power Output: 270 kilowatts
- Number of Cylinders: 10

Appendix A provides information for the engine that was operated in EU-TESTCELL7.

3.3 Emission Control System Description

The test cells are permitted to operate with and without production catalytic converters. Three (3) tests were performed with the engine exhaust routed to a catalyst catalyst and three (3) were performed without a catalyst.

The catalytic converters are designed to reduce air pollutant emissions through the catalytic conversion of combustion air pollutants to less harmful compounds (CO_2). The energy required for the catalytic conversion is provided by the heat of the engine exhaust gas. The installed catalysts are production catalysts which are typical of what is installed on a commercially available motor vehicle.

4.0 SAMPLING AND ANALYTICAL PROCEDURES

A test plan for the compliance testing was prepared by Derenzo and Associates and reviewed by the MDEQ-AQD. This section provides a summary of the sampling and analytical procedures that were used during the test and presented in the test plan.

4.1 Sampling Locations (USEPA Method 1)

The configuration of EU-TESTCELL7 exhaust stack sample locations satisfied the USEPA Method 1 criteria for a representative sample location. Two (2) equally-spaced sample ports were installed in the circular stack and a cross-sectional grid was developed for determining exhaust gas velocity. A stratification test was performed to verify the effluent gas was not stratified, and a singular point located at the centroid of the stack was used to for sampling exhaust gas pollutant concentrations (see section 4.7.3).

The sampling point locations were determined in accordance with USEPA Method 1.

Appendix B provides diagrams of the performance test sampling location.

4.2 Exhaust Gas Velocity and Flowrate Determination (USEPA Method 2)

Exhaust stack gas velocity was determined using USEPA Method 2 during each 60-minute sampling period. An S-type Pitot tube connected to a red-oil manometer was used to determine velocity pressure. Gas temperature was measured using a K-type thermocouple mounted to the Pitot tube. The Pitot tube and connective tubing were leak-checked to verify the integrity of the measurement system.

The absence of cyclonic flow for each sampling location was verified using an S-type Pitot tube and oil manometer. The Pitot tube was positioned at all of the velocity traverse points with the planes of the face openings of the Pitot tube perpendicular to the stack cross-sectional plane. The Pitot tube was then rotated to determine the null angle (rotational angle as measured from the perpendicular, or reference, position at which the differential pressure is equal to zero).

The calculated exhaust gas flowrate was used for calculating the mass emission rate for each pollutant for that test period.

4.3 Exhaust Gas Molecular Weight Determination (USEPA Method 3A)

CO_2 and O_2 content in the exhaust gas stream was measured continuously throughout each test period in accordance with USEPA Method 3A. The CO_2 content of the exhaust was monitored using a non-dispersive infrared (NDIR) gas analyzer. The O_2 content of the exhaust was monitored using a gas analyzer that utilizes a paramagnetic sensor.

During each pollutant sampling period, a continuous sample of the exhaust gas stream was extracted from the stack using a stainless steel probe connected to a Teflon® heated sample line. The sample probe was placed in the stack upstream from the sample port openings (to avoid any infiltration of ambient air into the sampling system). The sampled gas was filtered and conditioned by removing moisture prior to being introduced to the analyzer. Therefore, measurement of O_2 and CO_2 content correspond to standard dry gas conditions. Instrument response for each analyzer was recorded on an ESC Model 8816 data logging system that monitored the analog output of the instrumental analyzers continuously and logged data as one-minute averages. Prior to, and at the conclusion of each test, the instruments were calibrated using appropriate upscale calibration and zero gas to determine analyzer calibration error and system bias (described in Section 4.7.1 of this document).

Appendix C presents gas sampling procedures and diagrams for the USEPA Method 3A sampling train.

4.4 Exhaust Gas Moisture Content Determination (USEPA Method 4)

Moisture content of the exhaust gas was determined in accordance with USEPA Method 4 using a chilled impinger sampling train, which was performed concurrently with the instrumental analyzer sampling methodologies. During each sampling period, a gas sample was extracted at a predetermined rate from the source where moisture was removed from the sampled gas stream using impingers that were submersed in an ice bath. At the conclusion of each sampling period, the moisture gain in the impingers was determined gravimetrically by weighing each impinger to determine net weight gain.

Appendix E presents detailed gas sampling procedures and a diagram for the USEPA Method 4 sampling train.

4.5 NO_X and CO Concentration Measurements (USEPA Methods 7E and 10)

NO_X and CO pollutant concentrations in the engine test cell exhaust were determined using a chemiluminescence NO_X analyzer and NDIR CO analyzer.

