Final Report

DEMONSTRATION OF HUG FILTERSYSTEMS NAUTICLEAN SCR/DPF SYSTEM ON A MARINE VESSEL

Submitted to:

South Coast Air Quality Management District
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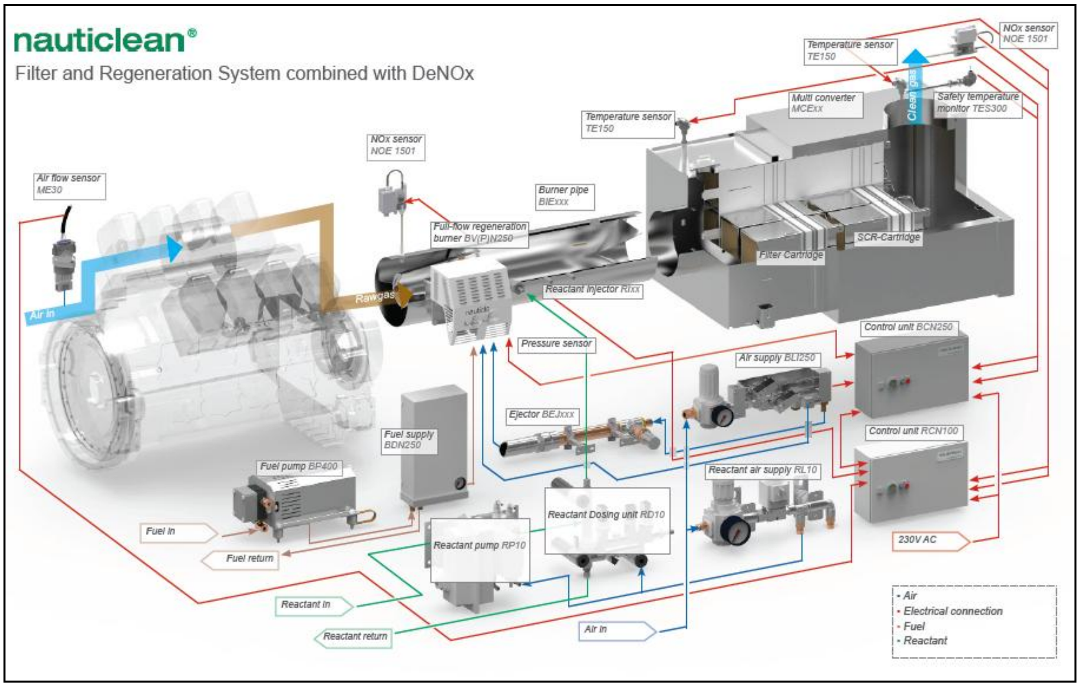

Submitted by:
Todd Jacobs
Project Engineer – Mobile Applications
Hug Filtersystems
123 Holmes Road, Units 1-3
Liberty Hill, TX 78642
512-548-6710

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SECTION 1 EXECUTIVE SUMMARY

Commercial harbor craft (CHC) vessels are a significant contributor to port oxides of nitrogen (NOx) and diesel particulate matter (PM) emissions. In the Initial Statement of Reasons for the Commercial Harbor Craft Regulation[1], CARB estimated that 2014 statewide emissions of NOx would be 50 tons per day of NOx and 2.1 tons per day of diesel PM emissions. A combined diesel particulate filter (DPF) and selective catalytic reduction (SCR) system is capable of reducing both NOx and PM emissions. This demonstration provided further information to assess the emission-reduction potential and reliability of the technology and could lead to early commercialization of the technology for CHC vessels.

The objective of the project was to demonstrate in-use durability as well as 4-way emission (PM, NOx, HC, CO) reduction efficiency of the fresh and aged Hug Nauticlean DPF+SCR retrofit system when installed on CHC propulsion engines. However, due to a number of delays in the project, the CARB grant ended before the demonstration and final tests were completed.

The Nauticlean DPF+SCR system consisted of wall flow silicon carbide DPFs to control PM, a diesel fuel burner to regenerate the DPF, SCR catalysts and urea dosing system to reduce NOx, and Programmable Logic Controllers (PLCs) programmed with algorithms developed by Hug Filtersystems to control DPF regeneration and the urea dosing system.

The Nauticlean DPF+SCR systems were installed on both propulsion engines. Initial emission tests were conducted before and after the system on the starboard engine. Two test series using the ISO 8178 E-3 marine engine test cycle were conducted: one in October 2013 using the urea dosing system algorithm for 70% NOx reduction and the second in April 2014 using the urea dosing system algorithm for 85% NOx reduction.

The weighted emission reduction results were as follows:

SCR Dosing Algorithm	NOx	PM	HC	CO	Ammonia
70% NOx Reduction	72%	90%	87%	40%	1.70 ppm
85% NOx Reduction	92%	96%	-6%	69%	0.49 ppm

Ammonia slip during the second degreened system testing was also reported as 0.24g/kW-hr.

Although the CARB grant ended, the demonstration project will be continued to complete 1000 in-use operating hours and final emissions tests.

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[1] Initial Statement of Reasons, Proposed Regulation for Commercial Harbor Craft, September 2007, page 15, Figures 2 and 3

SECTION 2 SCOPE OF WORK

This demonstration program consisted of the following five tasks:

Task 1 - Project Planning
Task 2 - Design and Fabrication of the Nauticlean DPF+SCR System
Task 3 - Installation of the Nauticlean DPF+SCR System
Task 4 - Demonstration of the Nauticlean DPF+SCR System
Task 5 - Emission Testing of the Nauticlean DPF+SCR System

Task 1 - Project Planning

Task 1 included execution of the grant and contract, kick-off meetings with Sause Bros, CARB, and SCAQMD staff, application for any necessary permits, and submittal of a preliminary verification application (PVA) to CARB.

Task 2 - Design and Fabrication of Nauticlean® DPF+SCR System

Figure 1: Sause Brothers Pushboat Apache

Task 2 included determination of appropriate system as well as design and fabrication the DPF+SCR systems for the Apache. The Apache is a push boat used mainly for moving and positioning barges. It is 60 foot in length with a 22 foot beam and an 8 foot, 4 inch molded depth. The Apache is equipped with two 525hp Detroit Diesel 12V-71 turbocharged and supercharged 2-stroke propulsion engines. Both engines were originally manufactured in 1976 and remanufactured in 2011 using Clean Cam Technology Systems engine rebuild kits. The kits were approved by CARB on October 26, 2010 as alternate technology for compliance with the Tier 2 requirement in CARB’s Commercial Harbor Craft Regulation.

Task 2.1: Inspect Vessel and Engines, Engine room, and Installation Requirements

Hug Filtersystems staff visited the Apache in order to determine the available space envelope for DPF and SCR components including the converter housings, exhaust pipe routing, and location of the control components. Hug personnel worked with Sause Brothers staff to determine preliminary locations for the various parts and components. Based on this onsite visit, Hug Filtersystems engineers were able to begin the design of the systems.

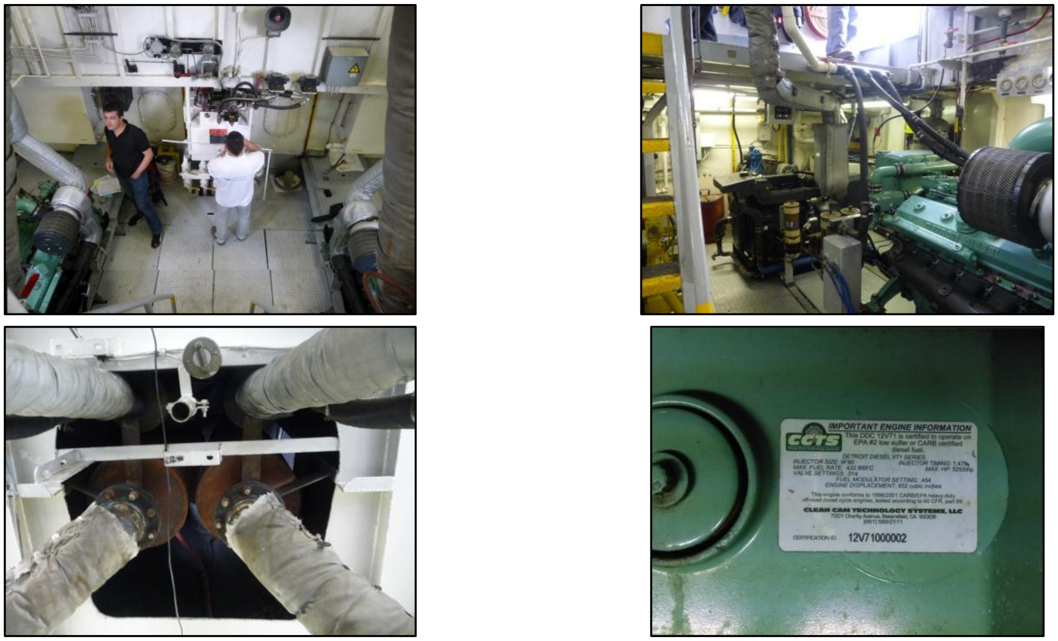


Figure 2: Apache Engine Room Photos

In addition to the space envelope, Hug Filtersystems collected data concerning the engine including displacement, maximum exhaust flow rate, maximum allowable back pressure, horsepower, and certified emission levels of PM and NOx in order to correctly size the DPF and SCR components.

Task 2.2: Collection of Exhaust Temperature Profile and Other Data

Exhaust temperature data was collected from each engine during normal vessel operation. A 1/8" diameter type K thermocouple was installed approximately 48 inches downstream of the turbochargers at the point where the Y-pipe merges into a single pipe (Figure 3). A Madgetech datalogger was used to collect the temperature readings every 5 seconds. Approximately 148 hours of in-use temperature data was collected from each engine. A Hug distributor, Maxx-Air, installed the loggers in August 2011.

Figure 3: Temperature Sampling Point

The analyzed exhaust data is shown in Figures 4 and 5 below.

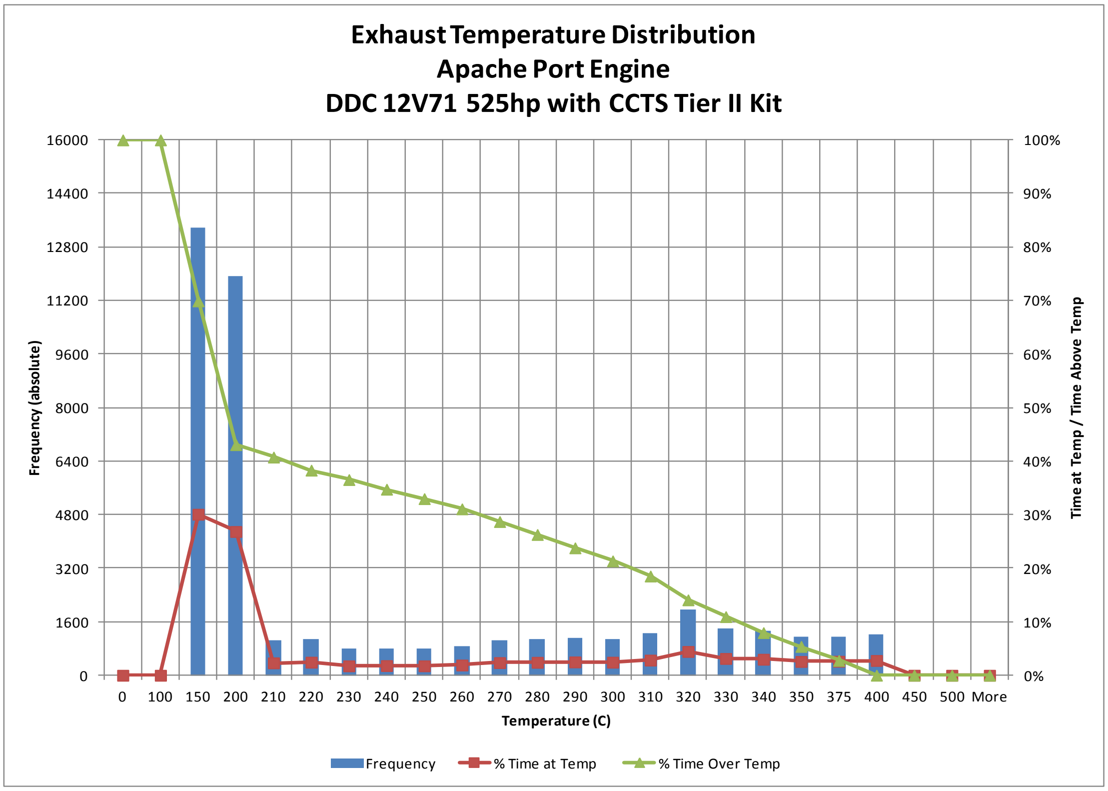


Figure 4: Exhaust Temperature Distribution, Port Engine

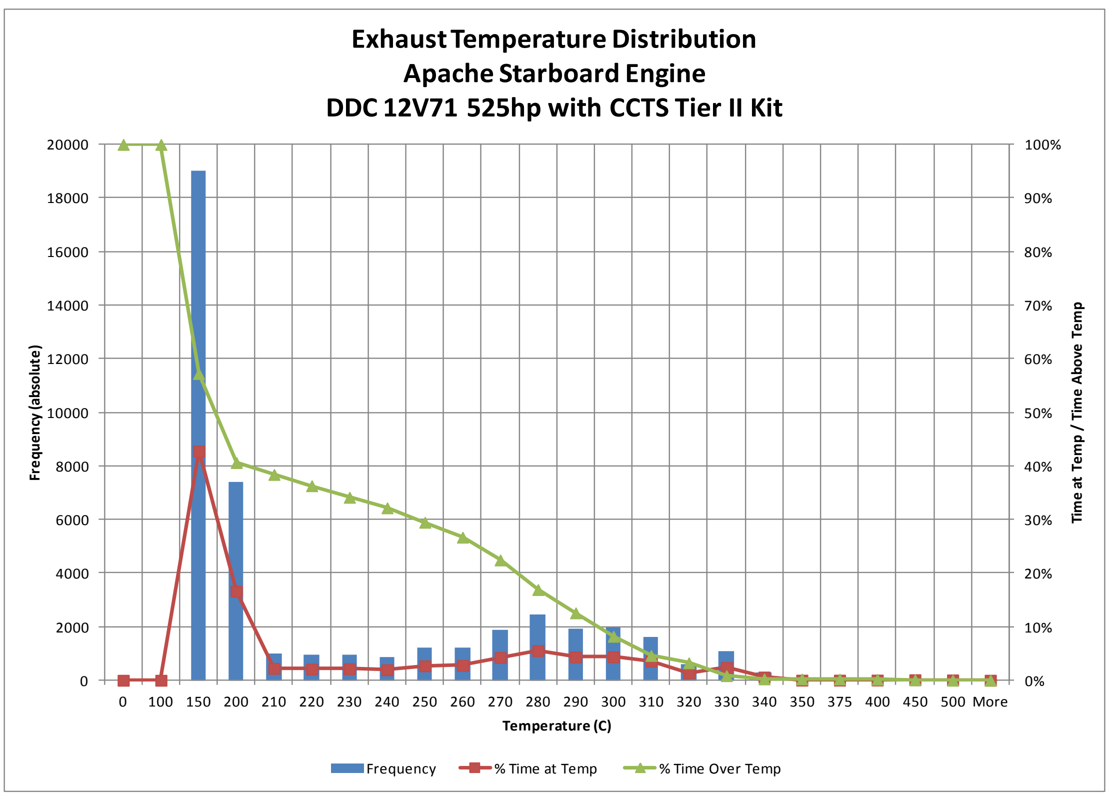


Figure 5: Exhaust Temperature Distribution, Starboard Engine

It is interesting to note that there is significant difference in the exhaust temperature profiles at the upper end of the measured temperatures. The exhaust temperature profiles from both engines are relatively similar for the percent of time exceeding 200°C (43% for the port engine and 40% for starboard). However, for the percent of time exceeding 300°C, the port engine spends approximately 21% while the starboard engine spends approximately 9%.

The group was unable to determine the exact cause for the difference in the exhaust profiles.

The starboard engine was selected for subsequent testing because the exhaust temperature represents worst case scenario.

Task 2.3: Design of DPF/SCR system

The Nauticlean was designed by Hug Engineering in Elsau Switzerland during Q1/Q2 of 2012. Hug Engineering is the Hug Filtersystems European counterpart and the site of Hug's design and engineering center. The Nauticlean DPF+SCR is a compact system that integrates the diesel particulate filters and SCR catalysts into the same reactor housing, shown in Figure 6, thereby reducing the total footprint and space necessary to install the system. In addition, the SCR catalyst module integrates an ammonia slip catalyst to control potential excess NH_3 emissions.

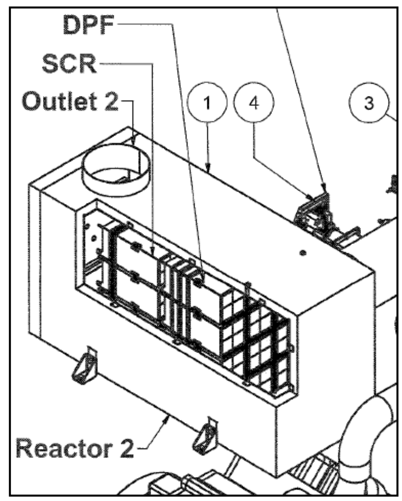


Figure 6: Cutaway view of reactor

After review of the vessel (Task 2.1), it was determined that the reactor housings would be mounted above the engines. In order to accommodate the length of exhaust pipe necessary to ensure homogeneous mixing of the injected DEF, it was decided that the respective reactor housings would be mounted above the opposite engines. Therefore the reactor for the port engine exhaust is located above the starboard engine and vice versa. Figure 7 shows the installed configuration.

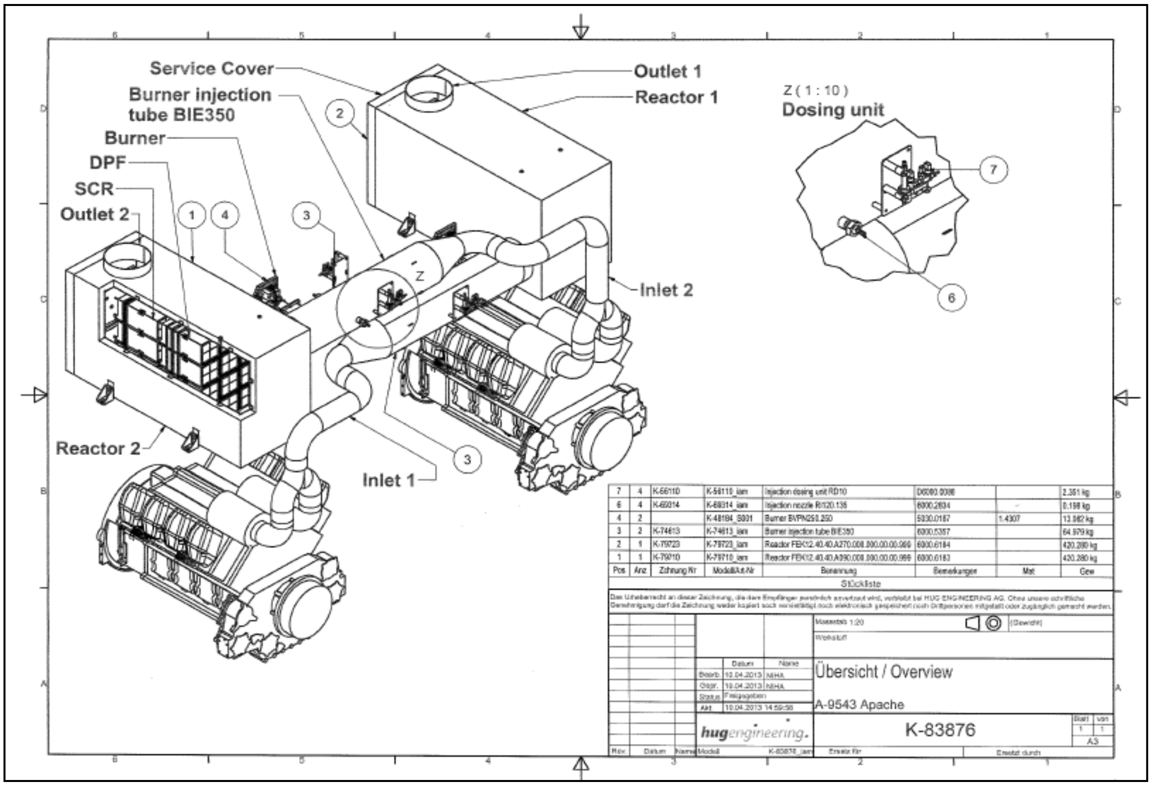


Figure 7: Nauticlean Layout Drawing for Apache

After the layout and design of the converter and mixing pipes was completed, Hug again reviewed the vessel to determine the best location for additional components and designed mounting parts as necessary. These parts include (but are not all inclusive):

1. DPF and SCR systems controls enclosure
   a. Separate control cabinets for the DPF and SCR PLCs would be located on the bulkhead next to the respective engine.
2. DEF Injection pump and Fuel pump for burner system
   a. Mounting bracket designed for mounting the components under the centrally mounted staircase.
3. Burner and DEF dosing manifold
   a. Provisions made to mount these components to the exhaust pipe.
4. DEF storage tank
   a. 80 gallon DEF storage tank to be located under engine room staircase

Controls Cabinets

DEF Pump, Fuel Pump and Fuel Filter

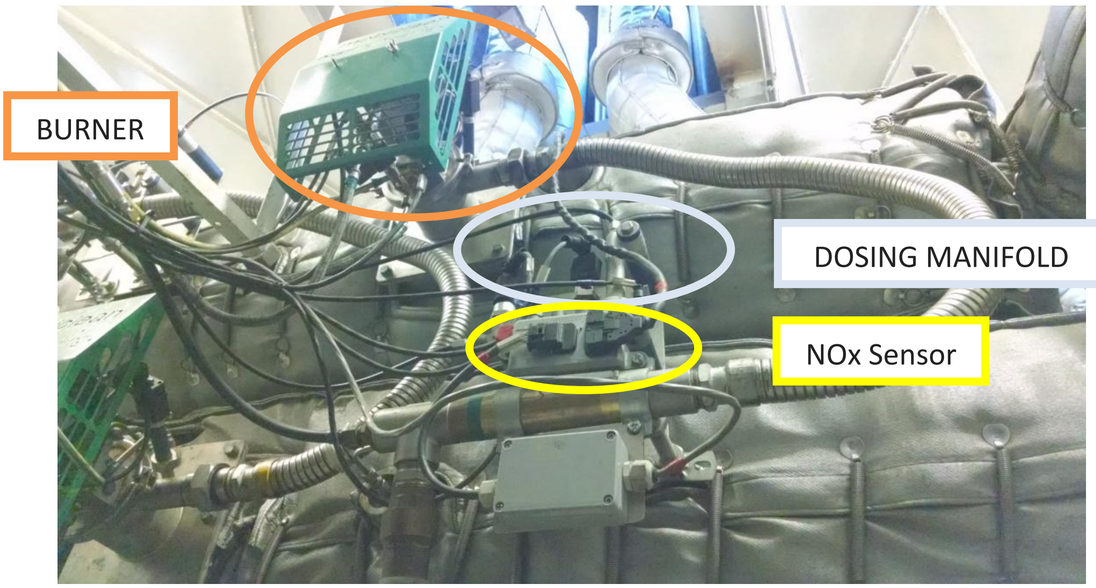


Figure 8: Components of the Nauticlean DPF+SCR System

Task 2.4: Fabricate and Deliver Completed DPF/SCR system

The various items included in the Hug Filtersystems scope of supply were manufactured by Hug Engineering in Switzerland during 2Q 2012. The systems were delivered to Sause Brothers dock in Long Beach, CA, during 3Q 2012.

Task 3 - Installation of Nauticlean DPF+SCR System

This section details the installation and commissioning of the Nauticlean DPF+SCR system on the Apache.

Task 3.1: Installation

Installation of the systems was carried out in November 2012. Labor was supplied by Sause Brothers. Hug Filtersystems provided engineering support during the installation. Sause Brothers maintenance personnel have extremely strong fabrication skills and a thorough understanding of the stresses incurred during vessel operation. Therefore brackets and exhaust pipes not included in the Hug scope of supply were fabricated in-house by Sause personnel. In addition, Sause Brothers provided the labor to route wiring and various piping for the regeneration burner fuel and the DEF. Hug technical personnel reviewed the installation and worked with Sause Brothers to correct any installation errors. Figure 9 shows several photographs of the systems being installed on the Apache.


Installing Port Reactor


Starboard Reactor


Injection Components in Mixing Duct


Exhaust Stack Pipe


DPF and SCR Compressed Air Regulators


DEF Pump and Fuel Filter

DPF and SCR Controls Cabinets

Insulated reactor housing

Figure 9: Nauticlean Installation Photos On-board Apache

In November 2012, the DPF substrates and SCR catalysts were removed from the reactor housings and the supporting hardware and electronics were left in a powered-down state after the installation was carried out because CARB had not approved the test plan by the time the installation was complete and Sause needed to use the vessel. Removing these components from service allowed Sause Brothers to operate the vessel without accumulating hours on durability sensitive and mission critical components while Hug continued to work with ARB to approve the PVA and test plan. The PVA and test plan approvals were granted in July 2013.

Task 3.2: Commissioning

Upon approval of the PVA and test plan by CARB, Hug Filtersystems visited the Apache in August 2013 to commission the systems and prepare for emissions testing of the engine baseline and DPF+SCR system. The DPF filter modules and SCR/ammonia slip catalyst modules were installed and the controls were powered-up in preparation for commissioning.