Throughout each one-hour test period, a continuous sample of the engine exhaust gas was extracted from the stack using the Teflon® heated sample line and gas conditioning system, and delivered to the instrumental analyzers. Instrument response for each analyzer was recorded on a data logging system that monitored the analog output of the instrumental analyzers continuously and logged data as one-minute averages. Prior to, and at the conclusion of each test, the instruments were calibrated using appropriate upscale calibration and zero gas to determine analyzer calibration error and system bias. Sampling times were recorded on field data sheets.

Appendix C presents detailed gas sampling procedures and a diagram for the USEPA sampling trains.

4.6 VOC Concentration Measurements (USEPA ALT-096/25A)

VOC emission rate was determined by measuring the nonmethane hydrocarbon (NMHC) concentration in the engine test cell exhaust gas. NMHC pollutant concentration was determined using a Thermo Environmental Instruments (TEI) Model 55i Methane / Nonmethane hydrocarbon analyzer. The TEI 55i analyzer contains an internal gas chromatograph column that separates methane from non-methane components and has been approved by the USEPA for measuring VOC relative to reciprocating engine compliance test demonstrations (Alternative Test Method 096 or ALT-096). The concentration of NMHC in the sampled gas stream, after separation from methane, is determined relative to a propane standard using a flame ionization detector in accordance with USEPA Method 25A.

Samples of the exhaust gas were delivered to the instrument analyzer using an extractive gas sampling system that prevents condensation or contamination of the sample. The exhaust gas samples were delivered directly to the instrument analyzer. Therefore, VOC measurements correspond to standard conditions with no moisture correction (wet basis).

The specified instrument analyzer was calibrated using certified propane concentrations in hydrocarbon-free air.

Figure 3 presents the instrument analyzer train. Appendix C presents detailed gas sampling procedures and a diagram for the USEPA sampling trains.

4.7 Instrumental Analyzer Quality Assurance Verification

4.7.1 Instrument Calibration and System Bias Checks

At the beginning of the test day, initial three-point instrument calibrations were performed by injecting calibration gas directly into the inlet sample port for each instrument. System bias checks were preformed prior to and at the conclusion of each sampling period by introducing the appropriate upscale calibration gas and zero gas into the sampling system (at the base of the stainless steel sampling probe prior to the particulate filter and Teflon® heated sample line) and verifying the instrument response against the initial instrument calibration readings. If the drift error is within 3% of the span over the period of the test run, the test run is considered acceptable.

The instruments were calibrated with USEPA Protocol 1 certified concentrations of CO_2, O_2, NO_X, CO, propane, and zeroed using pure nitrogen or hydrocarbon free air.

4.7.2 Sampling System Response Time Determination

The response time of the sampling system was determined prior to the compliance test program by introducing upscale gas and zero gas, in series, into the sampling system using a tee connection at the base of the sample probe. The elapsed time for the analyzer to display a reading of 95% of the expected concentration was determined using a stopwatch.

The individual test periods commenced once the sampling probe had been in place for at least twice the maximum system response time.

4.7.3 Determination of Exhaust Gas Stratification

A stratification test for each turbine exhaust stack was performed during the first performance test for each turbine. The stainless steel sample probe was positioned at sample points in the stack cross section correlating to 16.7, 50.0 (centroid) and 83.3% of the stack diameter. Pollutant concentration data were recorded at each sample point for a minimum of twice the maximum system response time.

The recorded data for the indicates that the measured O_2, CO_2 and NO_X concentrations varied by no more than 5%, therefore EU-TESTCELL7 was considered unstratified and a single point located at the centroid of the stack was used for sampling pollutant concentrations

Stratification calculation worksheets are provided in Appendix E.

4.7.4 NO_X Converter Test

The NO_2 – NO conversion efficiency of the TEI Model 42C instrumental analyzer was verified on-site prior to the commencement of the performance tests. The instrument analyzer NO_2 – NO converter uses a catalyst at high temperatures to convert the NO_2 to NO for measurement. A USEPA Protocol 1 certified NO_2 calibration gas was used to verify the efficiency of the NO_2 – NO converter.

The NO_2 – NO conversion efficiency test satisfied the USEPA Method 7E criteria (the calculated NO_2 – NO conversion efficiency is greater than or equal to 90%).