Hug technical personnel from Switzerland joined the Apache for a day of sea trials to verify proper functioning of the systems. Unfortunately, Hug Filtersystems USA personnel were not present during the commissioning because of turnover in the project management and field service positions. The Hug Switzerland technician commissioned the DPF+SCR systems following typical European protocols which call for greater than 70% NOx reduction. Therefore the systems as commissioned could not achieve Mark 5 NOx (>85% NOx reduction) which was the intended goal of the project. This oversight was not detected until the first set of emissions tests was carried out in October 2013.

During the commissioning process, it was also discovered that the air compressors on board the Apache were inadequate to support the air flow needs of the Nauticlean system and the compressed air needs of the vessel at the same time. Therefore, new compressors were specified by Hug Filtersystems and sourced by Sause Brothers (costs charged back to Hug). In addition, compressed air driers and filters were fitted to the onboard compressed air system to ensure clean dry compressed air was being delivered to the Nauticlean systems.

Hug Filtersystems filled the vacant Project Engineer – Mobile Applications position in November 2013. The new project engineer reviewed the emissions data generated in the October 2013 round of testing as well as the overall status of the project. After consulting with Hug Switzerland technical and engineering staff, the commissioning error was discovered.

CARB and SCAQMD staff was alerted to the error in commissioning. Hug petitioned the CARB executive officer for approval to change the program in the PLC to reflect the desired NOx reduction and retest the engine and DPF+SCR system. The executive officer granted permission to proceed in December 2013.

Hug technical personnel visited the Apache in February 2014 to recommission the two SCR systems using the correct PLC program with a dosing algorithm designed to provide 85% NOx reduction. A second set of emissions tests was scheduled after recommissioning.

Task 3.3: Training

Hug Filtersystems provided training to the Sause Brothers maintenance staff. Training consisted of identifying each component, its role in the system, and how the DPF and SCR controls interact. In addition, Hug walked the Sause maintenance personnel through the PLC displays; what is displayed and how to scroll through the menus. Error codes were discussed and critical errors were identified as were proper actions in the event of a critical error. Quick reference worksheets shown as Attachment 2 (DPF) and Attachment 3 (SCR) were developed and provided to Sause. Sause placed the quick reference cards in the wheelhouse for the Captain to review in the event an error goes active. Displays for the Nauticlean DPF+SCR systems were mounted in the wheel house as well as the engine room.

Task 4 - Demonstration of the Nauticlean DPF/SCR System

This section details the coordination of the durability phase of the project including data collection and analysis.

Task 4.1 Datalogging and Recordkeeping

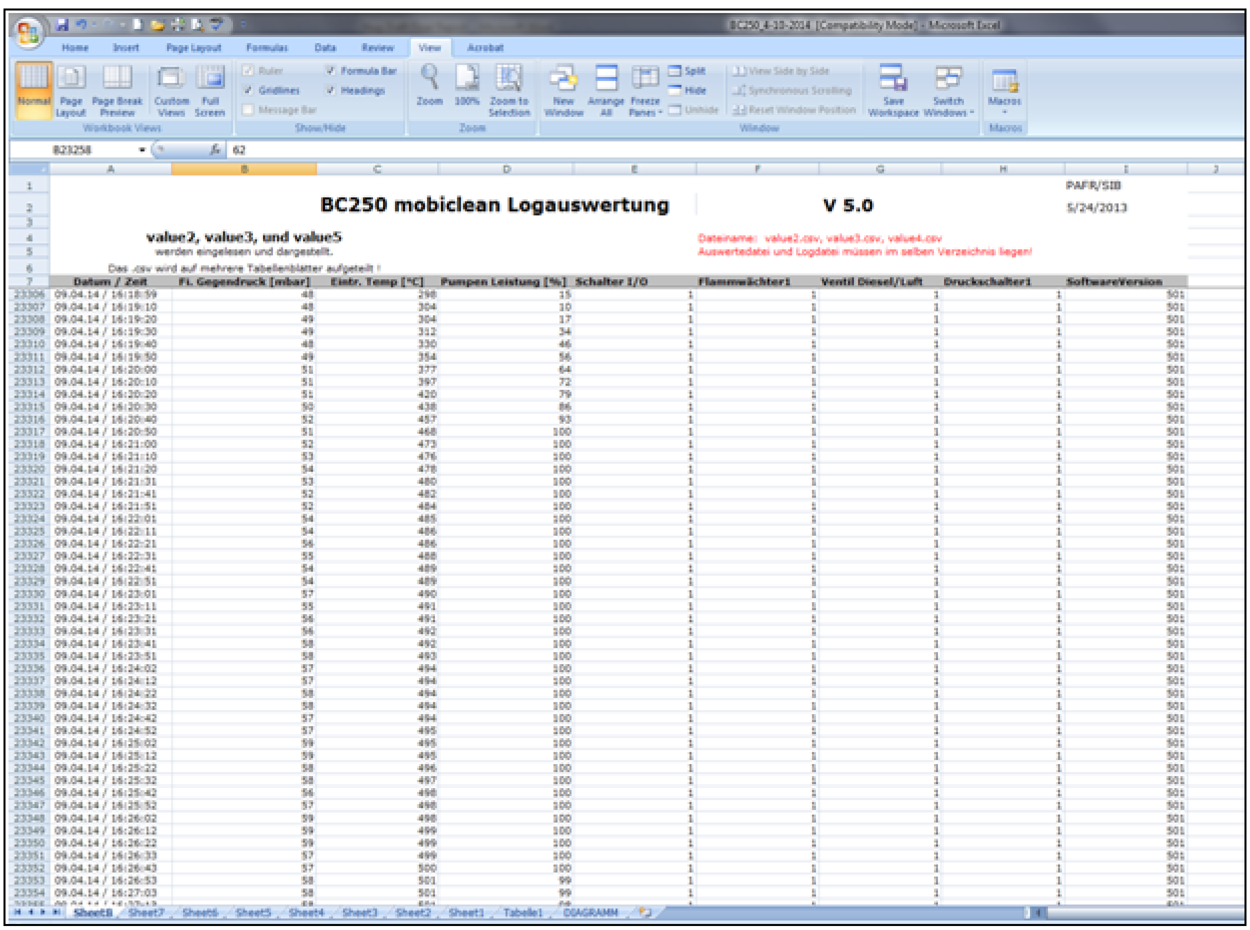
Each Nauticlean system is equipped with a datalogger programmed either for DPF or SCR service. The datalogger records system data while the engine is in operation. In this case, engine operation is indicated to the Nauticlean controls via a switch on the outlet of the engines oil pump. When oil pressure is present, the engine is presumed to be in operation and the Nauticlean DPF+SCR system is enabled. The Nauticlean can also receive digital CAN engine data from electronically controlled engines as well. This Nauticlean input (analog or digital) is preconfigured at Hug prior to shipping based on data collected during the vessel evaluation.

Each datalogger samples every second and records data every 10 seconds. All dataloggers are currently loaded with 4 gigabyte memory cards. The dataloggers are programmed to automatically overwrite the earliest data on a first in/first out basis when the SD card memory is full. It is expected that the cards will hold approximately 3 years of data if the vessel operates 12 hours per day, 7 days per week at a 10 second recording rate.

The DPF datalogger records the following information while the engine is running:

1. Date and time
2. Back pressure (mbar)
3. Inlet temperature (°C)
4. Fuel pump PWM rate (%)
5. Digital I/O
    a. SCR disable switch (indicates DPF is regenerating disabling the SCR system)
    b. Flame detector
    c. Diesel / Compressed air valve enabled

A sample of the data in its raw form is shown in Figure 10.



BC250 mobiclean Logauswertung — V 5.0 — PAFR/SIB 5/24/2013

value2, value3, und value5
werden eingelesen und dargestellt.
Das .csv wird auf mehrere Tabellenblätter aufgeteilt !

Dateiname: value2.csv, value3.csv, value4.csv
Auswertedatei und Logdatei müssen im selben Verzeichnis liegen!

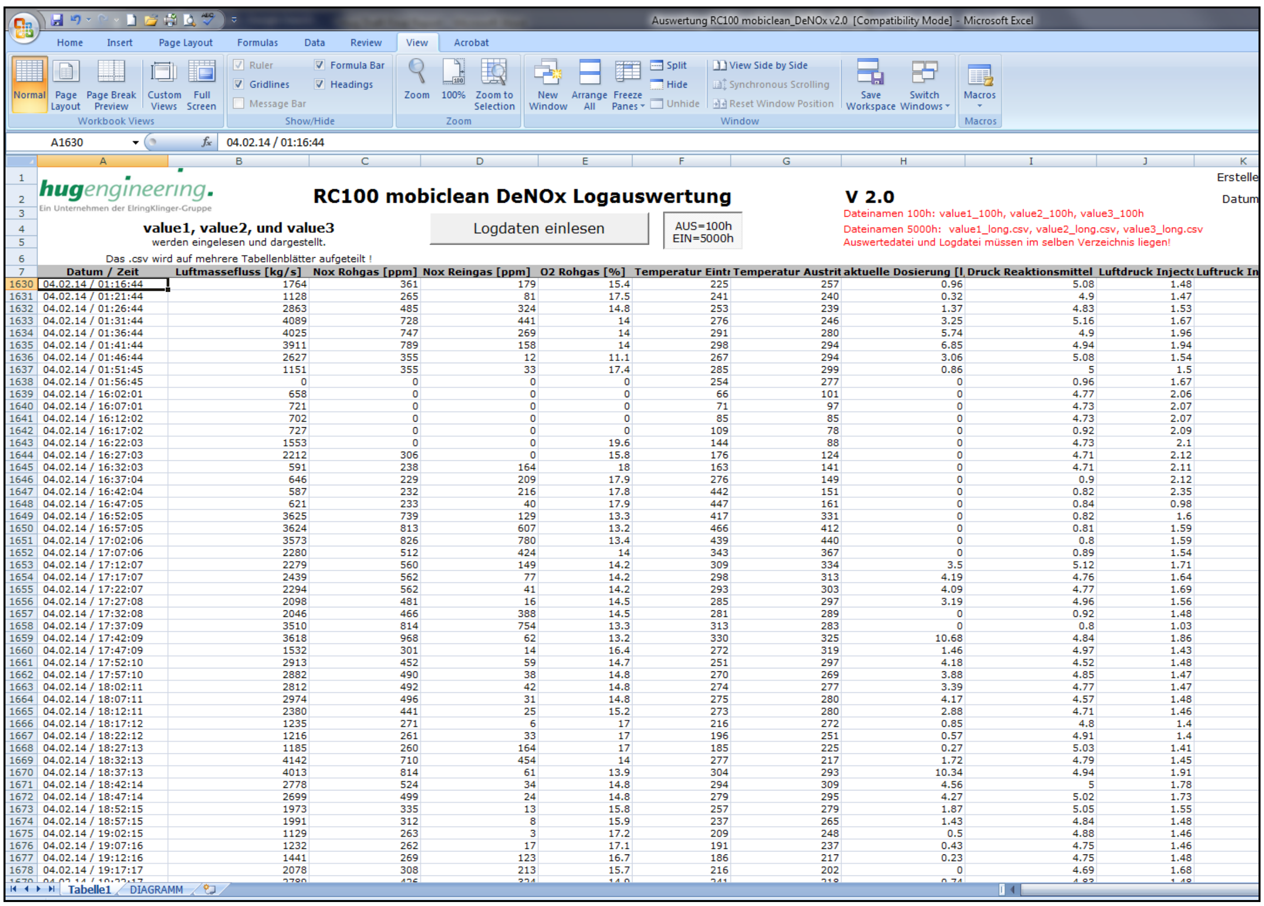
	Datum / Zeit	Fi. Gegendruck [mbar]	Eintr. Temp [°C]	Pumpen Leistung [%]	Schalter I/O	Flammwächter1	Ventil Diesel/Luft	Druckschalter1	SoftwareVersion
23306	09.04.14 / 16:18:59	48	298	15	1	1	1	1	501
23307	09.04.14 / 16:19:10	48	304	10	1	1	1	1	501
23308	09.04.14 / 16:19:20	49	304	17	1	1	1	1	501
23309	09.04.14 / 16:19:30	49	312	34	1	1	1	1	501
23310	09.04.14 / 16:19:40	48	330	46	1	1	1	1	501
23311	09.04.14 / 16:19:50	49	354	56	1	1	1	1	501
23312	09.04.14 / 16:20:00	51	377	64	1	1	1	1	501
23313	09.04.14 / 16:20:10	51	397	72	1	1	1	1	501
23314	09.04.14 / 16:20:20	51	420	79	1	1	1	1	501
23315	09.04.14 / 16:20:30	50	438	86	1	1	1	1	501
23316	09.04.14 / 16:20:40	52	457	93	1	1	1	1	501
23317	09.04.14 / 16:20:50	51	468	100	1	1	1	1	501
23318	09.04.14 / 16:21:00	52	473	100	1	1	1	1	501
23319	09.04.14 / 16:21:10	53	476	100	1	1	1	1	501
23320	09.04.14 / 16:21:20	54	478	100	1	1	1	1	501
23321	09.04.14 / 16:21:31	53	480	100	1	1	1	1	501
23322	09.04.14 / 16:21:41	52	482	100	1	1	1	1	501
23323	09.04.14 / 16:21:51	52	484	100	1	1	1	1	501
23324	09.04.14 / 16:22:01	54	485	100	1	1	1	1	501
23325	09.04.14 / 16:22:11	54	486	100	1	1	1	1	501
23326	09.04.14 / 16:22:21	56	486	100	1	1	1	1	501
23327	09.04.14 / 16:22:31	55	488	100	1	1	1	1	501
23328	09.04.14 / 16:22:41	54	489	100	1	1	1	1	501
23329	09.04.14 / 16:22:51	54	489	100	1	1	1	1	501
23330	09.04.14 / 16:23:01	57	490	100	1	1	1	1	501
23331	09.04.14 / 16:23:11	55	491	100	1	1	1	1	501
23332	09.04.14 / 16:23:21	56	491	100	1	1	1	1	501
23333	09.04.14 / 16:23:31	56	492	100	1	1	1	1	501
23334	09.04.14 / 16:23:41	58	492	100	1	1	1	1	501
23335	09.04.14 / 16:23:51	58	493	100	1	1	1	1	501
23336	09.04.14 / 16:24:02	57	494	100	1	1	1	1	501
23337	09.04.14 / 16:24:12	57	494	100	1	1	1	1	501
23338	09.04.14 / 16:24:22	58	494	100	1	1	1	1	501
23339	09.04.14 / 16:24:32	58	494	100	1	1	1	1	501
23340	09.04.14 / 16:24:42	57	494	100	1	1	1	1	501
23341	09.04.14 / 16:24:52	57	495	100	1	1	1	1	501
23342	09.04.14 / 16:25:02	59	495	100	1	1	1	1	501
23343	09.04.14 / 16:25:12	59	495	100	1	1	1	1	501
23344	09.04.14 / 16:25:22	58	496	100	1	1	1	1	501
23345	09.04.14 / 16:25:32	58	497	100	1	1	1	1	501
23346	09.04.14 / 16:25:42	56	498	100	1	1	1	1	501
23347	09.04.14 / 16:25:52	57	498	100	1	1	1	1	501
23348	09.04.14 / 16:26:02	59	498	100	1	1	1	1	501
23349	09.04.14 / 16:26:12	59	499	100	1	1	1	1	501
23350	09.04.14 / 16:26:22	59	499	100	1	1	1	1	501
23351	09.04.14 / 16:26:33	57	499	100	1	1	1	1	501
23352	09.04.14 / 16:26:43	57	500	100	1	1	1	1	501
23353	09.04.14 / 16:26:53	58	501	99	1	1	1	1	501
23354	09.04.14 / 16:27:03	58	501	99	1	1	1	1	501

Figure 10: Raw DPF Data Example

The SCR datalogger records the following information while the engine is running:

1. Date/Time
2. Mass air flow (kg/s)
3. Inlet NOx (ppm)
4. Outlet NOx (ppm)
5. Raw O2 (%)
6. Inlet Temp (°C)
7. Outlet temp (°C)
8. Urea dose rate (l/h)
9. Urea pressure (bar)
10. Air pressure (bar)

A sample of the SCR raw data is shown in Figure 11.



7	Datum / Zeit	Luftmassefluss [kg/s]	Nox Rohgas [ppm]	Nox Reingas [ppm]	O2 Rohgas [%]	Temperatur Eint	Temperatur Austrit	aktuelle Dosierung [l	Druck Reaktionsmittel	Luftdruck Inject	Luftruck In
1630	04.02.14 / 01:16:44	1764	361	179	15.4	225	257	0.96	5.08	1.48	
1631	04.02.14 / 01:21:44	1128	265	81	17.5	241	240	0.32	4.9	1.47	
1632	04.02.14 / 01:26:44	2863	485	324	14.8	253	239	1.37	4.83	1.53	
1633	04.02.14 / 01:31:44	4089	728	441	14	276	246	3.25	5.16	1.67	
1634	04.02.14 / 01:36:44	4025	747	269	14	291	280	5.74	4.9	1.96	
1635	04.02.14 / 01:41:44	3911	789	158	14	298	294	6.85	4.94	1.94	
1636	04.02.14 / 01:46:44	2627	355	12	11.1	267	294	3.06	5.08	1.54	
1637	04.02.14 / 01:51:45	1151	355	33	17.4	285	299	0.86	5	1.5	
1638	04.02.14 / 01:56:45	0	0	0	0	254	277	0	0.96	1.67	
1639	04.02.14 / 16:02:01	658	0	0	0	66	101	0	4.77	2.06	
1640	04.02.14 / 16:07:01	721	0	0	0	71	97	0	4.73	2.07	
1641	04.02.14 / 16:12:02	702	0	0	0	85	85	0	4.73	2.07	
1642	04.02.14 / 16:17:02	727	0	0	0	109	78	0	0.92	2.09	
1643	04.02.14 / 16:22:03	1553	0	0	19.6	144	88	0	4.73	2.1	
1644	04.02.14 / 16:27:03	2212	306	0	15.8	176	124	0	4.71	2.12	
1645	04.02.14 / 16:32:03	591	238	164	18	163	141	0	4.71	2.11	
1646	04.02.14 / 16:37:04	646	229	209	17.9	276	149	0	0.9	2.12	
1647	04.02.14 / 16:42:04	587	232	216	17.8	442	151	0	0.82	2.35	
1648	04.02.14 / 16:47:05	621	233	40	17.9	447	161	0	0.84	0.98	
1649	04.02.14 / 16:52:05	3625	739	129	13.3	417	331	0	0.82	1.6	
1650	04.02.14 / 16:57:05	3624	813	607	13.2	466	412	0	0.81	1.59	
1651	04.02.14 / 17:02:06	3573	826	780	13.4	439	440	0	0.8	1.59	
1652	04.02.14 / 17:07:06	2280	512	424	14	343	367	0	0.89	1.54	
1653	04.02.14 / 17:12:07	2279	560	149	14.2	309	334	3.5	5.12	1.71	
1654	04.02.14 / 17:17:07	2439	562	77	14.2	298	313	4.19	4.76	1.64	
1655	04.02.14 / 17:22:07	2294	562	41	14.2	293	303	4.09	4.77	1.69	
1656	04.02.14 / 17:27:08	2098	481	16	14.5	285	297	3.19	4.96	1.56	
1657	04.02.14 / 17:32:08	2046	466	388	14.5	281	289	0	0.92	1.48	
1658	04.02.14 / 17:37:09	3510	814	754	13.3	313	283	0	0.8	1.03	
1659	04.02.14 / 17:42:09	3618	968	62	13.2	330	325	10.68	4.84	1.86	
1660	04.02.14 / 17:47:09	1532	301	14	16.4	272	319	1.46	4.97	1.43	
1661	04.02.14 / 17:52:10	2913	452	59	14.7	251	297	4.18	4.52	1.48	
1662	04.02.14 / 17:57:10	2882	490	38	14.8	270	269	3.88	4.85	1.47	
1663	04.02.14 / 18:02:11	2812	492	42	14.8	274	277	3.39	4.77	1.47	
1664	04.02.14 / 18:07:11	2974	496	31	14.8	275	280	4.17	4.57	1.48	
1665	04.02.14 / 18:12:11	2380	441	25	15.2	273	280	2.88	4.71	1.46	
1666	04.02.14 / 18:17:12	1235	271	6	17	216	272	0.85	4.8	1.4	
1667	04.02.14 / 18:22:12	1216	261	33	17	196	251	0.57	4.91	1.4	
1668	04.02.14 / 18:27:13	1185	260	164	17	185	225	0.27	5.03	1.41	
1669	04.02.14 / 18:32:13	4142	710	454	14	277	217	1.72	4.79	1.45	
1670	04.02.14 / 18:37:13	4013	814	61	13.9	304	293	10.34	4.94	1.91	
1671	04.02.14 / 18:42:14	2778	524	34	14.8	294	309	4.56	5	1.78	
1672	04.02.14 / 18:47:14	2699	499	24	14.8	279	295	4.27	5.02	1.73	
1673	04.02.14 / 18:52:15	1973	335	13	15.8	257	279	1.87	5.05	1.55	
1674	04.02.14 / 18:57:15	1991	312	8	15.9	237	265	1.43	4.84	1.48	
1675	04.02.14 / 19:02:15	1129	263	3	17.2	209	248	0.5	4.88	1.46	
1676	04.02.14 / 19:07:16	1232	262	17	17.1	191	237	0.43	4.75	1.46	
1677	04.02.14 / 19:12:16	1441	269	123	16.7	186	217	0.23	4.75	1.48	
1678	04.02.14 / 19:17:17	2078	308	213	15.7	216	202	0	4.69	1.68	

Figure 11: Raw SCR Data Example

The contract stipulates that the information shown in Table 1 is required to be recorded during the project:

Table 1: Collected Data per Contractual Obligation

Required Parameter	How Recorded	Stored by DPF or SCR logger	Unit
Engine Hours	Calculated in the data set and captured by hour meters installed on the vessel	Both	Hours
Exhaust flow	Calculated by SCR PLC using mass airflow sensor before turbocharger	SCR	kg/s
Exhaust Temp	Type K thermocouples located at the inlet and outlet of the reactor housing	Both	°C
DPF regen frequency	Calculated from the data set	DPF	Number of regenerations
DPF regen fuel consumption	Calculated from the dataset	DPF	Liters
DPF regen duration	Calculated from the dataset	DPF	Hours
Engine fuel consumption	Sause Brothers records	N/A	Gallons (cumulative)
Engine out NOx	NOx sensor mounted on inlet exhaust pipe	SCR	Ppm
System out NOx	NOx sensor mounted in outlet of reactor	SCR	Ppm

In addition to the various operational parameters collected detailing the performance of the systems, both the DPF and SCR PLCs record detailed alarm histories. Error codes for the DPF system are shown in Attachment 4. Error codes for the SCR system are shown in Attachment 5.

Task 4.2: Accumulation of 1000 hours

The goal of this project was to accumulate a minimum of 1,000 hours of operation while the vessel performed typical day-to-day activities. It is estimated that between 200-300 hours will have been accumulated by the end date of the grant (May 30, 2014). Hug Filtersystems is committed to completing the project and accumulating over 1000 hours of real world operation followed by a final round of aged system emissions testing. Hug Filtersystems will incur the costs associated with completing the project.

Task 4.3: Technical Support to Sause

Hug Filtersystems lent our support to Sause in the following instances:

1. Installation: Hug technical support assisted Sause personnel with installation.
2. Commissioning: Hug technical personnel commissioned the system with the assistance of Sause personnel to operate the vessel.
3. Compressed air consumption: Hug and Sause personnel worked together to determine how much compressed air was generated by the existing compressors and specified new compressors to ensure the safety of the vessel was maintained.
4. Hug personnel will visit the Apache each week during the durability phase to collect in-use data from the DPF and SCR dataloggers. In addition, the Hug technician will

verify the system is not in an alarm state, or if it is in an alarm state, take corrective action.

Task 5 - Emissions Testing of the Nauticlean DPF+SCR System

This section details activity related to the in-use emissions testing onboard the vessel. Tests were performed before the DPF+SCR system (the engine baseline emissions) and after the DPF+SCR system. These tests provided data to calculate the per cent emissions reductions as well as emission levels to compare to emission standards. The tests in October 2013 were conducted with approximately 50 hours having been accumulated to "degreen" the catalysts and DPFs. The degreening process ensured that the catalyst and DPF performance had stabilized prior to beginning the emission tests. The tests in April 2014 were conducted with approximately 170 hours accumulated. Hug Engineering personnel do not believe that this difference in accumulated hours had any effect on emissions. A final series of tests will be conducted after accumulating 1000 hours of typical vessel operation.

Task 5.1: Select Testing Organization

Hug Filtersystems originally chose to partner with Emisstar, LLC to conduct emissions test services in support of this project. CARB approved Emisstar as qualified for the tests. However, in February 2014, Hug decided to partner with the University of California-Riverside, College of Engineering, Center for Environmental Research and Technology (CE-CERT) to carry out all emissions testing going forward.

Several factors contributed to replacing Emisstar with CE-CERT for emissions test services including:

1. Delay in issuing a report from October emissions testing: Emisstar did not submit a report to Hug until late January 2014, nearly 4 months after the testing was carried out.
2. Data report inaccuracies: Emisstar's original report contained incorrect fuel consumption figures resulting in incorrect and elevated emissions results. Data were corrected in the January 2014 report; however Emisstar's QC process remained suspect due to the incorrect data being released to Hug.

The decision to select CE-CERT was influenced by several factors including:

1. The university's extensive experience conducting in-use emissions tests onboard vessels.
2. The university staff which is widely recognized as experts in the field of emissions sampling.
3. The quality of the data is typically exceptional and accepted by CARB and other regulatory agencies.
4. The established relationship between CARB and the university.

Consequently, CE-CERT conducted engine baseline and system degreened emissions testing in April 2014. The decision to change emission testing organizations was approved by CARB and SCAQMD staff.

Task 5.2: Fuel Analysis

The Apache can hold approximately 11,000 gallons of fuel and is typically fueled to approximately 10,000 gallons. Fuel is stored in 3 tanks which are constantly balanced to ensure level trim and safe vessel operation.

Fuel is sourced based on the Apache's operating location. When operating at the "Thumbs" servicing the oil islands, the Apache is typically fueled at Yankcovich Company Marina (Berth 74, San Pedro, CA 90731). When the Apache is operating from the Sause Brothers location, it is fueled at the General Petroleum Terminal Island facility.

The fuel onboard Apache at the time of emissions testing in April 2014 was sourced from both facilities, therefore is a combination of fuels from both providers.

Analysis of the fuel sample is shown in Attachment 6 and confirms that it was ultra low (<15 ppm) sulfur diesel fuel.

Task 5.3: Testing

Engine baseline and degreened system emission testing was carried out twice; first by Emisstar LLC in October 2013 and second by CE-CERT in April 2014. In both cases, the baseline was tested prior to testing the degreened system. The second series of tests was carried out because Hug did not use the correct urea dosing program in the SCR controller when the system was originally commissioned and tested.

During the first commissioning, the Hug technician enabled the program that will allow for greater than 70% NOx reduction instead of greater than 85% which aligns with the goals of this project. This error was discovered after Emisstar LLC carried out emissions testing in October 2013. The Emisstar LLC test plan, equipment description, and personnel resumes are shown in Attachment 7.

Following a recommissioning in February 2014 to enable greater than 85% NOx reduction, CE-CERT retested the same engine and emissions control system. CE-CERT carried out engine baseline and degreened system emissions testing. The CE-CERT test plan, equipment description, and personnel resumes are shown in Attachment 8.

In both cases, engine baseline emissions samples were drawn from the exhaust pipe downstream of the turbochargers and upstream of the emissions control device. Emisstar and CE-CERT used the same sampling locations. The inlet sample locations were in the exhaust pipe entering the converter housing. Degreened system emissions were sampled from the outlet portion of the converter housing downstream of the SCR catalysts.

CE-CERT will continue working with Hug to carry out emissions testing after the system accumulates a minimum of 1000 hours of operation. Since the contract will end prior to fulfilling the 1000 hours of operation, Hug anticipates carrying out final emissions testing in the November 2014 timeframe.

Task 5.4a: Analysis of Test Data – Emisstar Results

Emisstar LLC conducted baseline and degreened system emissions testing on October 10, 2013. This testing was carried out with the incorrect NOx reduction program (70% reduction vs. 85% reduction) in the SCR PLC, therefore NOx reduction was less than anticipated. However, PM reduction exceeded CARB Level 3 reduction designation.

The following figures detail results of the emissions testing carried out by Emisstar on October 10, 2013. Figures 12 and 13 detail the CO, NO, NO_2, NO_x, and THC emissions for each load point of the ISO 8178-E3 test cycle.

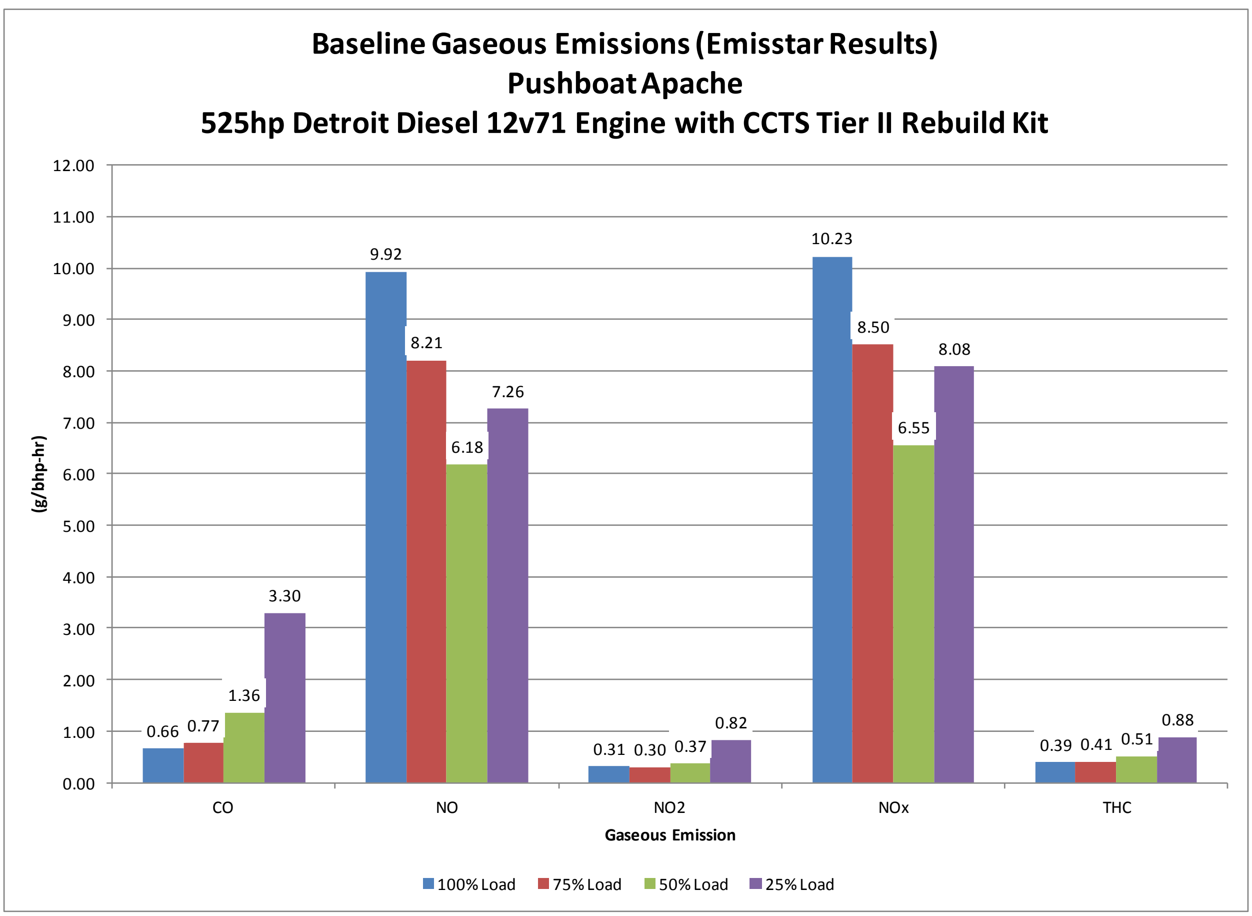


Figure 12: Engine Baseline Gaseous Emissions by Test Mode

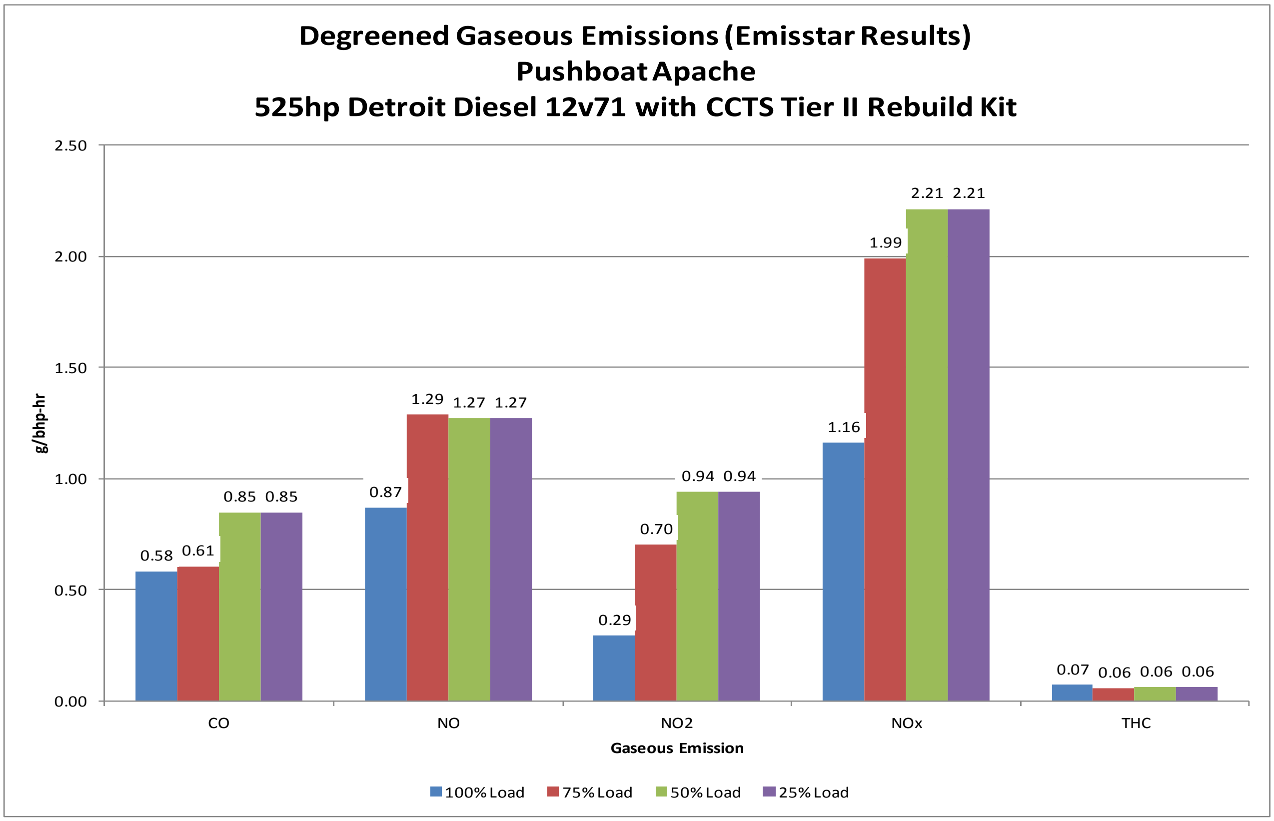


Figure 13: Degreened Nauticlean Gaseous Emissions by Test Mode

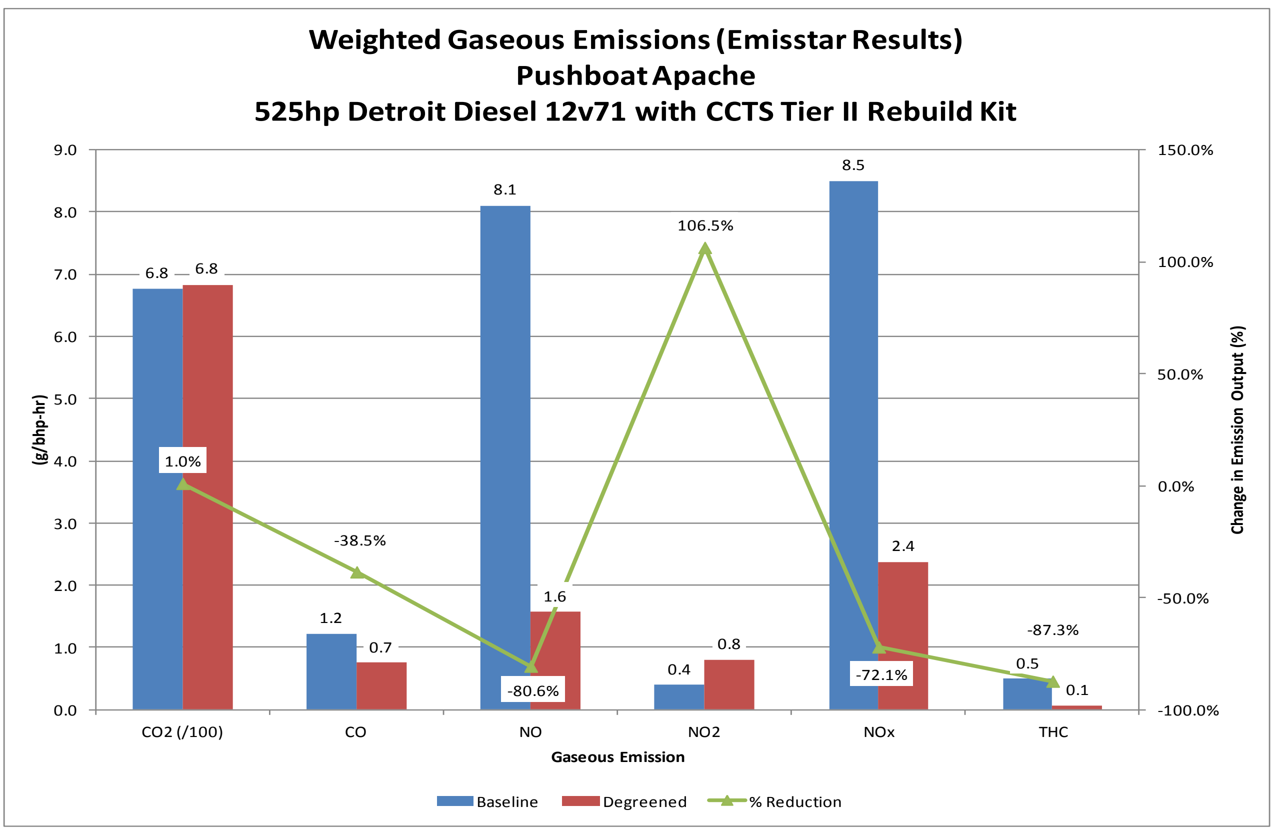


Figure 14: Weighted Gaseous Emissions with Percent Change from Baseline

Figure 14 shows the weighted emissions from engine baseline and compares to weighted emissions after the degreened Nauticlean DPF+SCR system. CO was reduced 38.5%; NOx was reduced 72.1% and THC was reduced 87.3% when compared to engine baseline. There was an overall increase in NO_2, however the increase is well below the 20% limit using the equation provided in §2706 (a) (5):

$$\text{Percent Increase} = 100\% * 0.5 * [(NO_2^{i} - NO_2^{b}) + (NO_2^{f} - NO_2^{b})]/NO_x^{b}$$

Where "NO_2" and "NOx" stand for the mass-based emission rates of NO2 and NOx, and the superscripts "i", "f", and "b" stand for "initial test", "final test", and "baseline test". Therefore

4.7% = 100% * 0.5 * [(0.8 – 0.4) + (0.8[1] – 0.4)]/8.5

Particulate matter emissions by test mode are shown in Figure 15.

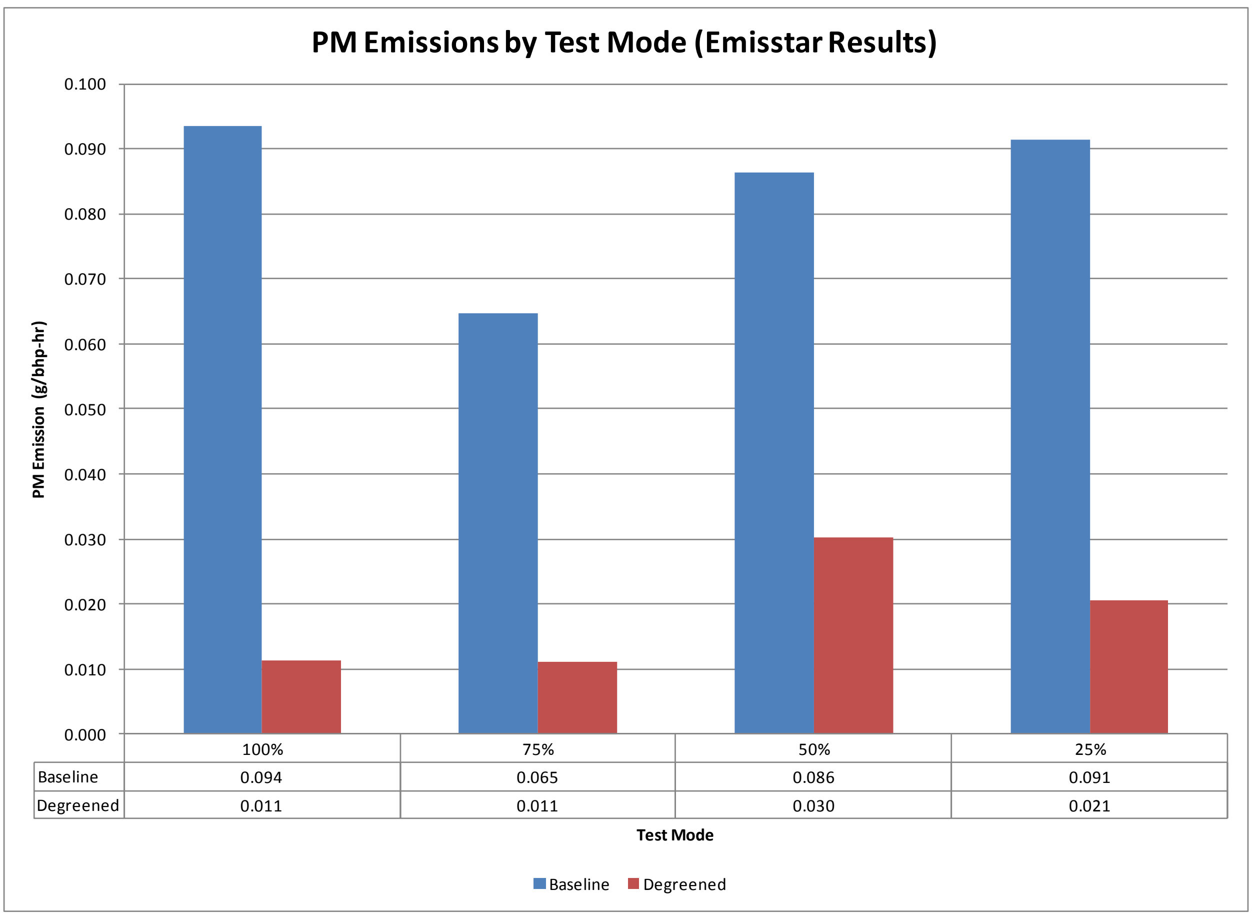


Figure 15: PM Emissions by Test Mode

[1] This value is assumed because final tests have not been carried out. Degreened NO2 is used in substitution.

Figure 16 details the weighted PM emissions results. In this case, PM emissions are reduced by approximately 90% when engine baseline and degreened system are compared.

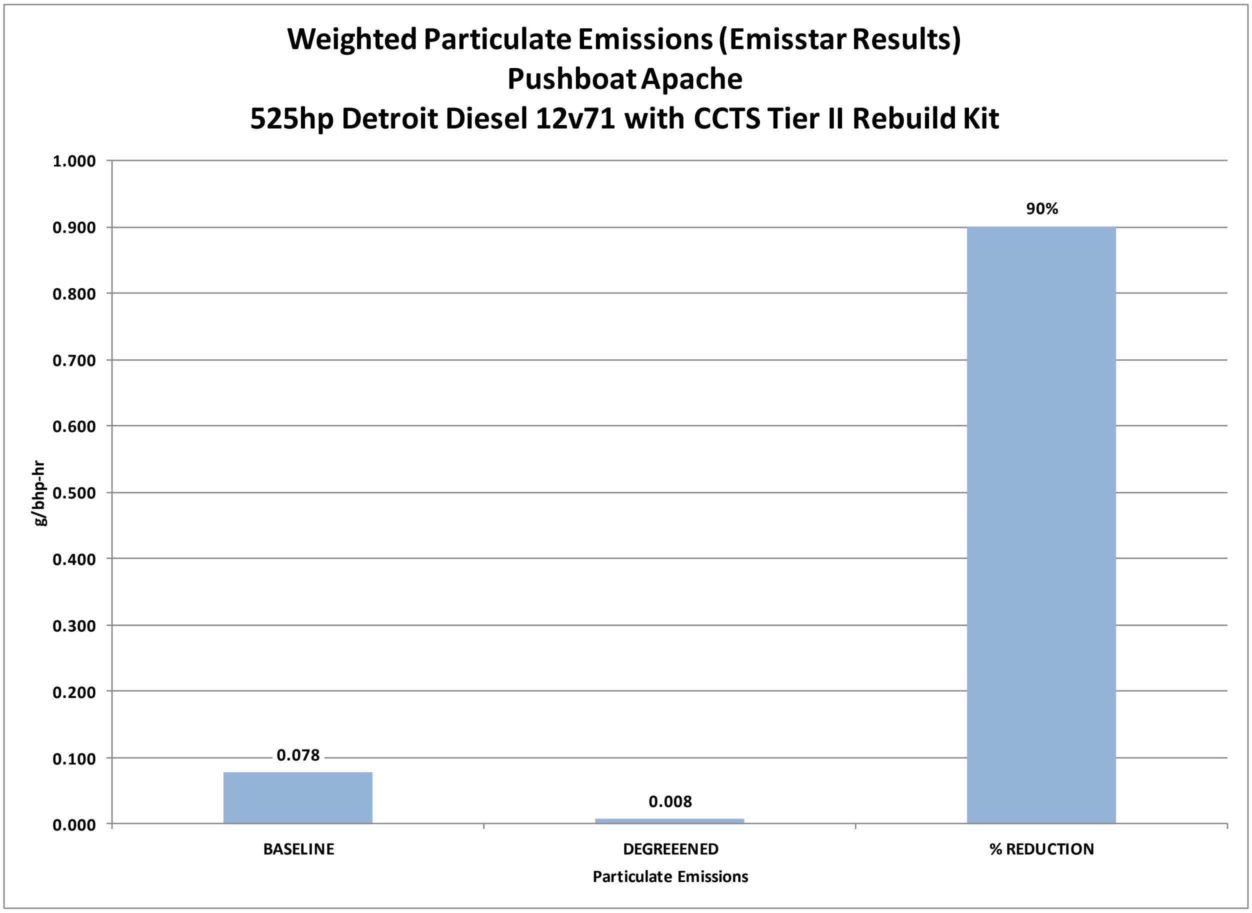


Figure 16: Weighted PM Emissions

The goals of the project included meeting or exceeding the California Air Resources Board requirements for a Level 3+ PM (>85% reduction) and Mark 5 NOx (>85% reduction) control system as well as exceeding the Tier 4 requirements set by US EPA for marine engines.

Figure 17 compares the reductions achieved by the Nauticlean DPF+SCR system to the CARB Level3+/Mark 4 (85%PM / 70%NOx) and Level 3+/Mark 5 (85%PM / 85%NOx). It can be seen that the Nauticlean exceeded 85% PM reduction and 70% NOx reduction. However, the system did not exceed the 85% NOx reduction required for Mark 5 designation. This was because Hug did not install the correct NOx reduction program in the SCR PLC when the system was originally commissioned in July 2013. This oversight was remedied in February 2014 when the correct program corresponding to 85% NOx reduction was enabled in the PLC.

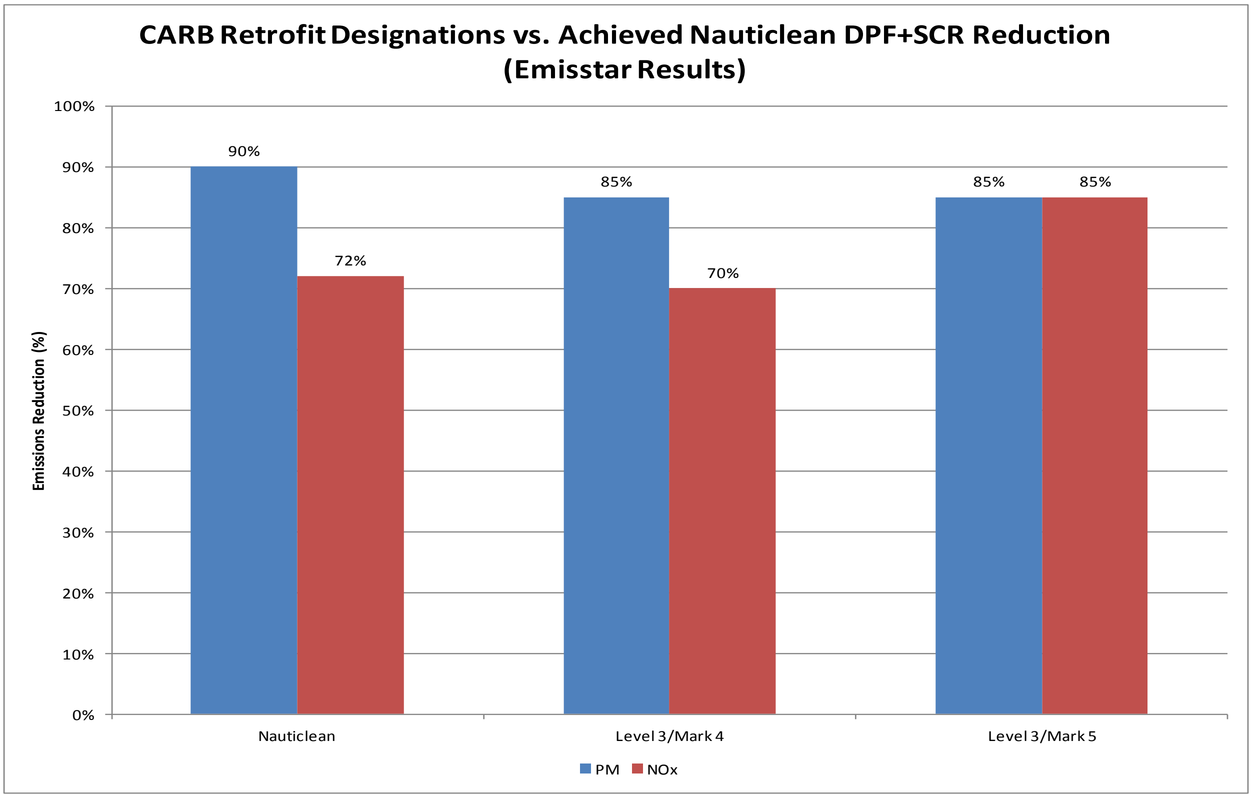


Figure 17: Nauticlean Emissions Reduction Compared to CARB Retrofit Designation

Table 2 details the US EPA Tier 3 limits for Category 1/2 marine diesel engines. Table 3 details the US EPA Tier 4 limits for the same engines.