4.7.5 Gas Divider Certification (USEPA Method 205)

A STEC Model SGD-710C 10-step gas divider was used to obtain appropriate calibration span gases. The ten-step STEC gas divider was NIST certified within the previous 12 months with a primary flow standard in accordance with Method 205. When cut with an appropriate zero gas, the ten-step STEC gas divider delivers calibration gas values ranging from 0% to 100% (in 10% step increments) of the USEPA Protocol 1 calibration gas introduced into the system. The field evaluation procedures presented in Section 3.2 of Method 205 were followed prior to use of gas divider.

4.7.6 Instrumental Analyzer Interference Check

The instrumental analyzers used to measure NO_X, CO, O_2 and CO_2 have had an interference response test performed prior to their use in the field, pursuant to the interference response test procedures specified in USEPA Method 7E. The appropriate interference test gases (i.e. gases that would be encountered in the exhaust gas stream) were introduced into each analyzer, separately and as a mixture with the analyte that each analyzer is designed to measure. All of analyzers exhibited a composite deviation of less than 3.0% of the span for all measured interferent gases. No major analytical components of the analyzers have been replaced since performing the original interference tests.

4.7.7 Meter Box Calibrations

The dry gas meter sampling console used for moisture determinations was calibrated prior to and after the testing program. This calibration uses the critical orifice calibration technique presented in USEPA Method 5. The metering console calibration exhibited no data outside the acceptable ranges presented in USEPA Method 5.

Appendix D presents test equipment quality assurance data (meter box calibration records, pitot tube certification, NO_2 – NO conversion efficiency test data, instrument calibration and system bias check records, calibration gas certifications, interference test results, gas divider certifications,).

5.0 TEST RESULTS AND DISCUSSION

5.1 Operating Conditions During the Compliance Test

During the compliance test program for EU-TESTCELL7 three tests were performed with the engine exhaust routed to the catalyst emission control device and three were performed without the catalyst (i.e., 6 total test periods). For each scenario, one test was performed during steady-state running conditions (i.e., constant speed and load) and two of the three tests were performed during transient engine cycling. The engine within the test cell was operated continuously for the entire test periods.

Westport Fuels recorded engine fuel use (kilograms per hour, kg/hr), speed (revolutions per minute, RPM), and torque (Newton-meters Nm) at 1-second intervals (1,000 milliseconds) using existing test cell monitoring instruments. The data were reduced to 15-minute averages. Full process data as presented by Westport to Derenzo and Associates can be found on a burned CD attached to the hard copy of the test report.

Power (kW) was calculated using the following equation:

$$P=T*\omega/9549$$

Where P is power (kW), T is torque (Nm), ω is speed (RPM), and 9549 is a constant derived from unit conversions and pi.

The engine in EU-TESTCELL7 was fueled with CNG during each test period. The average measured fuel consumption for each test period was 28.8 kg of CNG during steady state operating and 18.9 kg of CNG during transient testing. The engine was operated at an average speed of:

- 2,998 RPM under an average torque of 376 Nm, or a load of 118 kW, for steady state testing

- 3,000 RPM under an average torque of 214 Nm, or 67 kW, for transient testing.

A summary of the operating conditions are presented in the following table.

Table 5.1 Summary of EU-TESTCELL7 engine operating conditions

Test Number	Control Device	Load (kW)	Percent of Capacity	Fuel Usage (kg)
Test 1	Catalyst	118	43.8%	28.9
Test 2	Catalyst	67.5	25.0%	19.1
Test 3	Catalyst	67.5	25.0%	19.1
Test 4	No Catalyst	118	43.7%	28.7
Test 5	No Catalyst	66.8	24.7%	18.7
Test 6	No Catalyst	67.0	24.8%	18.8

Process data is provided in Appendix A.

5.2 Emission Rate Measurement Results and Discussion

Six sampling periods were performed on EU-TESTCELL7.

Table 5.2 presents measured exhaust gas conditions and pollutant emission rates for EU-TESTCELL7 during the controlled (catalyst) test periods.

Table 5.3 presents measured exhaust gas conditions and pollutant emission rates for EU-TESTCELL7 during the uncontrolled (no catalyst) test periods.

There was no discernable difference between the measured NO_X, CO and VOC emission rates for the catalyst and no catalyst emission control scenarios. Catalyst operating temperatures were not measured during the test periods. Based on the amount of dilution air added to the exhaust gas stream prior to the catalyst, the catalyst operating temperature may be too low for effective emissions reduction.

Appendix E provides field data and emission calculations for the test cell.

Appendix F provides raw instrumental analyzer response data for the test program.