Table 2: US EPA Tier 3 Emission Limits for Marine Diesel Engines

Power Density and Application	Displacement (L/cyl)	Maximum Engine Power	Model Year	PM (g/kW-hr)	NOx+HC (g/kW-hr) [b]
All	disp.< 0.9	kW <19	2009+	0.40	7.5
		19 ≤ kW < 75	2009-2013	0.30	7.5
			2014+	0.30	4.7
Commercial engines with kW/L ≤ 35[b]	disp.< 0.9	kW ≥ 75	2012+	0.14	5.4
	0.9 ≤ disp. < 1.2	all	2013+	0.12	5.4
	1.2 ≤ disp. < 2.5	kW < 600	2014-2017	0.11	5.6
			2018+	0.10	5.6
		kW ≥ 600	2014+	0.11	5.6
	2.5 ≤ disp. < 3.5	kW < 600	2013-2017	0.11	5.6
			2018+	0.10	5.6
		kW ≥ 600	2013+	0.11	5.6
	3.5 ≤ disp.< 7.0	kW < 600	2012-2017	0.11	5.8
			2018+	0.10	5.8
		kW ≥ 600	2012+	0.11	5.8
Commercial engines with kW/L > 35 and all recreational engines[b]	disp. < 0.9	kW ≥ 75	2012+	0.15	5.8
	0.9 ≤ disp. < 1.2	all	2013+	0.14	5.8
	1.2 ≤ disp. < 2.5		2014+	0.12	5.8
	2.5 ≤ disp. < 3.5		2013+	0.12	5.8
	3.5 ≤ disp. < 7.0		2012+	0.11	5.8

[a] No Tier 3 standards apply for commercial Category 1 engines at or above 3700 kW. See §1042.1(c) and paragraph (a)(7) of this section for the standards that apply for these engines.
[b] The applicable NOx+HC standards specified for Tier 2 engines in Appendix I of this part continue to apply instead of the values noted in the table for commercial engines at or above 2000 kW. FELs for these engines may not be higher than the Tier 1 NOx standard specified in Appendix I of this part.

Table 3: US EPA Tier 4 Emissions Limits for Marine Diesel Engines

Maximum engine power	Displacement (L/cyl)	Model year	PM (g/kW-hr)	NO_X (g/kW-hr)	HC (g/kW-hr)
600 ≤kW <1400	all	2017+	0.04	1.8	0.19
1400 ≤kW <2000	all	2016+	0.04	1.8	0.19
2000 ≤kW <3700[a]	all	2014+	0.04	1.8	0.19
kW ≥3700	disp. <15.0	2014-2015	0.12	1.8	0.19
	15.0 ≤disp.<30.0	2014-2015	0.25	1.8	0.19
	all	2016+	0.06	1.8	0.19

Figure 18 compares the emissions from the degreened Nauticlean to the requirements for US EPA Tier 4 per 40 CFR Part §1042.101 pertaining to new and in-use marine compression ignition engines and vessels. Again, due to the incorrect programming, the Nauticlean did not achieve the goal of US EPA Tier 4 equivalency.

It is important to note that US EPA Tier 4 would not apply to the Apache's Detroit Diesel 12V-71 engines because their power rating (approximately 394kW) is lower than 600kW. Tier 3 standards would apply to this engine which the Nauticlean easily achieves. Figure 19 compares US EPA Tier 3 standards to degreened emissions from the Nauticlean DPF + SCR.

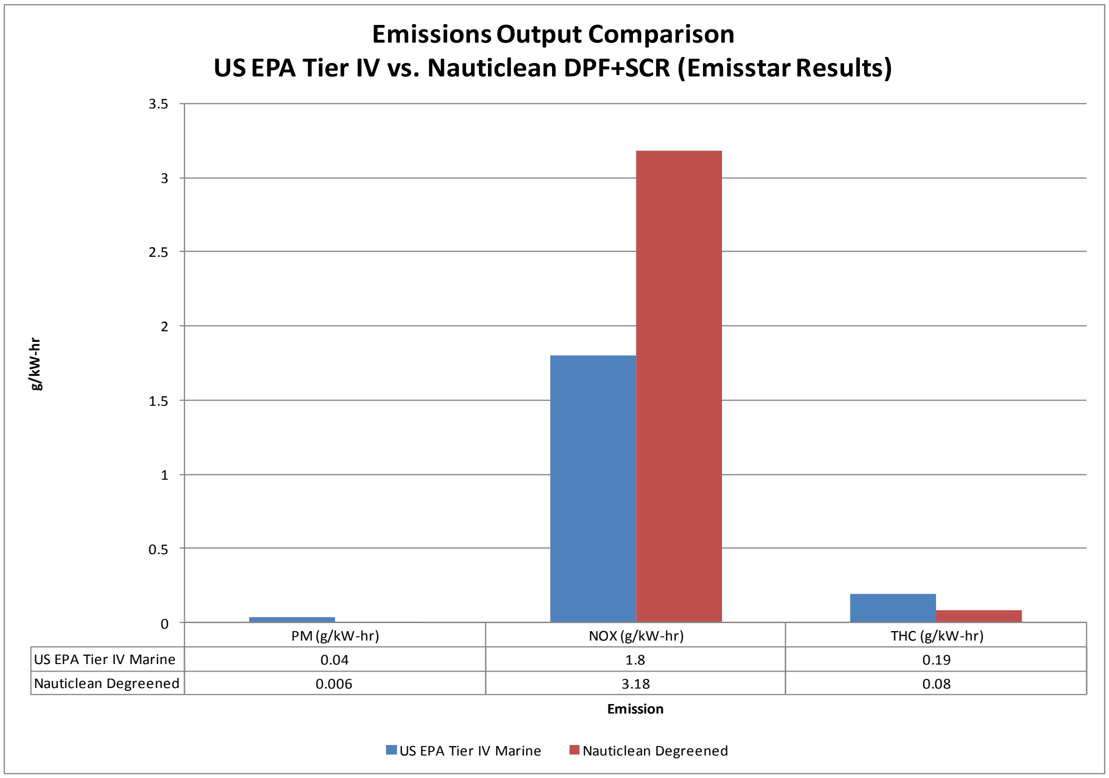


Figure 18: Tailpipe emissions with Nauticlean Compared to US EPA Tier 4 Limits for Category 1/2 Marine Diesel Engines

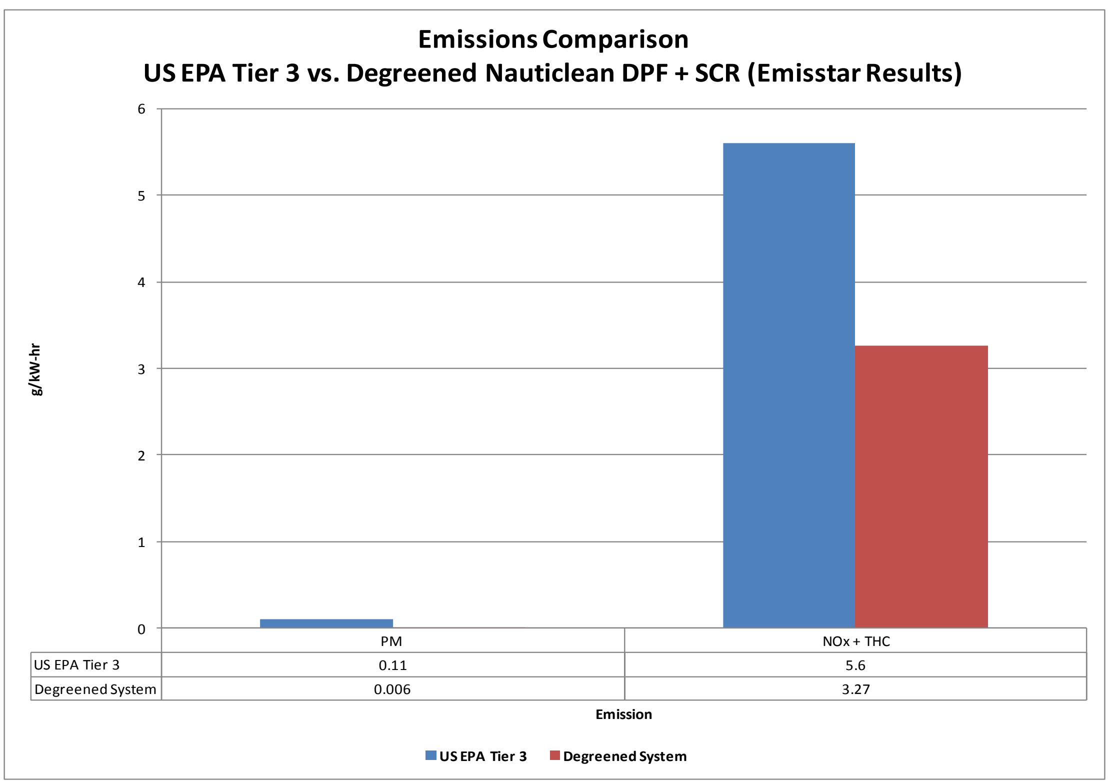


Figure 19: Tailpipe Emissions with Nauticlean Compared to US EPA Tier 3 Limits for Category 1/2 Marine Diesel Engines

Task 5.4b: Analysis of Test Data – UC Riverside CE-CERT Results

The University of California Riverside, College of Engineering - Center for Emissions Research and Technology conducted engine baseline and degreened Nauticlean DPF + SCR emissions testing onboard the Apache on April 9, 2014. The Nauticlean DPF+SCR system had accumulated 168 hours prior to CE-CERT performing the emissions testing. Summary data is shown in Table 4.

Table 4: Results from Nauticlean DPF+SCR Testing Conducted by UCR CE-CERT

	Weighted Emission Factors (g/kw-h)				
	NO_x	CO	CO_2	PM	THC
Baseline	8.35	0.49	819.46	0.169	0.371
Std. Deviation	0.54	0.03	0.06	0.015	0.015
Degreened	0.65	0.15	818.16	0.007	0.392
Std. Deviation	0.10	0.01	0.20	0.001	0.003
% Reduction	92.2%	69.2%	0.16%	95.7%	-5.8%

The following figures (Figure 20 through 22) detail weighted emissions output and emissions reductions.

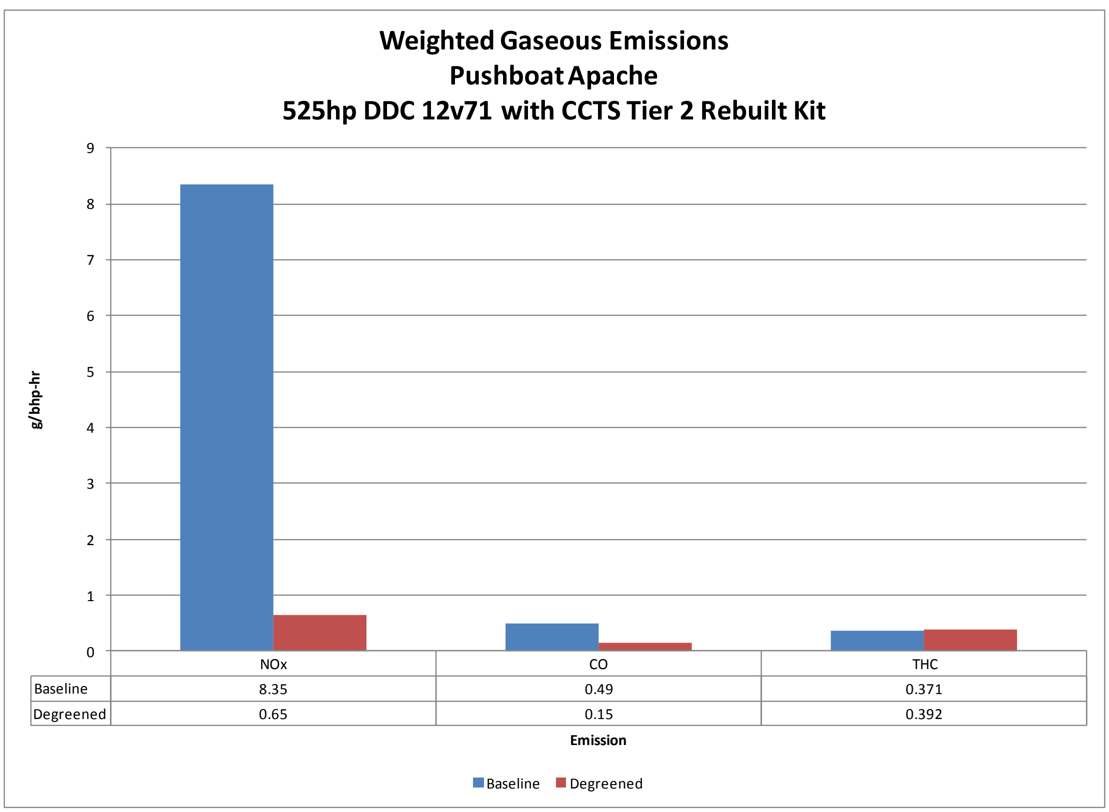


Figure 20: Weighted Gaseous Emissions Results

Based on these results, emissions testing indicate that THC emissions increased slightly when engine baseline is compared to tailpipe emissions. The results generated by Emisstar did not show an increase in HC emissions. Additional research is required to understand this inconsistent result.

This THC result does not meet US EPA Tier 4 emissions standard of 0.19 g/kW-hr, however, as mentioned previously, this engine would be subject Tier 3 standards due to its power rating. Tier 3 standards specify 5.6 g/kW-hr NOx + HC which is easily achieved by the Nauticlean.

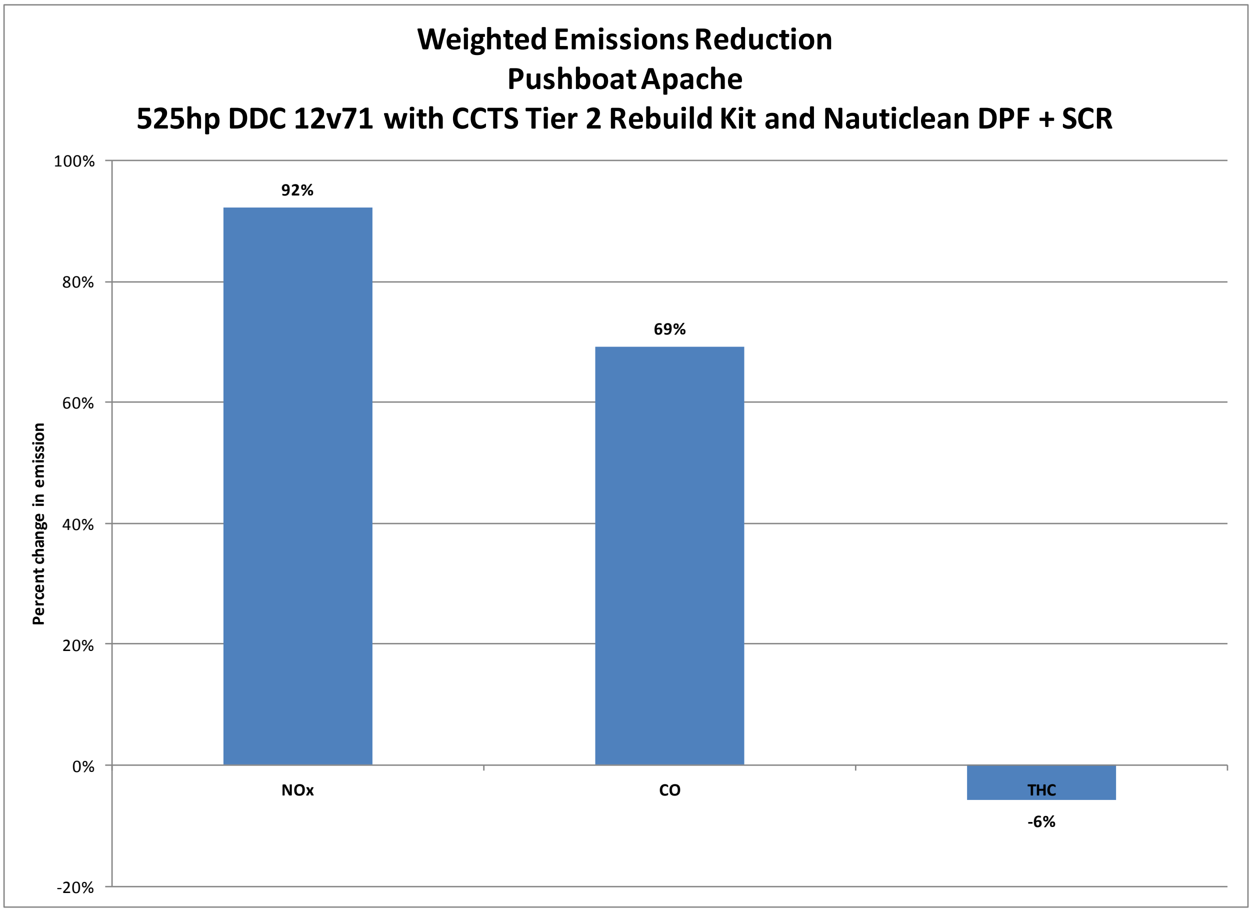


Figure 21: Weighted Gaseous Emissions Reduction

Figure 22 demonstrates the particulate reduction efficiency of the DPF. The Nauticlean DPF reduced PM 96% compared to engine baseline easily exceeding CARB Level 3 designation. In addition, the weighted mass of the PM was well below US EPA Tier 4 standard of 0.02 g/kW-hr.

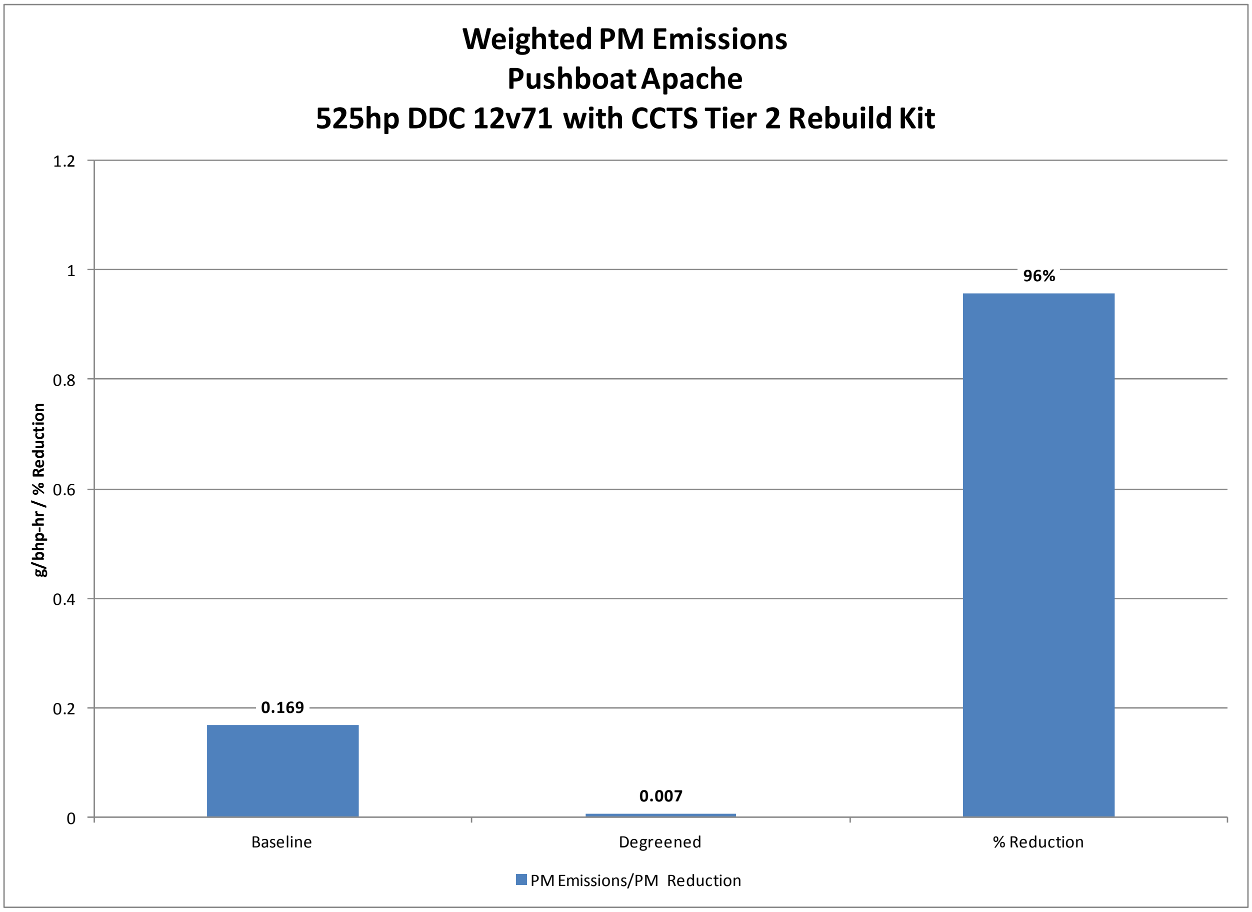


Figure 22: Weighted PM Emission Results

The goals of this project were to demonstrate that the Nauticlean DPF + SCR system would reduce emissions at least 85% so as to obtain CARB Level 3+/Mark 5 designation and also demonstrate Tier 4 emissions levels for marine category 1 and 2 diesel engines.

Figure 23 compares CARB Level 3+/Mark 5 designation to emissions reductions achieved by the degreened Nauticlean DPF+SCR system. CARB also requires that NO_2 emissions do not increase greater than 20% over baseline. The Nauticlean DPF+SCR system reduced PM by 96% and NOx by 92% and therefore meets the Level 3+/Mark 5 designation. NO_2 emissions were not reported by CE-CERT; however, testing carried out by Emisstar showed that NO_2 emissions were well within the allowed limit.

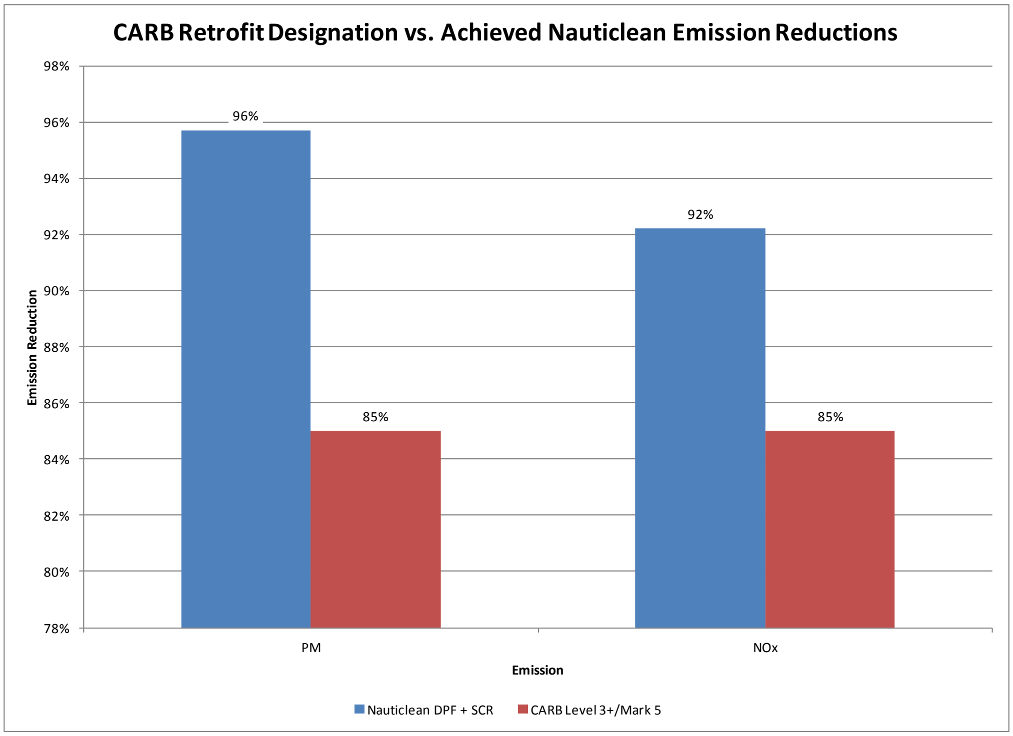


Figure 23: CARB Level 3+/Mark 5 Designation Compared to Degreened Nauticlean DPF+SCR Tailpipe Emissions Reduction

Figure 24 compares the degreened Nauticlean DPF + SCR tailpipe emissions to US EPA Tier 4 emission limits for marine category 1 and 2 diesel engines.