5.3 Variations from Normal Sampling Procedures or Operating Conditions

All instrument calibrations and sampling period results for EU-TESTCELL7 satisfied the quality assurance verifications required by USEPA Methods 1, 2, 3A, 4, 7E, 10, 25A, 205 and ALT-096.

The test plan specified that the engine within the test cell would be operated at 75% of maximum capacity. The recorded operating data indicate that the engine operated at approximately 44% kilowatt capacity during the steady-state test periods. Westport Fuels indicated that this is representative of normal engine operations.

Table 5.2. Summary of Test Cell No. 7 (EU-TESTCELL7) Test Results with catalyst installed
Westport Fuel System, Inc., Plymouth, Michigan

Test No.	1	2	3	
Steady State/Transient	Steady State	Transient	Transient	Three
Test date	10/22/14	10/22/14	10/22/14	Test
Test period (24-hr clock)	10:17-11:17	11:46-12:46	13:13-14:13	Averages
Engine Power (kW)	118	68	68	84
Engine Torque (Nm)	377	215	215	269
Engine Speed (RPM)	2,996	3,000	3,000	2,999
Fuel Usage (kg/hr)	28.93	19.12	19.12	22.39
Exhaust gas composition				
CO_2 content (% vol)	0.77	0.49	0.49	0.58
O_2 content (% vol)	19.68	20.22	20.17	20.03
Moisture (% vol)	2.1	2.3	2.3	2.2
Exhaust gas flowrate				
Standard conditions (scfm)	2,962	2,956	2,960	2,959
Dry basis (dscfm)	2,900	2,888	2,893	2,894
Nitrogen oxides emission rates				
NO_X concentration (ppmvd)*	173.3	100.6	93.2	122.4
NO_X emissions (lb/hr NO_2)	3.60	2.08	1.93	2.54
NO_X emissions (lb/kg fuel)	0.12	0.11	0.10	0.11
Carbon monoxide emission rates				
CO concentration (ppmvd)*	545.0	327.0	313.0	395.0
CO emissions (lb/hr)	6.90	4.12	3.95	4.99
CO emissions (lb/kg fuel)	0.24	0.22	0.21	0.22
VOC/NMHC emission rates				
VOC concentration (ppmv C_3)*	0.77	0.66	0.67	0.70
VOC emissions (lb/hr)	0.016	0.013	0.014	0.014
VOC emissions (lb/kg fuel)	5.41E-04	6.96E-04	7.09E-04	6.49E-04

* Corrected for calibration bias.

Table 5.3. Summary of Test Cell No. 7 (EU-TESTCELL7) Test Results with no catalyst
Westport Fuel System, Inc., Plymouth, Michigan

Test No.	1	2	3	
Steady State/Transient	Steady State	Transient	Transient	Three
Test date	10/23/14	10/23/14	10/23/14	Test
Test period (24-hr clock)	9:57-10:57	11:21-12:21	12:45-13:45	Averages
Engine Power (kW)	118	67	67	84
Engine Torque (Nm)	376	213	213	267
Engine Speed (RPM)	3,000	3,000	3,000	3,000
Fuel Usage (kg/hr)	28.70	18.75	18.76	22.07
Exhaust gas composition				
CO_2 content (% vol)	0.75	0.49	0.50	0.58
O_2 content (% vol)	19.69	20.28	20.24	20.07
Moisture (% vol)	2.3	2.1	2.1	2.2
Exhaust gas flowrate				
Standard conditions (scfm)	2,982	2,988	2,889	2,953
Dry basis (dscfm)	2,914	2,926	2,828	2,890
Nitrogen oxides emission rates				
NO_X concentration (ppmvd)*	165.8	104.4	113.0	127.8
NO_X emissions (lb/hr NO_2)	3.47	2.19	2.29	2.65
NO_X emissions (lb/kg fuel)	0.12	0.12	0.12	0.12
Carbon monoxide emission rates				
CO concentration (ppmvd)*	631.2	295.9	305.2	410.8
CO emissions (lb/hr)	8.03	3.78	3.77	5.19
CO emissions (lb/kg fuel)	0.28	0.20	0.20	0.23
VOC/NMHC emission rates				
VOC concentration (ppmv C_3)*	0.59	0.59	0.61	0.60
VOC emissions (lb/hr)	0.012	0.012	0.012	0.012
VOC emissions (lb/kg fuel)	4.21E-04	6.37E-04	6.36E-04	5.65E-04

* Corrected for calibration bias.