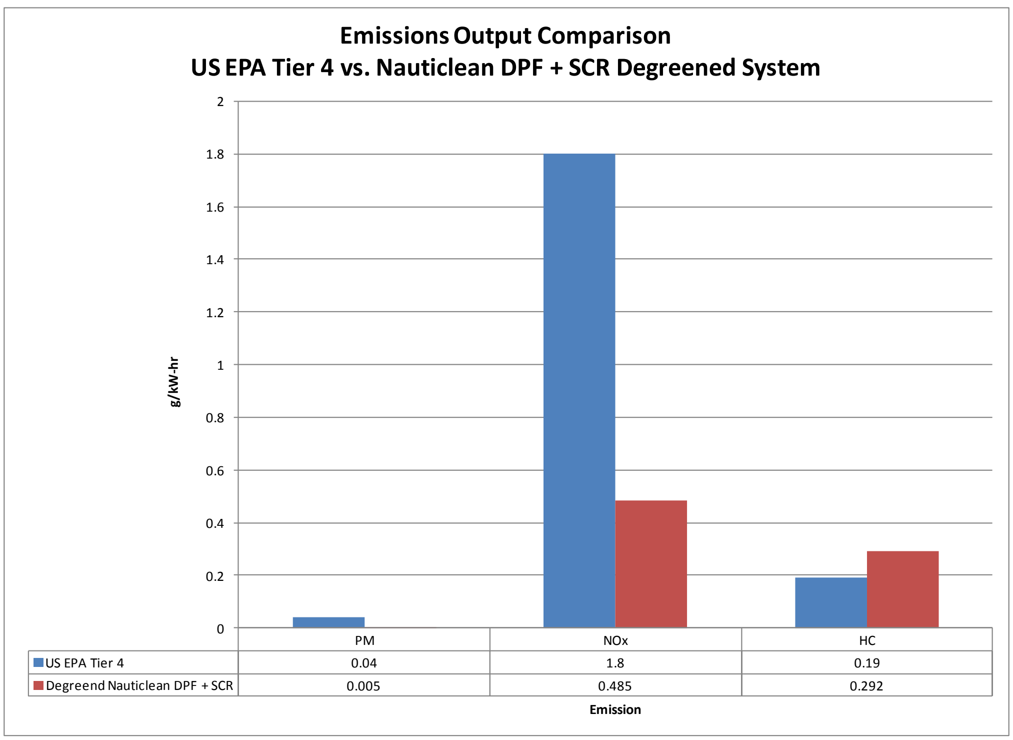
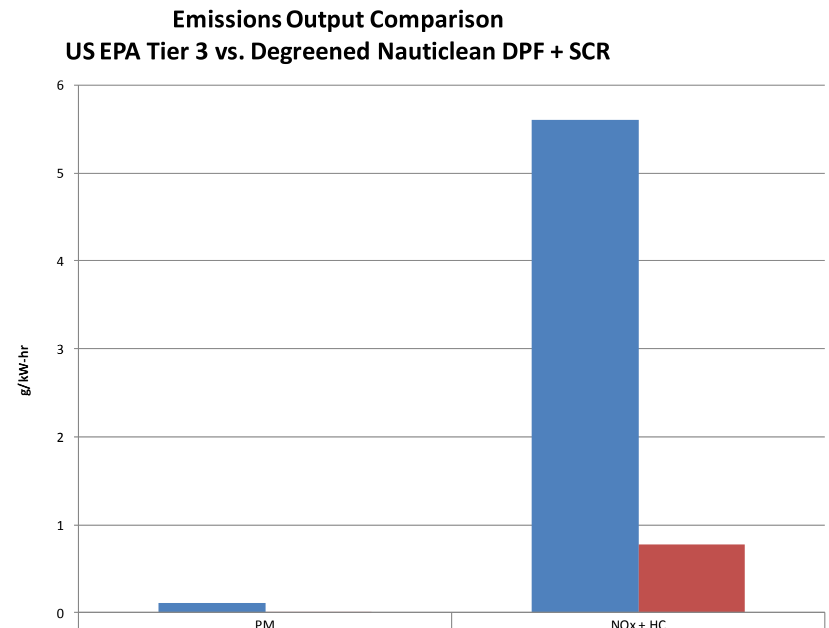


Figure 24: US EPA Tier 4 Limits Compared to Degreened Nauticlean DPF + SCR Tailpipe Emissions

Figure 24 clearly shows that the degreened Nauticlean DPF+SCR system exceeds US EPA requirements for PM and NOx emissions; however it did not meet HC standards. Further research is required to understand why the HC emissions were not reduced.

As mentioned previously, this engine's rated power falls under Tier 3 limits and would not be required to meet US EPA Tier 4. Figure 25 compares the tailpipe emissions from the Nauticlean to the US EPA Tier 3 limits. In this case, the Nauticlean easily enables compliance with US EPA Tier 3 emissions.



	PM	NOx + HC
US EPA Tier 3	0.11	5.6
Degreened Nauticlean DPF + SCR	0.005	0.777

Figure 25: US EPA Tier 3 Limits Compared to Degreened Nauticlean DPF+SCR Tailpipe Emissions

SECTION 3 DEMONSTRATON RESULTS

3.1 Durability Demonstration

The durability phase of the project followed the vessel with the Nauticlean DPF+SCR enabled as she performed duties operating in the Ports of Los Angeles and Ports of Long Beach. The vessel was put to work pushing barges and material from the shore to the oil islands area of the Port as shown in Figure 26.

Figure 26: Operational Area for the Apache

As mentioned in previous sections, both the DPF and SCR controllers have integrated dataloggers from which application specific operational details can be extracted to a Windows based PC for analysis. As part of the durability phase of the project, a Hug technician periodically visited the vessel to download data from each datalogger and visit briefly with the vessels crew to understand if the vessel operation has been affected.

As of May 9, 2014, the systems have accumulated approximately 100 hours since the April tests. This was calculated from the dataloggers and was corroborated with the vessel's hour meter installed in the engine room. To date, no alarms have been triggered during vessel operation.

Figure 27 details the successful operation of the DPF as evidenced by stable back pressure and the presence of regeneration events during April 2014. Regeneration events are initiated in one of three ways:

1. Back pressure: Regeneration is triggered if 75mbar is exceeded for 1 minute continuous.
2. Time: Regeneration is triggered if 20 hours of engine operation are recorded and a regeneration has not occurred
3. Manually enabling the regeneration through the controller.

Figures 27 and 28 indicate three regeneration events during April. The first regeneration event was manually triggered prior to emissions testing. The second event was triggered during the degreened emissions testing so that regeneration emissions can be quantified. The final regeneration event was triggered by time.

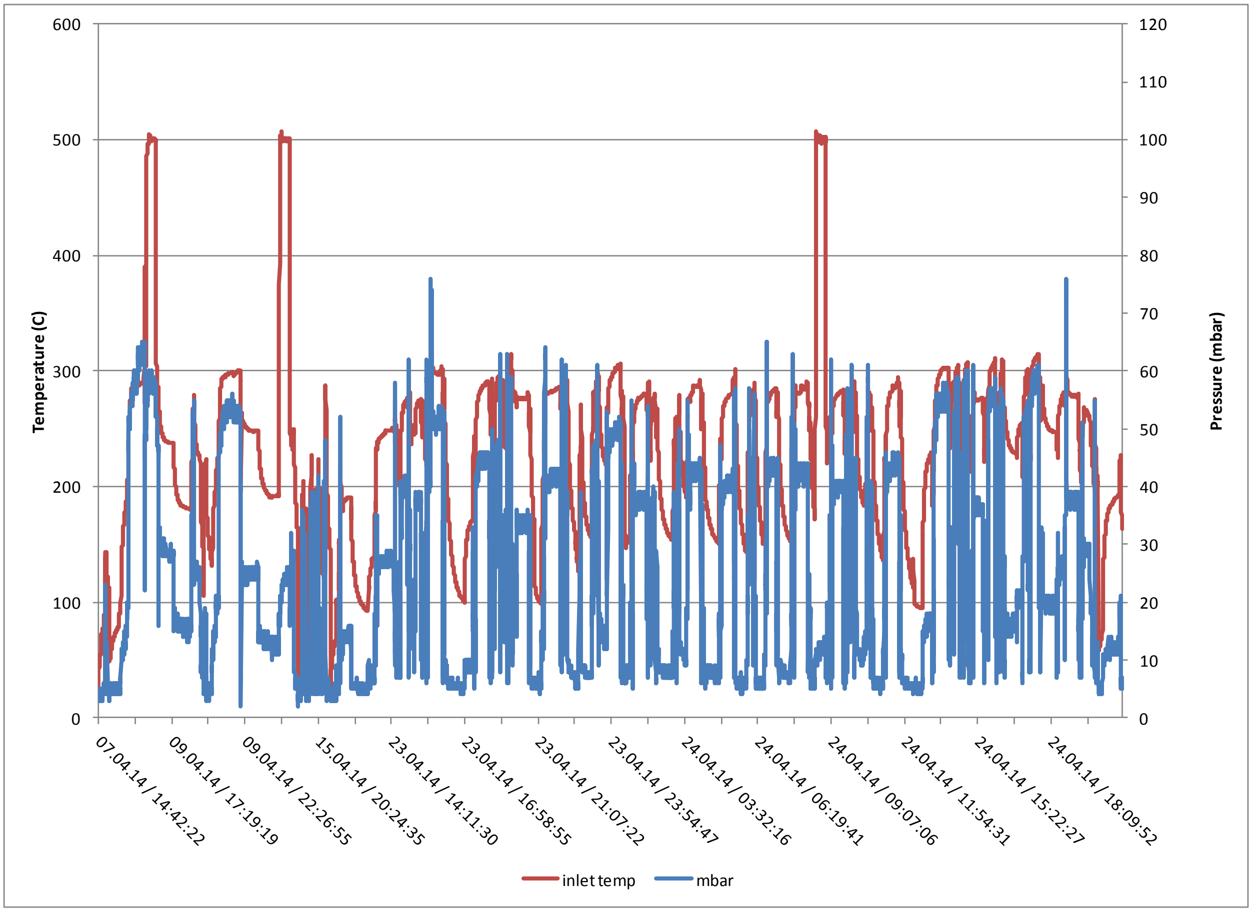


Figure 27: In-Use Nauticlean DPF Back Pressure and Temperature

The three temperature peaks reaching 500°C show that the DPF is regenerating. Other recorded parameters and units of measure include:

1. Fuel pump PWM (%)
2. Flame detector: digital hi/low reading
3. Fuel/Air mixing valve enabled: digital hi/low reading

Figure 28 details the operation of these devices using the exhaust temperature as a comparison during a single regeneration event. The fuel pump (red line) is enabled when the DPF PLC calls for a regeneration event to occur. Once adequate fuel pressure is developed, the air/fuel mixing valve (“X” in chart) is enabled as well as the igniter. The igniter ignites the fuel creating a flame. The flame detector reads the intensity and stability of the developed flame. When the flame intensity exceeds a preset value in the PLC and the flame is stable, the regeneration process is started. The enabling of the air/fuel valve and flame detection occurs almost simultaneously therefore they are very hard to separate in the chart. The regeneration timer is initiated after the inlet temperature of the DPF exceeds 450°C. The timer is set for 20 minutes on this system.

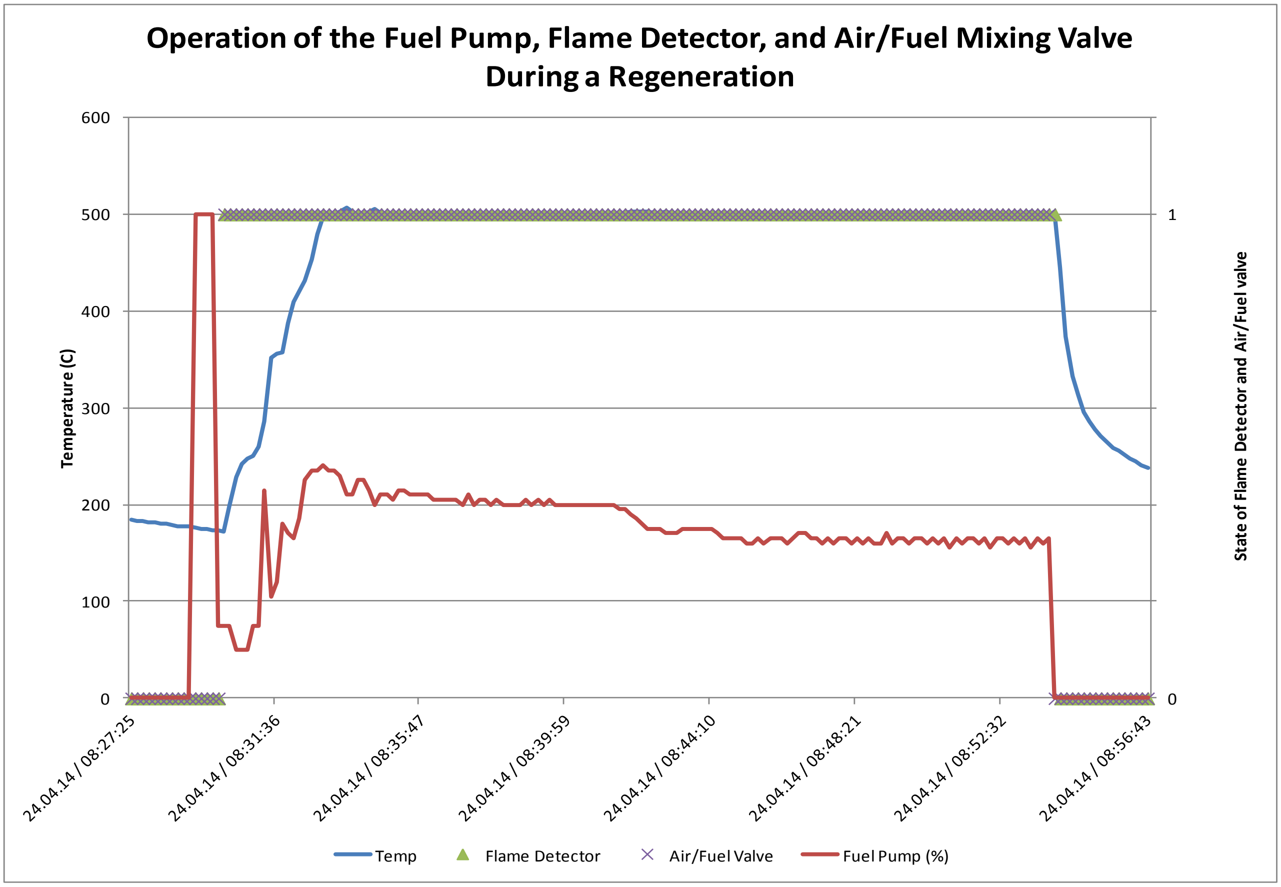


Figure 28: Nauticlean DPF Regeneration Event

Figure 29 demonstrates the data collected by the SCR datalogger. In this case, data is shown during the de-greened system emissions testing on April 9, 2014. The datalogger records the following information:

1. Mass air flow (kg/s)
2. Engine out NOx (ppm)
3. System out NOx (ppm)
4. Inlet and outlet exhaust temperatures (°C)
5. Urea dosing rate (l/hr)
6. Urea pressure at the dosing manifold (bar)
7. Air pressure at the dosing manifold (bar)

In this case, the 4 modes of the ISO8178 E3 test cycle are clearly demonstrated by following the steps in the mass air flow. This chart also demonstrates the NOx reduction efficiency of the SCR system. At the 100% and 75% load points, NOx is reduced over 90% even at the low exhaust temperatures of approximately 290°C generated by this engine.

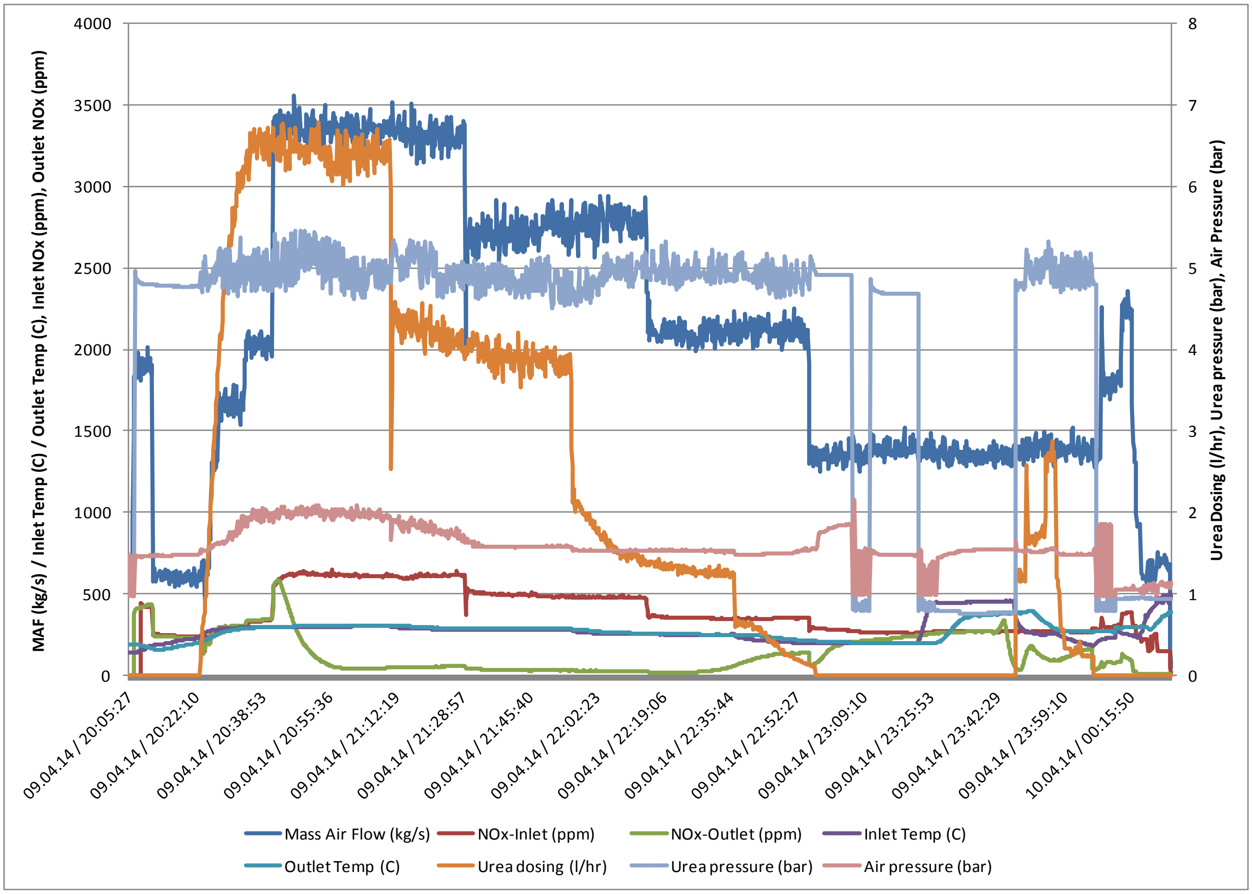


Figure 29: Data Collected by the SCR Datalogger

In addition, the urea injection algorithm developed by Hug Engineering is demonstrated by the system's ability to react to changing exhaust conditions by following the inlet NOx and exhaust temperature inputs. By monitoring the urea injection algorithm, the amount of urea used can be calculated. In this case, the system consumed approximately 6.56 liters of urea during the degreened emissions test cycle. Broken down by mode, this equates to 3.73L @ 100% load, 2.25L @ 75% load, 0.6L @ 50% load, and 0.002L @ 25% load.

It's also interesting to note that at low loads, some NOx reduction is achieved even though the system is not injecting urea. The catalyst has the ability to store ammonia enabling some NOx reduction when the urea injection temperature parameters are not being met and the urea pump is shut down to prevent excess generation of ammonia. While this reduction is minor, it does demonstrate the strength of the NOx reduction algorithms used by the Nauticlean.

One final item of interest, Figure 30 shows the NOx reduction after DPF regeneration. The inlet temperature is raised to approximately 450°C when a regeneration event occurs. When regeneration is initiated, the SCR system is disabled to prevent the decomposition of ammonia. However, as soon as the regeneration is complete, urea injection restarts almost immediately due to take advantage of the heat generated during the regeneration event being retained in the SCR catalyst.

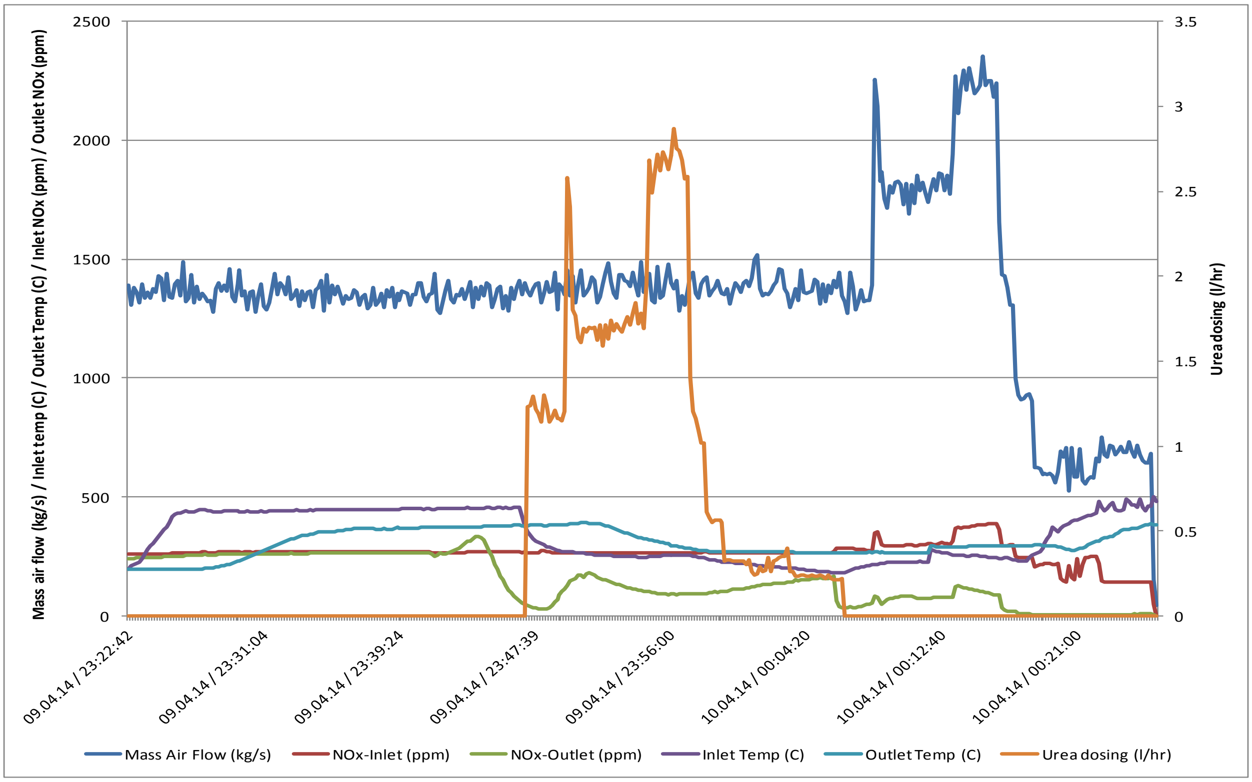


Figure 30: NOx Reduction after a DPF Regeneration

3.2 Expected Results vs. Actual Outcomes

There were several goals for this project including:

1. Demonstrate that the Nauticlean DPF+SCR system would operate successfully on marine propulsion engines.
2. Demonstrate that the Nauticlean DPF+SCR system would operate successfully on 2-stroke diesel engines.
3. Demonstrate that the Nauticlean DPF+SCR system would reduce PM and NOx emissions from the engines in amounts greater than 85% respectively
4. Demonstrate that the Nauticlean DPF+SCR system would reduce emissions below US EPA Tier 4 for Marine Category 1/2 engines (40 CFR §1042.101)

Goals 1 and 2 are ongoing and will be demonstrated through the 1000 hour durability period. Goal 3 has been demonstrated by the emissions testing carried out by CE-CERT. Goal 4 was demonstrated for PM and NOx emissions, however HC emissions during the CE-CERT tests in April 2014 were higher than Tier 4 marine limits. The Emisstar tests during October 2013 should good HC emission reductions and if combined with the low NOx emissions during the April tests, would have met the Tier 4 marine limits.

There were several challenges in this project. The primary challenge was the lack of project management/engineering resource as a result of employee turnover within Hug Filtersystems. Turnover in the project management position resulted in delays and lapses in effective communication between stakeholders. Other challenges include:

1. Miscommunication between US project management and Swiss engineering resource resulting in the incorrect NOx reduction being enabled in the SCR controller.
2. Miscommunication between US project management and Sause Brothers resulting in compressed air supply issues.
3. Lack of project management by Hug Filtersystems resulted in long delays between milestone attainment and project completion within the contractual period.
4. Originally selected emissions testing contractor was slow to respond.

Once Hug Filtersystems stabilized project management, the project moved forward relatively quickly and generated emissions reductions on par with the goals of the project.

3.3 Costs

The grant amount was $388,145.

Capital costs associated with this project included:

1. Nauticlean DPF+SCR systems; One for the port engine and one for the starboard engine
2. Non-recurring engineering cost to design the systems for the Apache (NRE)
3. Installation expenses on the Apache
4. Commissioning of the system
5. Upgrade of the Apache's compressed air system
6. Travel costs for Hug personnel from Switzerland
7. Emissions testing

Table 5: Costs to Retrofit Apache with Two Nauticlean DPF+SCR Systems

Description	UoM	Qty	Cost (USD)	Extended (USD)
Nauticlean DPF + SCR system	ea	2	$ 193,827.50	$ 387,655.00
Non recurring engineering (NRE)	ea	1	$ 28,500.00	$ 28,500.00
Shipping and Import Tariffs	ea	1	$ 26,473.00	$ 26,473.00
Installation costs	ea	1	$ 15,774.48	$ 15,774.48
Commissioning	ea	2	$ 7,000.00	$ 14,000.00
Compressed air upgrades	ea	1	$ 20,000.00	$ 20,000.00
Travel costs	ea	1	$ 28,545.00	$ 28,545.00
Emissions testing	ea	1	$ 123,000.00	$ 123,000.00
Labor costs	ea	1	$ 182,575.00	$ 182,575.00
			Subtotal	$ 826,522.48

Table 6: Sause Brothers Costs Associated with the Retrofit of Apache

Description	UoM	Qty	Cost (USD)	Extended (USD)
Captain and Crew, 161 hours	ea	170	$ 70.50	$ 11,985.00
Fuel	gal	8,000	$ 3.80	$ 30,400.00
Urea	gal	1500	$ 3.60	$ 5,400.00
Installation labor	hour	80	$ 70.50	$ 5,640.00
Misc labor	hour	60	$ 70.50	$ 4,230.00
			Subtotal	$ 57,655.00

The total project cost was the sum of Hug, Sause, and SCAQMD expenses. The CARB grant required a recipient cost share of at least 50%. This match is demonstrated for costs to date in Tables 5 and 6 plus the SCAQMD administration expenses as follows:

Hug	$826,522
Sause	$ 57,665
SCAQMD	$ 41,565
Total Cost	$925,752
CARB Grant	$388,145
Match	$537,607

A final emissions test will be carried out after the Nauticlean accumulates over 1,000 durability hours. It is estimated that this emissions testing will cost an additional $55,000 with approximately $2,500 travel expenses and an additional $8000 labor costs.

Operating costs of the Nauticlean DPF+SCR include:

1. Urea: Urea consumption is estimated at 1.5% of fuel consumption. Therefore, for every 10,000 gallons of diesel, 150 gallons of urea will be consumed.

2. Fuel: Each regeneration event uses between 1l and 2l of fuel depending on the temperature of the system prior to the regeneration event.

3. Long term maintenance: As with any DPF, the Nauticlean DPF will require ash cleaning periodically. The interval between cleanings is expected to be 8,000 hours; however this is directly influenced by the engine's rate of oil consumption. For this project, it is estimated that 1.5 g/kW-hr of oil will be consumed as part of combustion.

Bulk rate for urea is approximately is approximately $3.60/gallon. Based on this cost, it is estimated that $1080.00 of urea (300 gal * 3.60/gal) will be consumed by both Nauticlean systems per 10,000 gallons of fuel.

Assuming that 2l of fuel will be consumed during each DPF regeneration and a fuel cost of \$3.80/gal, each DPF regeneration will cost approximately \$1.95. If it assumed that a regeneration event is triggered every 20 hours by each system, than each system will regenerate 50 times during the 1000hr durability period. When a 25% buffer is added, approximately \$260.00 of fuel will be consumed by the Nauticlean DPF during the durability period.

3.4 Future Work

Future work includes:

1. Completing the durability period of 1000 hours of in-use operation
2. Carrying out a final round of emissions testing after the system has accumulated over 1000 hours of service.
3. Complete CARB verification of the Nauticlean DPF+SCR system at Level 3+/Mark 5 (85% reduction of PM and NOx).
4. Further quantify HC emissions during regeneration

SECTION 4 CONCLUSIONS AND RECOMMENDATIONS

The collaboration between CARB, SCAQMD, Sause Brothers, CE-CERT and Hug Filtersystems has shown that significant PM and NOx emissions reductions can be achieved from marine diesel propulsion engines used in harbor craft operating in California's coastal areas such as ports. Emissions testing carried out onboard the Apache demonstrated that achieving CARB Level 3+/Mark 5 designation and reducing tailpipe emissions below US EPA Tier 4 for category 1/2 marine diesel engines is possible with the Nauticlean DPF + SCR system.

Recommendations include:

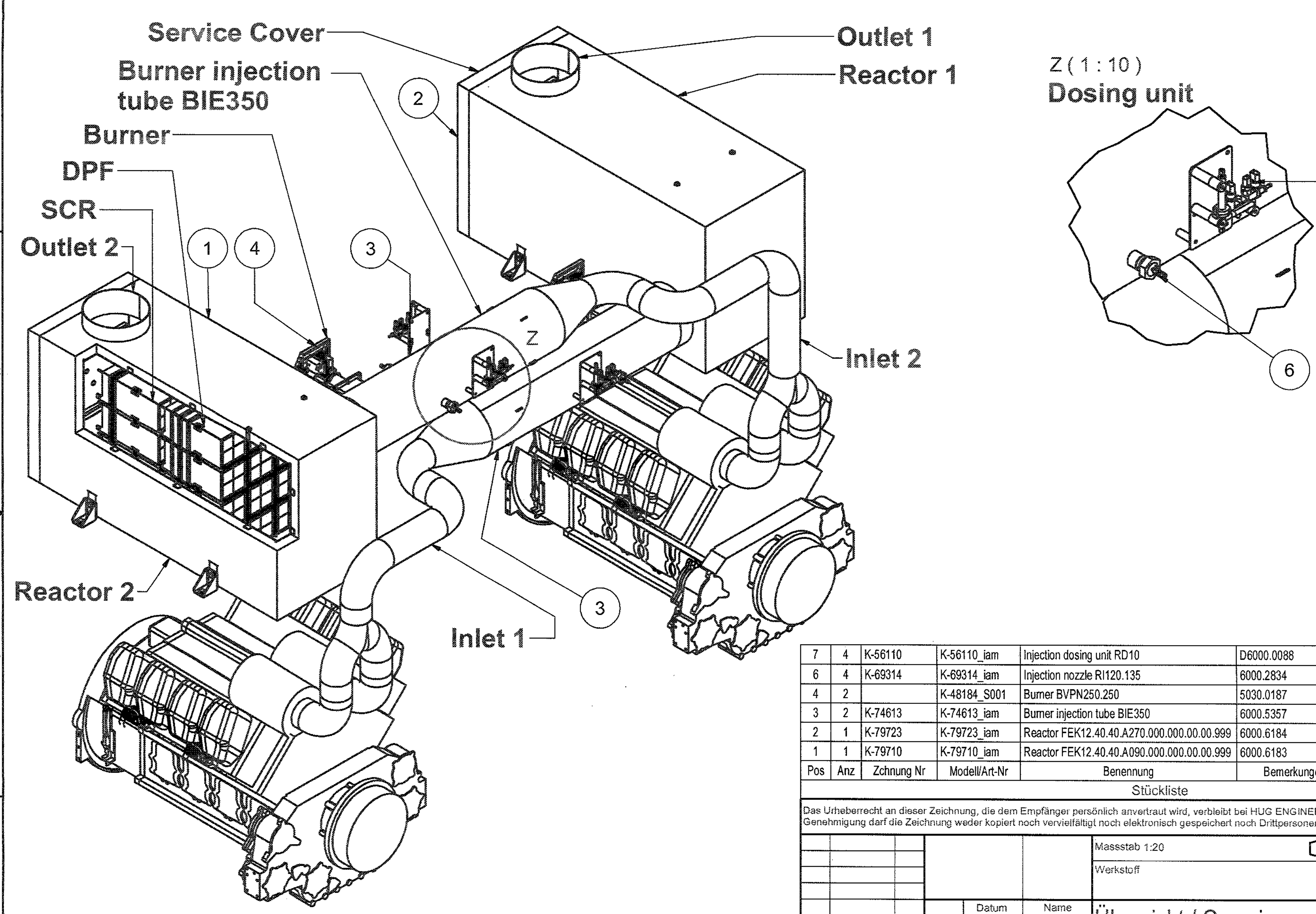
1. Since CARB Level 3+/Mark 5 verification is contingent upon maintaining a minimum of 85% reduction for both PM and NOx, the Nauticlean SCR controller should be preprogrammed during the manufacturing process with 85% NOx reduction enabled rather than enabling during commissioning.
    a. The commissioning process would verify this value and be noted on the warranty registration documents.

2. Hug needs to develop a pre-installation checklist that addresses compressed air availability onboard the vessel possibly with some way to measure the maximum CFM output of the compressor(s) and how quickly the compressor(s) are able to rebound.

3. Develop and carry out a test program to quantify regeneration HC emissions.

4. Complete the 1000 hour durability phase and carry out a final round of emissions testing.

LIST OF ATTACHMENTS



Pos	Anz	Zchnung Nr	Modell/Art-Nr	Benennung	Bemerkungen	Mat	Gew
7	4	K-56110	K-56110_iam	Injection dosing unit RD10	D6000.0088		2.351 kg
6	4	K-69314	K-69314_iam	Injection nozzle RI120.135	6000.2834		0.198 kg
4	2		K-48184_S001	Burner BVPN250.250	5030.0187	1.4307	13.082 kg
3	2	K-74613	K-74613_iam	Burner injection tube BIE350	6000.5357		64.979 kg
2	1	K-79723	K-79723_iam	Reactor FEK12.40.40.A270.000.000.00.00.999	6000.6184		420.280 kg
1	1	K-79710	K-79710_iam	Reactor FEK12.40.40.A090.000.000.00.00.999	6000.6183		420.280 kg

Stückliste

Massstab 1:20 (Gewicht)

Werkstoff

	Datum	Name
Bearb.	10.04.2013	NIHA
Gepr.	10.04.2013	NIHA
Status	Freigegeben	
Akt.	10.04.2013 14:59:58	

hugengineering.

Übersicht / Overview

A-9543 Apache

K-83876

Blatt 1 von 1

A3

Rev. Datum Name Modell K-83876_iam Ersatz für Ersetzt durch

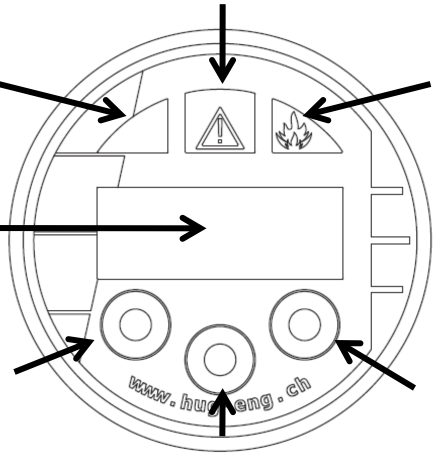
Nauticlean Diesel Particulate Filter Quick Reference Guide

Middle Red LED: Lights up red as soon as an alarm is detected.

Green LED: Flashes when system is powered up

Right Red LED: Flashes every 2 seconds when DPF is in regeneration mode.

Display: Two lines of text can be displayed. Error codes and operating values can be displayed.



< Button: Scrolls the screen to the left

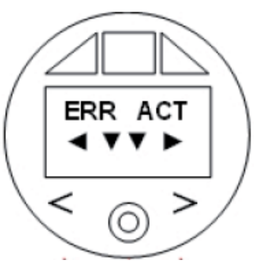
> Button: Scrolls the screen to the right

O Button: Acts as an "Enter " key

Please Note: If air pressure falls below 85psi while the DPF is in regeneration mode please STOP the regeneration process by following the "Regeneration Menu" below.

Normal Operation Display State

Press < button to view errors

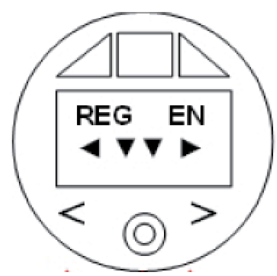


Press > button to view pressure and temperature

Press O button to move to Regeneration menu

Regeneration Menu

Press <	Displays
Once	Regen time remaining
Twice	START regen
Three times	STOP regen

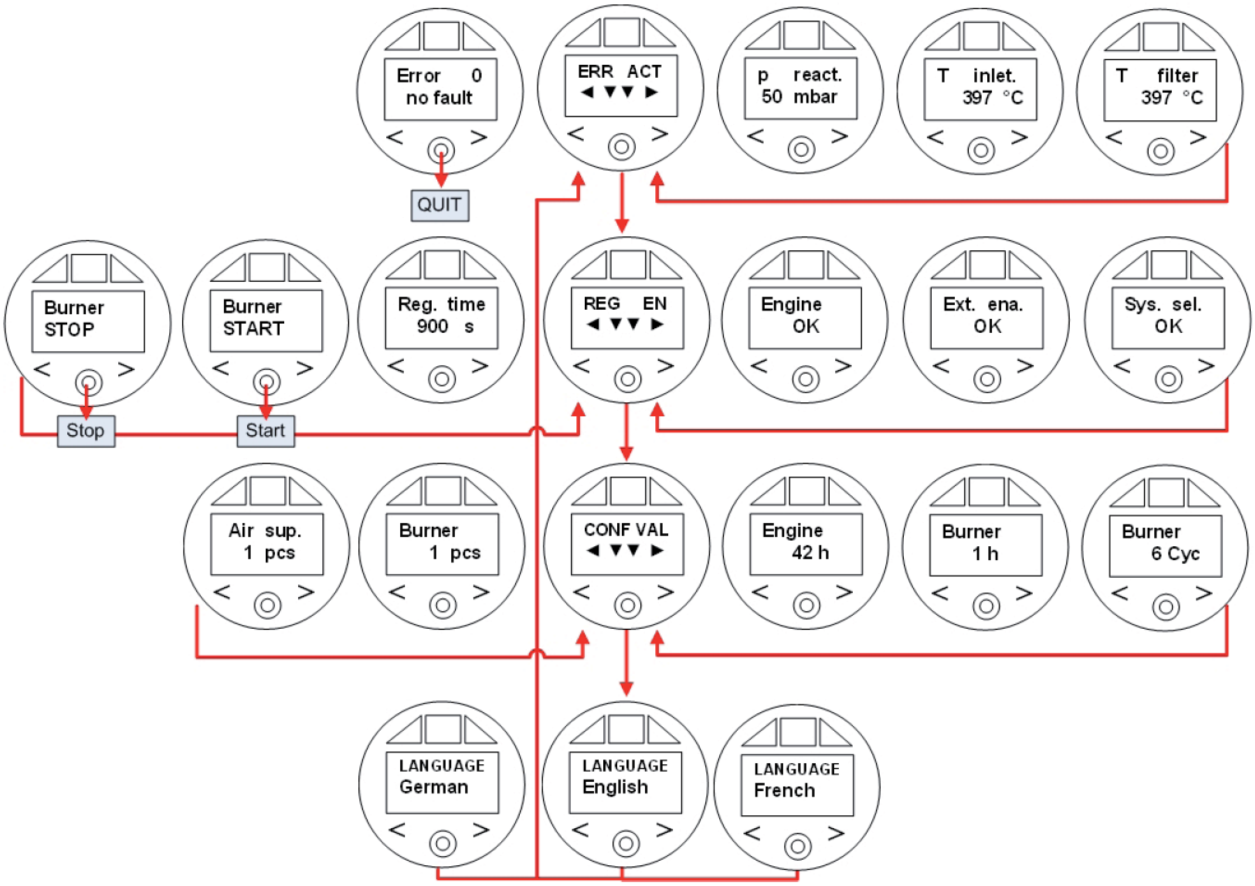


Note: "EN" menu not used in normal operation

CON VAL and LANGUAGE Menus

These menus are not used during operations. Press O button to return display to Normal Operation.

Nauticlean Display Flow Chart



Nauticlean Alarm Reference Table

Error Code	Message	Typical Cause	Remedy
11	Pressure To High	The filter back pressure to too high.	-Press O button to acknowledge fault -Press O button to REG -Press < button twice to show “Burner START” -Press O button to start regeneration ***If regeneration does not start, alert maintenance immediately!***

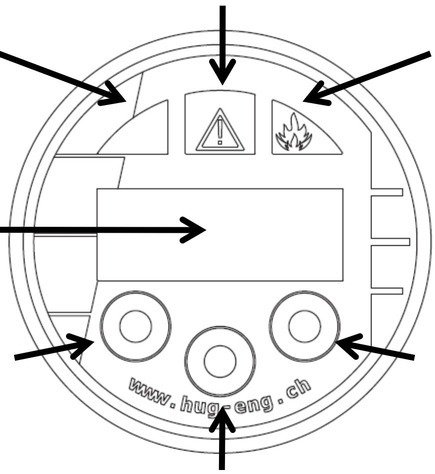
Nauticlean SCR System Quick Reference Guide

Middle Red LED: Lights up red as soon as an alarm is detected.

Green LED: Flashes when system is powered up

Right Red LED: Solid Red when filter is in regeneration mode

Display: Two lines of text can be displayed. Error codes and operating values can be displayed.



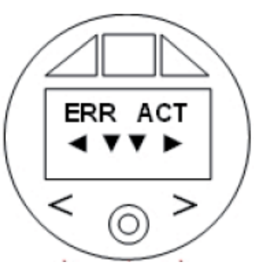
< Button: Scrolls the screen to the left

> Button: Scrolls the screen to the right

O Button: Acts as an "Enter " key

Normal Operation Display State

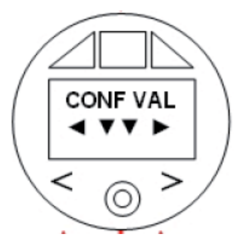
Press < button to view errors



Press > button to view system sensor readings

Press O button to move to Regeneration menu

CON VAL and LANGUAGE Menus



These menus are not used during operations. Press O button to return display to Normal Operation.

Error Code	Message	Typical Cause	Remedy
01	Reactant Tank Empty	Urea storage tank needs filling	**-Add urea to holding tank** *Contact maintenance if filling the tank does not reset the LED*
All others	Various	Various	Note the Alarm Code and contact maintenance when safe to do so

Please note: There are NO alarms that present a safety hazard to the vessel. Please contact maintenance if an Alarm is active and let them know the Error Code.

▷ This section is a part of the documentation for the 'Exhaust gas purification system'. You must also observe the chapters ‘Foreword’, Definition, Safety, Disposal in Index 1 of the folder 'Exhaust gas purification system'.

B1 Faults

B1.1 General

The following summary has been drawn up to aid trouble-shooting and fault elimination procedures. You should contact Hug Engineering AG or an authorised partner if a fault occurs that is not described in this section or cannot be put down to a particular cause. (→ Maintenance Manual folder)

B1.2 Particulate filter

11 Pressure too high

Meaning	The exhaust gas back-pressure upstream of the particulate filter has risen above the configured maximum limit value
Consequences	The fault is merely indicated
Fault generation	The 4...20 mA signal at terminal X2:24 is greater than the parameterized limit value
Possible causes	- The particulate filter is loaded above the limit value (full-flow regeneration burners are not working) - Pressure sensor defective
Procedure	- Check parameters - Acknowledge fault and press 'Start' button (manual start) - Check the pressure shown on manometer - Check the pressure sensor - Check full-flow regeneration burners

12 Calculation load (B)

Meaning	The calculated load (B) is too high
Consequences	The fault is merely indicated
Fault generation	Internal calculation (PLC)
Possible causes	- Burn-off temperature of full-flow regeneration burners is unsatisfactory - Regeneration parameters set incorrectly
Procedure	- Acknowledge fault and press the 'Start' button to start the full-flow regeneration burners manually. - Check parameters

13 Pressure too low

Meaning	The exhaust gas back-pressure upstream of the particulate filter has fallen below the configured limit value
Consequences	The fault is merely indicated
Fault generation	The 4...20 mA signal at terminal X2:24 is less than the parameterized limit value
Possible causes	- The particulate filter is defective (not sealed) - Pressure sensor removed - Pressure sensor defective - Limit value too high
Procedure	- Check the pressure shown on manometer - Check the pressure sensor - Check parameters

B1.2.1 Ignition

21 Ignition burner 1

Meaning	The controls attempted unsuccessfully three times to start the full-flow regeneration burner
Consequences	The fault halts the full-flow regeneration burner or prevents an ignition
Fault generation	Flame failure controller - internal (PLC)
Possible causes	- No fuel - Fuel / air valve disconnected - Fuel pump disconnected - Full-flow regeneration burner is carbonized - Fuel line interrupted - Ignition transformer defective or disconnected - Flame failure controller defective or disconnected - Scavenging air valve or burner air valve disconnected - Compressed-air pressure too high - Parameters set incorrectly
Procedure	- Acknowledge fault and press the 'Start' button to start the full-flow regeneration burners manually. - Check all connectors on the full-flow regeneration burner - Measure voltage across fuel/air valves (24 VDC) - Is the fuel pump running; is fuel being supplied - Measure voltage across ignition transformer (24 VDC); replace if necessary - Measure voltage across flame failure controller (12 VDC); replace if necessary - Measure voltage across scavenging air and burner air valves (24 VDC) - Check pressure settings of compressed-air supply - Remove and clean full-flow regeneration burner - Check parameters

22 Ignition burner 2

Meaning	The controls attempted unsuccessfully three times to start the full-flow regeneration burner
Consequences	The fault halts the full-flow regeneration burner or prevents an ignition
Fault generation	Flame failure controller - internal (PLC)
Possible causes	- No fuel - Fuel / air valve disconnected - Fuel pump disconnected - Full-flow regeneration burner is carbonized - Fuel line interrupted - Ignition transformer defective or disconnected - Flame failure controller defective or disconnected - Scavenging air valve or burner air valve disconnected - Compressed-air pressure too high - Parameters set incorrectly
Procedure	- Acknowledge fault and press the 'Start' button to start the full-flow regeneration burners manually. - Check all connectors on the full-flow regeneration burner - Measure voltage across fuel/air valves (24 VDC) - Is the fuel pump running; is fuel being supplied - Measure voltage across ignition transformer (24 VDC); replace if necessary - Measure voltage across flame failure controller (12 VDC); replace if necessary - Measure voltage across scavenging air and burner air valves (24 VDC) - Check pressure settings of compressed-air supply - Remove and clean full-flow regeneration burner - Check parameters

B1.2.2 Flame

31 Flame - burner 1

Meaning	The flame has extinguished for a third time
Consequences	The fault halts the full-flow regeneration burner or prevents an ignition
Fault generation	Flame failure controller - internal (PLC)
Possible causes	- Fuel pump defective - Fuel line interrupted - Flame failure controller defective - Air in fuel system
Procedure	- Is the fuel pump running; is fuel being supplied - Measure voltage across flame failure controller (12 VDC); replace if necessary

32 Flame - burner 2

Meaning	The flame has extinguished for a third time
Consequences	The fault halts the full-flow regeneration burner or prevents an ignition
Fault generation	Flame failure controller - internal (PLC)
Possible causes	- Fuel pump defective - Fuel line interrupted - Flame failure controller defective - Air in fuel system
Procedure	- Is the fuel pump running; is fuel being supplied - Measure voltage across flame failure controller (12 VDC); replace if necessary

B1.2.3 Air supply unit

41 Pressure switch - air supply unit 1

Meaning	The pressure is too low at the pressure switch for more than 5 seconds while the burner air valve is actuated
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 24 VDC signal at terminal X2:32 drops out
Possible causes	- Pressure range of pressure switch set incorrectly - Insufficient compressed-air supply pressure - Compressed-air line interrupted - Break in the electrical connection
Procedure	- Check compressed air supply - Check pressure range of pressure switch - Check the electrical connections

42 Pressure switch - air supply unit 2

Meaning	The pressure is too low at the pressure switch for more than 5 seconds while the burner air valve is actuated
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 24 VDC signal at terminal X2:33 drops out
Possible causes	- The pressure range of pressure switch set incorrectly - Insufficient compressed-air supply pressure - Compressed-air line interrupted - Break in the electrical cable
Procedure	- Check compressed air supply - Check pressure range of pressure switch - Check the electrical connection

43 LMS compressor - flow

Meaning	The flow at the air flow sensor is lower than the parameterized limit value while the burner air valve is actuated
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 0..0.5V signal at terminal X2:30 is less than the parameterized limit value
Possible causes	- Motor protection switch of the compressor tripped - Door contract open (applies only to BK50) - Compressor defective - Intake filter blocked - Parameters set incorrectly (threshold value)
Procedure	- Check motor protection switch - Check the intake filter - Check the compressor - Check parameters

44 LMS compressor - reverse flow

Meaning	A reverse flow has developed at the side channel compressor
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 0...5 V signal at the terminal X2:30 is less than 1 V
Possible causes	- Non-return valve at the air supply unit defective - Air flow sensor defective or power supply failure - Air flow sensor installed incorrectly - Side channel compressor defective
Procedure	- Check non-return valve - Check the position of the air flow sensor - Check the power supply to the air flow sensor - Check side channel compressor

B1.2.4 Filter temperature

51 Filter temperature too high

Meaning	The temperature measured by the temperature sensor has risen above the parameterized maximum limit value
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 4...20 mA signal at terminal X2:25 is greater than the parameterized limit value
Possible causes	- Limit value set too low - Control temperature parameters set too high - Full-flow regeneration burner too powerful
Procedure	- Check parameters - Check the ratings of the full-flow regeneration burner

52 Filter temperature too low

Meaning	The temperature measured by the temperature sensor has fallen below the parameterized minimum limit value
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 4...20 mA signal at terminal X2:25 is less than the parameterized limit value
Possible causes	- Limit value set too high - Control temperature parameters set too low - Full-flow regeneration burner not powerful enough
Procedure	- Check parameters - Check the ratings of the full-flow regeneration burner

B1.2.5 Flame failure controller

61 Flame failure controller - burner 1

Meaning	The flame failure controller detects a flame before ignition
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	A 6...11V signal is applied to the terminal X2:28
Possible causes	- Flame failure controller removed - There is burning fuel in the exhaust gas pipe
Procedure	- Remove flame failure controller, look through sight glass to ensure there is no burning fuel in the exhaust gas pipe - Replace flame failure controller

62 Flame failure controller - burner 2

Meaning	The flame failure controller detects a flame before ignition
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	A 6...11V signal is applied to the terminal X2:29
Possible causes	- Flame failure controller removed - There is burning fuel in the exhaust gas pipe
Procedure	- Remove flame failure controller, look through sight glass to ensure there is no burning fuel in the exhaust gas pipe - Replace flame failure controller

B1.2.6 Sensors

71 Open circuit - temperature sensor

Meaning	Break in the wiring to the temperature sensor
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 4...20 mA signal at the terminal X2:25 is less than 2 mA
Possible causes	- Cable in the temperature sensor head (form B) not connected - Open circuit
Procedure	- Measure the current signal - Check the connections in the temperature sensor head (form B) - Perform continuity test on cable

72 Open circuit - pressure sensor

Meaning	Break in the wiring to the pressure sensor
Consequences	The fault is merely indicated
Fault generation	The 4...20 mA signal at the terminal X2:24 is less than 2 mA
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure the current signal - Perform continuity test on cable

73 Range - temperature sensor

Meaning	The temperature sensor range is not correct
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 4...20 mA signal at the terminal X2:25 is greater than 19.8 mA
Possible causes	- Temperature outside of range of temperature sensor - Wrong temperature sensor connected - Short-circuit in the cable
Procedure	- Measure the current signal - Check temperature sensor - Check cable

74 Range - pressure sensor

Meaning	The pressure sensor range is not correct
Consequences	The fault halts the full-flow regeneration burners or prevents an ignition
Fault generation	The 4...20 mA signal at the terminal X2:24 is greater than 19.8 mA
Possible causes	- Pressure outside of range of pressure sensor - Wrong pressure sensor connected - Short-circuit in the cable
Procedure	- Measure the current signal - Check pressure sensor - Check cable

75 Short-circuit - temperature sensor

Meaning	A short-circuit has occurred in the thermocouple and it only indicates the ambient temperature
Consequences	The fault halts the full-flow regeneration burner or prevents an ignition
Fault generation	The 4...20mA signal at terminal X2:25 indicates a constant current signal despite a change in temperature
Possible causes	- Sensor defective
Procedure	- Measure current - Replace the temperature sensor

B1.2.7 Maintenance

81 Maintenance required

Meaning	Particulate filter requires maintenance (blow-out ash)
Consequences	The fault is merely indicated
Fault generation	Internal (PLC)
Possible causes	- The configured limit value has been reached
Procedure	- Contact Hug Engineering AG or an authorized partner

This section is a part of the documentation for the 'Exhaust gas purification system'. You must also observe the chapters 'Foreword', Definition, Safety, Disposal in Index 1 of the folder 'Exhaust gas purification system'.

B1 Faults

B1.1 General

The following summary has been drawn up to aid troubleshooting and fault elimination procedures. You should contact Hug Engineering AG or an authorised partner if a fault occurs that is not described in this section or cannot be put down to a particular cause. (→ Maintenance Manual folder)

B1.2 Reactant tank (red LED flashes 1x)

01 Reactant tank empty

Meaning	The level of reactant has sunk below the minimum level
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 24-VDC signal at terminal X2:9 drops out for more than 5 seconds
Possible causes	- Level of reactant too low - Sensor defective - Open circuit
Procedure	- Check the level of reactant in the reactant tank - Check the level sensor - Check the electrical connections

B1.3 Compressed air supply (red LED flashes 2x)

02 Air pressure too low (Sensor 30B5, system / RC100

Meaning	Air pressure measured at pressure sensor 30B5 below 1.35 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:16 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

03 Air pressure too high (sensor 30B5, system/RC100)

Meaning	- The air pressure measured at the pressure sensor 30B5 has exceeded the value 3.5 bar for more than 30 seconds or has exceeded the value 1.2 bar absolute for more than 3 minutes.
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5-VDC signal at the terminal X3:16 is greater than the limit value (5 bar when the main air valve is open, 1.2 bar when the main air valve is closed)
Possible causes	- Reactant nozzle blocked - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Compressed-air pressure too high for pressure reducing valve - Pressure sensor defective - Note: The air pressure is measured immediately in front of the reactant injector. It does not correspond to the pressure set at the pressure reducing valve.
Procedure	- Check the reactant nozzle is not blocked - Check the setting of pressure reducing valve - Check pressure of compressed-air supply - Check pressure sensor

04 Open circuit (Sensor 30B5, system / RC100)

Meaning	Break in the wiring to the pressure sensor 30B5
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:16 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

05 Range of pressure (Sensor 30B5, system / RC100)

Meaning	Range of pressure sensor 30B5 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:16 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

10 Air pressure too low (Sensor 30B1, system / RCE20_1)

Meaning	Air pressure measured at pressure sensor 30B1 below 1.35 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:2 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

11 Air pressure too high (Sensor 30B1, system / RCE20_1)

Meaning	The air pressure measured at the pressure sensor 30B1 has exceeded the value 3.5 bar for more than 30 seconds or has exceeded the value 1.2 bar absolute for more than 3 minutes.
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5-VDC signal at the terminal X3:2 is greater than the limit value (5 bar when the main air valve is open, 1.2 bar when the main air valve is closed)
Possible causes	- Reactant nozzle blocked - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Compressed-air pressure too high for pressure reducing valve - Pressure sensor defective - Note: The air pressure is measured immediately in front of the reactant injector. It does not correspond to the pressure set at the pressure reducing valve.
Procedure	- Check the reactant nozzle is not blocked - Check the setting of pressure reducing valve - Check pressure of compressed-air supply - Check pressure sensor

12 Open circuit (Sensor 30B1, system / RCE20_1)

Meaning	Break in the wiring to the pressure sensor 30B1
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:2 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

13 Range of pressure (Sensor 30B1, System / RCE20_1)

Meaning	Range of pressure sensor 30B1 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:2 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

18 Air pressure too low (Sensor 30B3, system / RCE20_1)

Meaning	Air pressure measured at pressure sensor 30B3 below 1.35 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:10 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

19 Air pressure too high (Sensor 30B3, system / RCE20_1)

Meaning	The air pressure measured at the pressure sensor 30B3 has exceeded the value 3.5 bar for more than 30 seconds or has exceeded the value 1.2 bar absolute for more than 3 minutes.
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5-VDC signal at the terminal X3:10 is greater than the limit value (5 bar when the main air valve is open, 1.2 bar when the main air valve is closed)
Possible causes	- Reactant nozzle blocked - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Compressed-air pressure too high for pressure reducing valve - Pressure sensor defective - Note: The air pressure is measured immediately in front of the reactant injector. It does not correspond to the pressure set at the pressure reducing valve.
Procedure	- Check the reactant nozzle is not blocked - Check the setting of pressure reducing valve - Check pressure of compressed-air supply - Check pressure sensor

20 Open circuit (Sensor 30B3, system / RCE20_1)

Meaning	Break in the wiring to the pressure sensor 30B3
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:10 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

21 Range of pressure (Sensor B0B3, system / RCE20_1)

Meaning	Range of pressure sensor 30B3 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:10 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

26 Air pressure too low (Sensor 30B1, System / RCE20_2)

Meaning	Air pressure measured at pressure sensor 30B1 below 1.35 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:2 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

27 Air pressure too high (Sensor 30B1, system / RCE20_2)

Meaning	The air pressure measured at the pressure sensor 30B1 has exceeded the value 3.5 bar for more than 30 seconds or has exceeded the value 1.2 bar absolute for more than 3 minutes.
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5-VDC signal at the terminal X3:2 is greater than the limit value (5 bar when the main air valve is open, 1.2 bar when the main air valve is closed)
Possible causes	- Reactant nozzle blocked - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Compressed-air pressure too high for pressure reducing valve - Pressure sensor defective - Note: The air pressure is measured immediately in front of the reactant injector. It does not correspond to the pressure set at the pressure reducing valve.
Procedure	- Check the reactant nozzle is not blocked - Check the setting of pressure reducing valve - Check pressure of compressed-air supply - Check pressure sensor

28 Open circuit (Sensor 30B1, system / RCE20_2)

Meaning	Break in the wiring to the pressure sensor 30B1
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:2 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

29 Range of pressure (Sensor 30B1, system / RCE20_2)

Meaning	Range of pressure sensor 30B1 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:2 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

34 Air pressure too low (Sensor 30B3, system / RCE20_2)

Meaning	Air pressure measured at pressure sensor 30B3 below 1.35 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:10 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

35 Air pressure too high (Sensor 30B3, system / RCE20_2)

Meaning	The air pressure measured at the pressure sensor 30B3 has exceeded the value 3.5 bar for more than 30 seconds or has exceeded the value 1.2 bar absolute for more than 3 minutes.
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5-VDC signal at the terminal X3:10 is greater than the limit value (5 bar when the main air valve is open, 1.2 bar when the main air valve is closed)
Possible causes	- Reactant nozzle blocked - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Compressed-air pressure too high for pressure reducing valve - Pressure sensor defective - Note: The air pressure is measured immediately in front of the reactant injector. It does not correspond to the pressure set at the pressure reducing valve.
Procedure	- Check the reactant nozzle is not blocked - Check the setting of pressure reducing valve - Check pressure of compressed-air supply - Check pressure sensor

36 Open circuit (Sensor 30B3, system / RCE20_2)

Meaning	Break in the wiring to the pressure sensor 30B3
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:10 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

37 Range of pressure (Sensor 30B3, system / RCE20_2)

Meaning	Range of pressure sensor 30B3 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:10 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

42 Compressed air not available (Sensor 30B5, system / RC100)

Meaning	Air pressure measured at pressure sensor 30B5 below 1.2 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:16 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor covered or defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check pressure of compressed-air supply - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

43 Compressed air not available (Sensor 30B1, system / RCE20_1)

Meaning	Air pressure measured at pressure sensor 30B1 below 1.2 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:2 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor covered or defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check pressure of compressed-air supply - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

44 Compressed air not available (Sensor 30B3, system / RCE20_1)

Meaning	Air pressure measured at pressure sensor 30B3 below 1.2 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:10 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor covered or defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check pressure of compressed-air supply - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

45 Compressed air not available (Sensor 30B1, system / RCE20_2

Meaning	Air pressure measured at pressure sensor 30B1 below 1.2 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:2 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor covered or defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check pressure of compressed-air supply - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

46 Compressed air not available (Sensor 30B3, system / RCE20_2

Meaning	Air pressure measured at pressure sensor 30B3 below 1.2 bar (absolute) for more than 30 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:10 is less than the limit value
Possible causes	- No compressed air - Pressure reducing valve on air supply unit RLxx set incorrectly or defective - Air line blocked - Main air valve does not open - Leak in one of the lines - Pressure sensor covered or defective - Open circuit
Procedure	- Check the setting at the pressure reducing valve - Check pressure of compressed-air supply - Check lines are not blocked - Check lines for leaks - Check the main air valve is functioning correctly - Check pressure sensor - Check the electrical connections

B1.4 Reactant supply (red LED flashes 3x)

6 Reactant pressure too low (Sensor 30B4, system / RC100)

Meaning	Reactant pressure measured at pressure sensor 30B4 below 4.6 bar (absolute) for more than 5 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:12 is less than the limit value
Possible causes	- Air in the pressure line - Air in the suction line - Pressure sensor defective - Ice build-up
Procedure	- Actuate dosing valve several times - Purge system - Check system for build-up of ice - Check pressure sensor

7 Reactant pressure too high (Sensor 30B4, system / RC100)

Meaning	Reactant pressure measured at pressure sensor 30B4 above 6 bar (absolute) for more than 3 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:12 is greater than the limit value
Possible causes	- Pressure sensor defective
Procedure	- Check pressure sensor

8 Open circuit (Sensor 30B4, system / RC100)

Meaning	Break in the wiring to the pressure sensor 30B4
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:12 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

9 Range of pressure sensor (Sensor 30B4, system / RC100)

Meaning	Range of pressure sensor 30B4 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:12 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

14 Reactant pressure too low (Sensor 30B2, system / RCE20_1)

Meaning	Reactant pressure measured at pressure sensor 30B2 below 4.6 bar (absolute) for more than 5 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:6 is less than the limit value
Possible causes	- Air in the pressure line - Air in the suction line - Pressure sensor defective - Ice build-up
Procedure	- Actuate dosing valve several times - Purge system - Check system for build-up of ice - Check pressure sensor

15 Reactant pressure too high (Sensor 30B2, system / RCE20_1)

Meaning	Reactant pressure measured at pressure sensor 30B2 above 6 bar (absolute) for more than 3 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:6 is greater than the limit value
Possible causes	- Pressure sensor defective
Procedure	- Check pressure sensor

16 Open circuit (Sensor 30B2, system / RCE20_1)

Meaning	Break in the wiring to the pressure sensor 30B2
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:6 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

17 Range of pressure sensor (Sensor 30B2, system / RCE20_1)

Meaning	Range of pressure sensor 30B2 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:6 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

22 Reactant pressure too low (Sensor 30B4, system / RCE20_1)

Meaning	Reactant pressure measured at pressure sensor 30B4 below 4.6 bar (absolute) for more than 5 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:14 is less than the limit value
Possible causes	- Air in the pressure line - Air in the suction line - Pressure sensor defective - Ice build-up
Procedure	- Actuate dosing valve several times - Purge system - Check system for build-up of ice - Check pressure sensor

23 Reactant pressure too high (Sensor 30B4, system / RCE20_1)

Meaning	Reactant pressure measured at pressure sensor 30B4 above 6 bar (absolute) for more than 3 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:14 is greater than the limit value
Possible causes	- Pressure sensor defective
Procedure	- Check pressure sensor

24 Open circuit (Sensor 30B4, system / RCE20_1)

Meaning	Break in the wiring to the pressure sensor 30B4
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:14 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

25 Range of pressure sensor (Sensor 30B4, system / RCE20_1)

Meaning	Range of pressure sensor 30B4 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:14 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

30 Reactant pressure too low (Sensor 30B2, system / RCE20_2)

Meaning	Reactant pressure measured at pressure sensor 30B2 below 4.6 bar (absolute) for more than 5 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:6 is less than the limit value
Possible causes	- Air in the pressure line - Air in the suction line - Pressure sensor defective - Ice build-up
Procedure	- Actuate dosing valve several times - Purge system - Check system for build-up of ice - Check pressure sensor

31 Reactant pressure too high (Sensor 30B2, system / RCE20_2)

Meaning	Reactant pressure measured at pressure sensor 30B2 above 6 bar (absolute) for more than 3 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:6 is greater than the limit value
Possible causes	- Pressure sensor defective
Procedure	- Check pressure sensor

32 Open circuit (Sensor 30B2, system / RCE20_2)

Meaning	Break in the wiring to the pressure sensor 30B2
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:6 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

33 Range of pressure sensor (Sensor 30B2, system / RCE20_2)

Meaning	Range of pressure sensor 30B2 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:6 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

38 Reactant pressure too low (Sensor 30B4, system / RCE20_2)

Meaning	Reactant pressure measured at pressure sensor 30B4 below 4.6 bar (absolute) for more than 5 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:14 is less than the limit value
Possible causes	- Air in the pressure line - Air in the suction line - Pressure sensor defective - Ice build-up
Procedure	- Actuate dosing valve several times - Purge system - Check system for build-up of ice - Check pressure sensor

39 Reactant pressure too high (Sensor 30B4, system / RCE20_2)

Meaning	Reactant pressure measured at pressure sensor 30B4 above 6 bar (absolute) for more than 3 seconds
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:14 is greater than the limit value
Possible causes	- Pressure sensor defective
Procedure	- Check pressure sensor

40 Open circuit (Sensor 30B4, system / RCE20_2)

Meaning	Break in the wiring to the pressure sensor 30B4
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:14 is less than 200 mV
Possible causes	- The cable is not connected to the pressure sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

41 Range of pressure sensor (Sensor 30B4, system / RCE20_2)

Meaning	Range of pressure sensor 30B4 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:14 is greater than 4.8 VDC
Possible causes	- Pressure outside of range of pressure sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check pressure sensor - Check cable

B1.5 Sensors (red LED flashes 4x)

74 Open circuit air flow sensor (30B1, system / RC100)

Meaning	Break in the wiring to the air flow sensor 30B1
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:5 is less than 500 mV
Possible causes	- The cable is not connected to the air flow sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

75 Range air flow sensor (30B1, system / RC100)

Meaning	Range of air flow sensor 30B1 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:5 is greater than 5.2 VDC
Possible causes	- Air flow rate outside of range of air flow sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check the air flow sensor - Check cable

76 Open circuit air flow sensor (30B7, system / RC100)

Meaning	Break in the wiring to the air flow sensor 30B7
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:26 is less than 500 mV
Possible causes	- The cable is not connected to the air flow sensor - Open circuit
Procedure	- Measure voltage - Perform continuity test on cable

77 Range of air flow sensor (30B7, system / RC100)

Meaning	Range of air flow sensor 30B7 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:26 is greater than 5.2 VDC
Possible causes	- Air flow rate outside of range of air flow sensor - Short-circuit in the cable
Procedure	- Measure voltage - Check the air flow sensor - Check cable

79 Short-circuit (Sensor 17B1, system / RC100)

Meaning	NOx sensor 17B1 has a short-circuit
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- NOx sensor short-circuited
Procedure	- Replace NOx sensor

80 Open circuit (Sensor 17B1, system / RC100)

Meaning	Break in the wiring to the NOx sensor 17B1
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- Open circuit
Procedure	- Check electrical connections and cables

81 Invalid value (Sensor 17B1, system / RC100)

Meaning	NOx sensor 17B1 not supplying valid measurement values
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- NOx sensor defective
Procedure	- Replace NOx sensor

82 Short-circuit (Sensor 17B5, system / RC100)

Meaning	NOx sensor 17B5 has a short-circuit
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- NOx sensor short-circuited
Procedure	- Replace NOx sensor

83 Open circuit (Sensor 17B5, system / RC100)

Meaning	Break in the wiring to the NOx sensor 17B5
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- Open circuit
Procedure	- Check electrical connections and cables

84 Invalid value (Sensor 17B5, system / RC100)

Meaning	NOx sensor 17B5 not supplying valid measurement values
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- NOx sensor defective
Procedure	- Replace NOx sensor

85 Open circuit temperature sensor (30B2, system / RC100)

Meaning	Break in the wiring to the temperature sensor 30B2
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 4...20 mA signal at the terminal X3:8 is less than 2 mA
Possible causes	- Cable in the temperature sensor head (form B) not connected - Open circuit
Procedure	- Measure the current signal - Check the connections in the temperature sensor head (form B) - Perform continuity test on cable

86 Range of temperature sensor (30B2, system / RC100)

Meaning	Range of temperature sensor 30B2 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 4...20 mA signal at the terminal X3:8 is greater than 21 mA
Possible causes	- Temperature outside of range of temperature sensor - Wrong temperature sensor connected - Short-circuit in the cable
Procedure	- Measure the current signal - Check temperature sensor - Check cable

87 Open circuit temperature sensor (30B3, system / RC100)

Meaning	Break in the wiring to the temperature sensor 30B3
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 4...20 mA signal at the terminal X3:10 is less than 2 mA
Possible causes	- Cable in the temperature sensor head (form B) not connected - Open circuit
Procedure	- Measure the current signal - Check the connections in the temperature sensor head (form B) - Perform continuity test on cable

88 Range of temperature sensor (30B3, system / RC100)

Meaning	Range of temperature sensor 30B3 is not correct
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - The 4...20 mA signal at the terminal X3:10 is greater than 21 mA
Possible causes	- Temperature outside of range of temperature sensor - Wrong temperature sensor connected - Short-circuit in the cable
Procedure	- Measure the current signal - Check temperature sensor - Check cable

B1.6 Internal bus communication error (red LED flashes 5x)

93 Communication error with RCE20_1

Meaning	Communications with RCE20_1 disturbed
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- PLC of RCE20_1 not in 'Running' mode - Open circuit CAN bus
Procedure	- Check PLC - Check CAN-Bus for open circuit

94 Communication error with RCE20_2

Meaning	Communications with RCE20_2 disturbed
Consequences	This fault stops the reactant injection process
Fault generation	RC100 - Internal (PLC)
Possible causes	- PLC of RCE20_2 not in 'Running' mode - Open circuit CAN bus
Procedure	- Check PLC - Check CAN-Bus for open circuit

B1.7 Incorrect run-on function (red LED flashes 6x)

△ Monitoring is active only during the air run-on functions. The main air valve is cycled open or closed during these functions. After the signal 'Engine running' is again applied the controls visualise the alarm through a red LED flashing 6 times.

61 Reactant – pressure relief (Sensor 30B4, system / RC100)

Meaning	The reactant pressure measured at pressure sensor 30B4 has not fallen below 2 bar absolute for more than 14 seconds
Consequences	- The dosing unit will be destroyed if the reactant freezes
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:12 is greater than the limit value
Possible causes	- Pressure relief valve on pump defective - Kink in the reactant line - Reactant pressure sensor defective - Reactant injector blocked
Procedure	- Check reactant line - Check pressure sensor signal - Check pressure relief valve - Check reactant injector

62 Reactant – pressure relief (Sensor 30B2, system / RCE20_1)

Meaning	The reactant pressure measured at pressure sensor 30B2 has not fallen below 2 bar absolute for more than 14 seconds
Consequences	- The dosing unit will be destroyed if the reactant freezes
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:6 is greater than the limit value
Possible causes	- Pressure relief valve on pump defective - Kink in the urea line - Urea pressure sensor defective - Reactant injector blocked
Procedure	- Check reactant line - Check pressure sensor signal - Check pressure relief valve - Check reactant injector

63 Reactant – pressure relief (Sensor 30B4, system / RCE20_1)

Meaning	The reactant pressure measured at pressure sensor 30B4 has not fallen below 2 bar absolute for more than 14 seconds
Consequences	- The dosing unit will be destroyed if the reactant freezes
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:14 is greater than the limit value
Possible causes	- Pressure relief valve on pump defective - Kink in the urea line - Urea pressure sensor defective - Reactant injector blocked
Procedure	- Check reactant line - Check pressure sensor signal - Check pressure relief valve - Check reactant injector

64 Reactant – pressure relief (Sensor 30B2, system / RCE20_2)

Meaning	The reactant pressure measured at pressure sensor 30B2 has not fallen below 2 bar absolute for more than 14 seconds
Consequences	- The dosing unit will be destroyed if the reactant freezes
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:6 is greater than the limit value
Possible causes	- Pressure relief valve on pump defective - Kink in the urea line - Urea pressure sensor defective - Reactant injector blocked
Procedure	- Check reactant line - Check pressure sensor signal - Check pressure relief valve - Check reactant injector

65 Reactant – pressure relief (Sensor 30B4, system / RCE20_2)

Meaning	The reactant pressure measured at pressure sensor 30B4 has not fallen below 2 bar absolute for more than 14 seconds
Consequences	- The dosing unit will be destroyed if the reactant freezes
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:14 is greater than the limit value
Possible causes	- Pressure relief valve on pump defective - Kink in the urea line - Urea pressure sensor defective - Reactant injector blocked
Procedure	- Check reactant line - Check pressure sensor signal - Check pressure relief valve - Check reactant injector

66 No compressed-air during run-on function (Sensor 30B5, system / RC100)

Meaning	The compressed-air measured at the pressure sensor 30B5 has not risen above 1.2 bar absolute for more than 25 seconds.
Consequences	- The injector will not be purged or cleaned, and can become blocked due to crystallisation. - No air cushion upstream of control valve (on the reactant supply side); this will cause the dosing unit to be destroyed if the reactant freezes
Fault generation	RC100 - The 0...5 VDC signal at the terminal X3:16 is less than the limit value
Possible causes	- No compressed-air during the run-on functions - Leak in the compressed-air line - Compressed-air regulator unit set incorrectly or defective - Air supply line blocked - Air valve does not open - Blocked or defective - Pressure pick-up defective or covered
Procedure	- Check all lines - Check compressed-air valve and pressure sensor

67 No compressed-air during run-on function (Sensor 30B1, system / RCE20_1)

Meaning	The compressed-air measured at the pressure sensor 30B1 has not risen above 1.2 bar absolute for more than 25 seconds.
Consequences	- The injector will not be purged or cleaned, and can become blocked due to crystallisation. - No air cushion upstream of control valve (on the reactant supply side); this will cause the dosing unit to be destroyed if the reactant freezes
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:2 is less than the limit value
Possible causes	- No compressed-air during the run-on functions - Leak in the compressed-air line - Compressed-air regulator unit set incorrectly or defective - Air supply line blocked - Air valve does not open - Blocked or defective - Pressure pick-up defective or covered
Procedure	- Check all lines - Check compressed-air valve and pressure sensor

68 No compressed-air during run-on function (Sensor 30B3, System / RCE20_1)

Meaning	The compressed-air measured at the pressure sensor 30B3 has not risen above 1.2 bar absolute for more than 25 seconds.
Consequences	- The injector will not be purged or cleaned, and can become blocked due to crystallisation. - No air cushion upstream of control valve (on the reactant supply side); this will cause the dosing unit to be destroyed if the reactant freezes
Fault generation	RCE20_1 - The 0...5 VDC signal at the terminal X3:10 is less than the limit value
Possible causes	- No compressed-air during the run-on functions - Leak in the compressed-air line - Compressed-air regulator unit set incorrectly or defective - Air supply line blocked - Air valve does not open - Blocked or defective - Pressure pick-up defective or covered
Procedure	- Check all lines - Check compressed-air valve and pressure sensor

69 No compressed-air during run-on function (Sensor 30B1, system / RCE20_2)

Meaning	The compressed-air measured at the pressure sensor 30B1 has not risen above 1.2 bar absolute for more than 25 seconds.
Consequences	- The injector will not be purged or cleaned, and can become blocked due to crystallisation. - No air cushion upstream of control valve (on the reactant supply side); this will cause the dosing unit to be destroyed if the reactant freezes
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:2 is less than the limit value
Possible causes	- No compressed-air during the run-on functions - Leak in the compressed-air line - Compressed-air regulator unit set incorrectly or defective - Air supply line blocked - Air valve does not open - Blocked or defective - Pressure pick-up defective or covered
Procedure	- Check all lines - Check compressed-air valve and pressure sensor

70 No compressed-air during run-on function (Sensor 30B3, system / RCE20_2)

Meaning	The compressed-air measured at the pressure sensor 30B3 has not risen above 1.2 bar absolute for more than 25 seconds.
Consequences	- The injector will not be purged or cleaned, and can become blocked due to crystallisation. - No air cushion upstream of control valve (on the reactant supply side); this will cause the dosing unit to be destroyed if the reactant freezes
Fault generation	RCE20_2 - The 0...5 VDC signal at the terminal X3:10 is less than the limit value
Possible causes	- No compressed-air during the run-on functions - Leak in the compressed-air line - Compressed-air regulator unit set incorrectly or defective - Air supply line blocked - Air valve does not open - Blocked or defective - Pressure pick-up defective or covered
Procedure	- Check all lines - Check compressed-air valve and pressure sensor

71 Run-on function not terminated (system / RC100)

Meaning	The run-on functions are started once the 'Engine running' signal drops out. These are active for 5 minutes. An alarm is generated if the run-on functions cannot be run until they are completed. An exception to this is if the functions are aborted because the 'Engine running' signal is reapplied. In this case no alarm will be generated.
Consequences	- The injector will not be purged or cleaned, and can become blocked due to crystallisation. - No air cushion upstream of control valve (on the reactant supply side); this will cause the dosing unit to be destroyed if the reactant freezes
Fault generation	After the signal 'Engine running' is again applied the controls visualise the alarm through a red LED flashing 6 times.
Possible causes	- Power failure
Procedure	- Check fuse - Check main power switch - Check power supply line

B1.8 Bus communication – customer interface (red LED flashes 7x)

97 Communication error CANopen

Meaning	Communication error to customer controls (CANopen gateway)
Consequences	Customer visual display system fails: - System continues to function - Use LED and illuminated push-button to diagnose error in system
Fault generation	Communication between customer controls and RC100 failed for 1 second
Possible causes	- Open circuit - CAN bus not terminated with 2x 120 Ω - CAN bus crash on RC100 or customer controls - EMC faults on CAN bus
Procedure	- Restart customer controls and/or RC100 - Consult customer personnel with knowledge of CAN bus or Hug Engineering AG

Inspectorate
22934 Lockness Avenue
Torrance, California 90501 USA
T. 310-326-4429
F. 310-326-4470

Certificate of Analysis

INSPECTORATE

Vessel / Shore Tank :	**Shore Tank 8**	Sample Submitted By :	IAC Los Angeles
Product :	**Diesel**	Analysis Performed By :	IAC Los Angeles
Client Reference :	**N/A**	Date Sampled :	28-Feb-2014
Terminal / Port / Office :	PDI Berth-83 / Long Beach, CA	Date Reported :	07-Mar-2014
Job ID :	2014-081-00127	Submission ID :	2014-081-00127
Comments :	PDI Month-End Inventory		

	Shore Tank 8	
	2014-081-00127-029	Running
Method	**Test**	**Result**
ASTM D4052	API Gravity	37.7
ASTM D5453	Sulfur Content, ppm (mg/kg) / wt %	1.4 / 0.0001
ASTM D5949	Pour Point, ° C / ° F	-18.0 / 0
ASTM D93 Proc. A	Flash Point, ° C / ° F	63.0 / 145
ASTM D5186	Total Aromatics, mass %	5.6
M(d)	Total Aromatics, vol %	6.4
CB ASTM D4176 Proc. 1	Visual Observance	C and B
	Sample Temperature, ° C	22
ASTM D976	Calculated Cetane Index	52.0
ASTM D613	Cetane Number	53.4
ASTM D5773	Cloud Point, ° C / ° F	-11.8 / 11
ASTM D1500	ASTM Color	L0.5
	Sample Diluted	No
ASTM D7688	Lubricity, Major Axis, mm	0.52
	Lubricity, Minor Axis, mm	0.47
	Lubricity, Wear Scar Diameter, um	500
	Wear Scar Area Description	None
	Test Temperature, ° C	60
ASTM D445	Test Temperature	40°C (104°F)
	Kinematic Viscosity , cSt	3.093
ASTM D86	Observed Barometric Pressure, kPa	101.5
	Initial Boiling Point, ° F	368.4
	5% Recovered, ° F	418.1
	10% Recovered, ° F	437.8
	20% Recovered, ° F	457.7
	30% Recovered, ° F	475.4
	40% Recovered, ° F	493.1
	50% Recovered, ° F	511.6
	60% Recovered, ° F	532.6
	70% Recovered, ° F	555.8
	80% Recovered, ° F	583.5
	90% Recovered, ° F	625.1
	95% Recovered, ° F	663.4
	Endpoint, ° F	680.9

[M(d)] **Modification (d) - Result reported with a different unit than prescribed in the method.**

[CB] **C and B is defined as clear and bright, P is particles, W is water.**

For Inspectorate: ____________________
Anthony Riccardi, Assistant Laboratory Manager

Appendix A

Emisstar Test Report

Baseline and Degreened Emissions of Hug Nauticlean S SCR+ ADPF System

EMISSTAR

HUG Filtersystems

Interim Report, Data Comparison (corrected fuel flow)

Independent Third Party Performance Testing of Nauticlean S SCR+ADPF

Wednesday, February 5, 2014

Prepared by:

Michael Block, Principal,
Emisstar LLC

1. Objective

Emisstar was contracted by Hug Filtersystems to perform in-use emissions testing using portable emissions measurement systems (PEMS) instrumentation. The testing was performed on October 9th and 10th, 2013 on the Sause Brothers Apache workboat, at Sause's Port of Long Beach (POLB) facility. Baseline testing was performed on Wednesday, October 9th, followed by degreened testing on Thursday, October 10th. Subsequent aged testing was slated to be performed on a second deployment after 1000 (minimum) hours of actual in-use operations were obtained.

Two key issues prompt the preparation and issuance of this Interim Report:

- NOx Reduction – Subsequent to this initial phase of testing, the data showed the level of NOx reduction produced by the Nauticlean system was less than the Mark 5 California Air Resources Board (ARB) target of ≥85%. As such, Emisstar will be returning to POLB in early March, 2014 to perform repeat testing of both the baseline and degreened system configurations.
- Fuel Flow – Fuel flow is a critical parameter in the determination of instantaneous gaseous emissions in grams/second, which when aggregated over the entire duration of the specific test mode and divided by the work performed (over the same test mode), yields brake-specific emissions values in g/bhp-hr. After submission of the initial data set comprising both the baseline and degreen configurations, it was discovered that the fuel flow values were erroneous, thereby adversely affecting the gaseous as well as PM emissions values. This Interim Report focuses on this latter issue and provides an explanation of the fuel flow error, and documents the corrective action that was taken by Emisstar. Upon completion of the entirety of the program, including the rerun set of baseline and degreen tests and the aged testing, Emisstar will issue a Final Report encompassing all aspects of the testing program.

2. Scope of Work

The project scope encompassed four primary components: a) equipment and staff mobilization; b) the engine, fuel economy and PEMS testing itself; c) data QA/QC and d) issuance of this Interim Report.

2.1. Test Cycle

As exhibited in Table 1, testing was conducted in accordance with the International Standards Organization (ISO) steady-state ISO 8178-4 E-3 four-mode test cycle. This is the standard reference cycle used for testing of marine vessels.

Test Sequence Mode	ISO 8178 E-3		Weighting Factor
	RPM	Load	
1	100%	100%	0.2
2	91%	75%	0.5
3	80%	50%	0.15
4	63%	25%	0.15
Idle	Not Applicable		

Table 1 – ISO 8178-4 E-3 Four Mode Test Cycle, Idle Added, With + Weighting Factors

Emissions data-gathering was performed on a modal basis in that each test mode was sampled for a sufficient period of time to ensure a statistically significant gaseous sample data set. Additionally, a final overall value for each emissions constituent over the entire four-mode test was calculated as per ISO procedure using the weighting factors shown in Table 1. All testing was performed under real-world operating conditions, with the Apache being motored in the Port of Long Beach harbor. Because this vessel has modest power emanating from the two MTU/DDC 12V-71 engines, it was unnecessary to push a loaded barge to attain adequate power: all testing was conducted with the mass of the vessel itself being sufficient to attain the speed and load points shown in Table 1.

2.2. Fuel Economy, Engine and Emissions Testing

Emisstar deployed a qualified team of two test engineers to the Sause site location at POLB.

The Emisstar team installed all test instrumentation, including the following:

- SEMTECH-DS gaseous emissions analyzer – for the measurement and recording of carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO2), and oxides of nitrogen (NOx).

- Sensors ECOSTAR PM System – for the measurement of PM using filter-weighing, gravimetric techniques.
- KRAL BEM500/OME20 digital fuel flow meters – for the direct measurement and recording of fuel flow. The measurement is performed volumetrically, with subsequent conversion to mass basis (grams) using the fuel specific gravity.
- Binsfield Engineering engine performance benchmarking system, including torque meter and optical RPM sensor package – for the measurement and recording of engine speed (RPM) and load (torque and horsepower). Measurement is achieved through the implementation of strain gauges installed on the vessel propeller shafts. Because there is a gear ratio reduction from the engine to the propeller shafts, a constant correction factor of 6:1 is applied to the raw data output from the prop shafts to convert to data output from the engine.
- MKS MultiGas 2030 FTIR – for ammonia measurement.

Pre-test commissioning, instrument warm-up, stabilization and final calibrations were performed by the Emisstar team on-vessel prior to actual test commencement. A minimum of three test repeats were conducted at each of the engine load points to ensure that a statistically significant data set was generated. Time-aligned raw data from each instrument output was recorded and stored for the analysis presented in this report. These time-aligned data sets encompassed a distinct set for gaseous emissions, PM emissions, fuel flow, and engine speed and load.

2.3. Testing Instrumentation – Portable Emission Measurement Systems (PEMS)

2.3.1. Gaseous Emissions Measurement – the Sensors SEMTECH-DS

Mass emissions rates and fuel consumption are measured using a SEMTECH-DS™ unit (Figure 1 and Table 2). The SEMTECH-DS™ determines fuel consumption based on a carbon balance of measured emissions. Emissions that are measured and recorded include total hydrocarbons (THC), nitrogen oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2) and oxygen (O_2). In addition, engine data from available diagnostic ports (via the ECU), weather conditions and GPS data are all recorded on a real-time basis.

The SEMTECH-DS instruments measure CO_2 and CO using non-dispersive infra-red spectroscopy (NDIR), and simultaneous NO and NO_2 using non-dispersive ultra-violet spectroscopy (NDUV). These analyzers are designed and manufactured by Sensors, as well. A heated flame ionization detector (HFID) measures total hydrocarbons, and an electrochemical sensor provides oxygen measurements. Raw exhaust is sampled through heated transport tubing and particulate filtration. Ambient pressure, temperature and humidity measurements are used for NOx humidity correction. SEMTECH-DS will use real time fuel flow rate data to calculate instantaneous and total mass emissions. Volumetric fuel flow will be measured and recorded through the use of an external positive displacement pump design (PDP) fuel flow meter. The meter incorporates real-time temperature compensation, and measures and records inlet and return line fuel flow. The flow meter provides a 0-5 or 0-10 volt signal which is inputted into the analogue input of the SEMTECH emissions analyzer. This instrument is calibrated by the manufacturer and certified within 0.1% accuracy.

Figure 1 – SEMTECH – DS Analyzer and EFM Exhaust Flow Meter

Emissions Constituent	Range	Resolution	Accuracy
CO_2	0 - 20%	0.01%	0.1% or 3% of reading
CO	0 – 8%	10 ppm	50 ppm or 3%
	0 – 8%	0.001%	3% or 0.02% of reading
THC	0 – 100 ppm	0.1 ppm	2 ppm or 1% of reading
	0 – 1,000 ppm	1 ppm	5 ppm or 1% of reading
	0 – 40,000 ppm	1 ppm	10 ppm or 1% of reading
NO	0 – 2,500 ppm	1 ppm	15 ppm or 3% of reading
NO_2	0 – 500 ppm	1 ppm	10 ppm or 3% of reading
Warm Up Time:	60 Minutes		
Sample Flow Rate:	8 LPM		
Ambient Operating Temp:	2 to 40 ^oC		
Data Capture Rate:	$\geq$ 1 Hz		

Table 2 – SEMTECH Specifications

Figure 2 – KRAL fuel flow meter

Figure 3 – KRAL Electronic Control Unit

2.3.2. Fuel Flow Measurement – the Kral OME20

Volumetric fuel flow was measured in gallons per second (GPS) using the Kral OME20 fuel flow meter (an industry standard) coupled with their BEM500 data acquisition system. Volumetric data was converted to gallons per hour and then to a mass basis through computation knowing the specific gravity of the diesel fuel used.

2.3.3. Engine Torque Measurement

Emisstar utilized an engine torque measurement system for this project, as illustrated in Figure 7, below. The system includes a torque meter and two engine rpm optical sensors. A data acquisition device recorded and stored all parameters for further analysis. As noted above, a constant correction factor of 4.515 is applied to the RPM, torque and horsepower output data to account for the gear ratio reduction from the engine to the propeller shafts.

Figure 4 – Engine Torque and Fuel Economy Performance Measurement System

2.3.4. PM Measurement – the Sensors ECOSTAR PM System

For PM measurement, Emisstar employs the SEMTECH ECOSTAR Particulate Filter System ("SEMTECH ECOSTAR-PFS"), along with the Sensors Micro-Proportional Sampling System ("SEMTECH ECOSTAR-MPS"). Together, they are capable of testing a range of engines for PM based upon traditional gravimetric-based measurement principles as outlined by EPA in accordance with the newer "40 CFR Part 1065 Testing Procedures", as well as the ISO 16183 regulations. This system, as well as the SEMTECH-DS analyzer for gaseous emissions described above, is *identical* to the sampling systems that EPA, ARB and the government of China employ for a variety of in-use emissions testing for PM and criteria gaseous emissions. Indeed, EPA staff in Ann Arbor[1] extensively contributed to the FPMS and MPS development and this was a determining factor for Emisstar adopting this instrumentation as our gold-standard PM measurement system.[2] ARB has approved the use of this PM measurement system, in writing, for stationary source emissions control device *verification*. (see Appendix A).

The complete PM measurement system integrates the SEMTECH ECOSTAR-PFS and the SEMTECH ECOSTAR-MPS into one complete system, which is time-aligned with the SEMTECH-DS gaseous measurement system, resulting in a complete PM, NO_x, HC, CO and CO_2 emissions measurement package. The PM System dilutes a portion of the raw exhaust in proportion to the exhaust flow as per EPA 40 CFR, part 1065. For transient test cycle

[1] Specifically Matt Spears and Carl Fulper.

[2] For programs where a) less precise PM measurement is appropriate and/or b) the PM composition in the exhaust is characterized by a low proportion of soluble organic fraction (SOF), Emisstar offers the lower cost option of PM measurement through laser light scattering. This method *is not* approved by ARB for verification.

applications, the SEMTECH ECOSTAR-MPS uses proportional sampling, while under steady-state test conditions that only require constant dilution, constant volume sampling is employed. This constant-volume configuration will be employed for this project, since the duty-cycle of the engines, described above, is steady-state/modal in nature, with the flow rate being manually determined and set for the test. There is no requirement for cleaning or decontaminating the instrument due to direct filter deposition.

There is no cleaning or decontaminating procedure required before actual measurement for both the gaseous and PM measurement systems due to pre analysis particulate filtration and direct filter deposition, respectively.

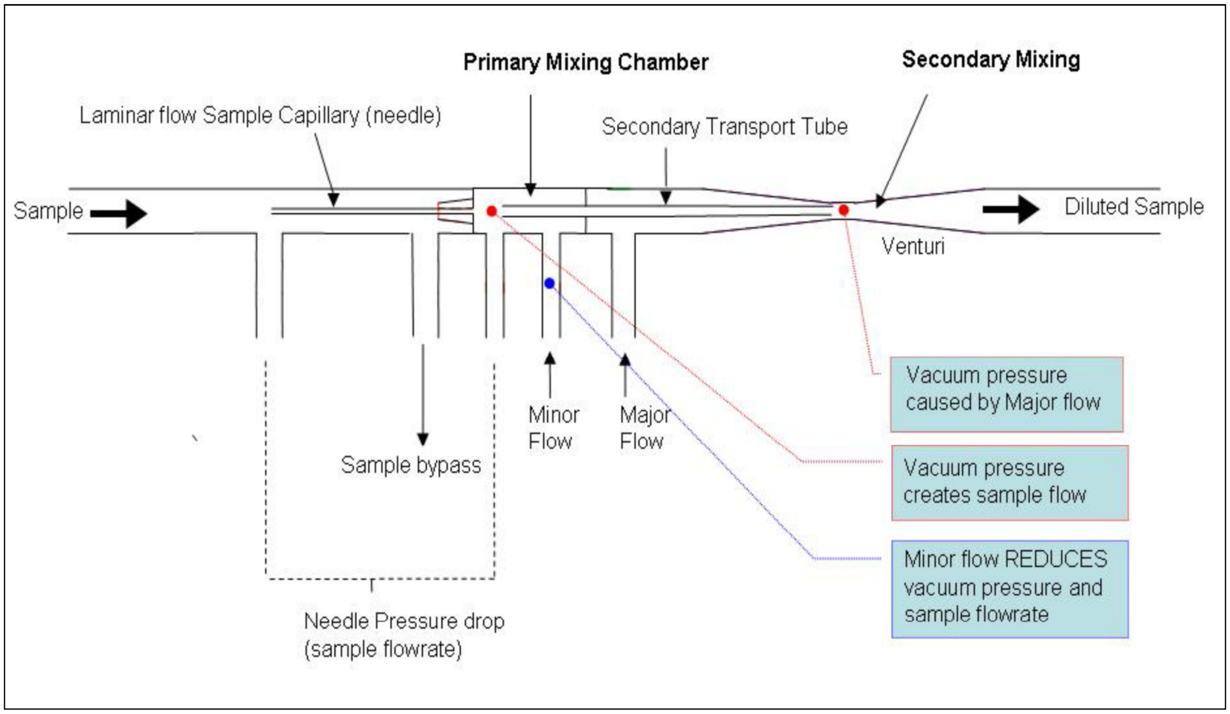
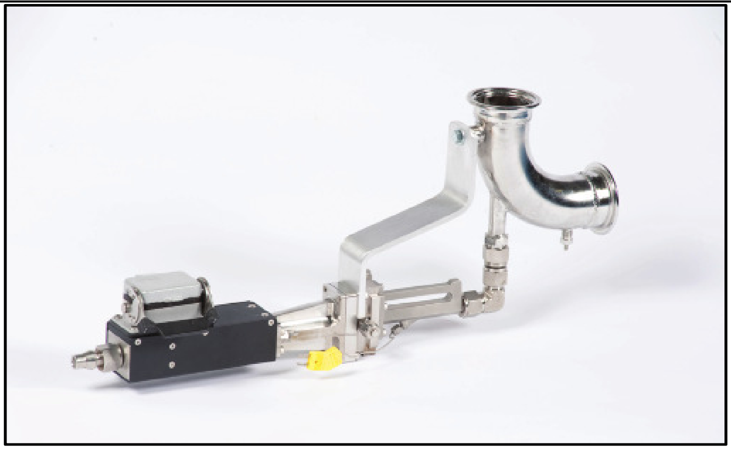


Figure 5 – Sensors SEMTECH ECOSTAR-MPS Schematic



<u>Figures 6</u> – SEMTECH ECOSTAR-PM System Components:
From Top to Bottom: MPS, PFS, Remote Diluter

SEMTECH ECOSTAR-MPS Specifications	
Sample Flow Rate	<5.01 l/min
Outlet Flow	Up to 14 l/min
Constant Dilution Ratio	User selectible 4:1 to 60:1
Proportional Dilution Ratio	5:1 to 7:1 at maximun exhaust flow
Operating Speed	10 Hz
Power Requirement	12 VDC; 110-220 VAC
Storage Temperature	Dry -10^{o} to 60^{o}C ambient
Operating Temperature	-10° to 45^{o}C ambient
Communications	Ethernet, USB
Dimensions	43.6 x 30.8 x 18.0 (W x D x H in cm)
Weight	19 kg
Electromagnetic Interference and Susceptibility	CE Standards: IEC 61326:2002-2

Table 3 – SEMTECH ECOSTAR-MPS Specifications

SEMTECH ECOSTAR-PFS Specifications	
Operating Temperature	-10^{o}C to 45^{o}C
Storage Temperature	-10^{o}C to 60^{o}C
Sample Flow Rate	5-15 SLPM
Warm Up Time	60 minutes at 20^{o}C ambient
Power Requirement	12 VDC; 110-220 VAC
Dimensions	43.6 x 30.8 x 18.0 (W x D x H in cm)
Weight	21 kg
Communications	Ethernet, USB
Filter Element Diameter	47 mm
Holder Material (PM contact surface)	Stainless steel

Table 4 – SEMTECH ECOSTAR-PFS Specifications

2.4. Ammonia Measurement – Fourier Transform Infrared Spectrometry (FTIR)

Because the Nauticlean S active system utilizes urea for the selective catalytic reduction (SCR) component of the system, Emisstar will measure and record ammonia emissions in accordance with CCR requirements[3]. Ammonia will be simultaneously measured utilizing the MKS MultiGas 2030 system for Fourier Transform Infrared Spectrometry (FTIRS) (FTIR

[3] CCR §2706(b)(3)

Spectroscopy, FTIR Spectrometry, FTIR Spectrography), a technique that exploits the phenomenon of molecular IR absorption to accurately measure gas concentrations. With an FTIR Spectrometer, the IR beam passes through a gas sample. Gas molecules interact with IR radiation, absorbing light at specific wavelengths. Every gas species examined with FTIR Spectrometry has a unique fingerprint spectrum. Since no two chemical species have the same IR spectrum, Fourier Transform Infrared Spectrometry is a highly-effective method of gas analysis. Figure 7 and Table 5 show the FTIR unit and specifications.

Figure 7 – MKS MultiGas 2030 FTIR

Parameter	Range
Measurement Technique	FTIR Spectrometry
Detector Type	21 µm 0.25 mn LN2
Gas Cell	Nickel/Gold coated Al
Ranges	Full scale setting 10ppb & 100% full scale
FTIR	2102 Process FTIR
Operating Temperature	70-85 Deg. F (optimal), 50-90 Deg. F (acceptable)
Spectral Resolution	0.5-128 cm^{-1}
Scan Speed	2 scans/sec @0.5cm^{-1}
Scan Time	1-300 sec
Infrared Source	Silicon Carbide @ 1200 Deg. C
Reference Laser	Helium Neon (15798.2 cm^{-1})
Purge Pressure	20 psig (1.5 bar) max
Power	120 or 240V AC, 50/60 Hz, 3 amps
Weight	110 lbs.
Sample Flow	0.2 – 10 lpm
Sample Pressure	0.01 – 4 atm
Allowances	Can handle gas streams with up to 30% moisture
Lowest detectable limit for Ammonia (NH_3)	24 ppb
Lowest detectable limit for Formaldehyde (H_2CO)	36 ppb
Lowest detectable limit for Methane (CH_4)	36 ppb

Table 5 – FTIR Specifications

3. Results – Resultant Gaseous Emissions Comparative Analysis

The six tables presented below show the change in all parameters – gaseous and PM emissions and engine parameters – between the initial and revised data analysis:

BASELINE WEIGHTED EMISSIONS (g/bhp-hr)							
	CO2	CO	NO	NO2	NOx	THC	PM
REVISED	676.43	1.22	8.10	0.39	8.49	0.49	0.08
INITIAL	4779.04	8.60	57.24	2.75	60.00	3.47	0.55

Table 6 – Baseline Weighted Emissions – Initial and Revised

DEGREENED WEIGHTED EMISSIONS (g/bhp-hr)								
	CO2	CO	NO	NO2	NOx	THC	PM	NH3 (ppm)
REVISED	683.42	0.75	1.57	0.80	2.37	0.06	0.01	1.70
INITIAL	4706.98	5.15	10.86	5.53	16.39	0.43	0.05	

Table 7 – Degreened Weighted Emissions – Initial and Revised

BASELINE FUEL CONSUMPTION (GPH)		
MODE	REVISED	INITIAL
100	22.81	160.9
75	15.63	110.5
50	8.22	57.9
25	3.19	22.6

Table 8 – Baseline Fuel Consumption Emissions – Initial and Revised

DEGREEN FUEL CONSUMPTION (GPH)		
MODE	REVISED	INITIAL
100	23.62	166.9
75	16.30	115.4
50	9.04	63.8
25	3.31	23.3

Table 9 – Degreened Fuel Consumption Emissions – Initial and Revised

	BASELINE HP	
MODE	REVISED	INITIAL
100	361.2	361.2
75	245.3	245.3
50	121.1	121.1
25	43.5	43.5

Table 10 – Baseline HP – Initial and Revised

	DEGREEN HP	
MODE	REVISED	INITIAL
100	364.6	364.6
75	252.4	252.4
50	130.6	130.6
25	47.4	47.4

Table 11 – Degreened HP – Initial and Revised

A few observations are noteworthy:

- As expected, the change in the fuel consumption calculation (described below) dramatically affects both gaseous and PM emissions since fuel consumption is used in the exhaust mass flow calculation.
- Baseline NOx is still high at 8.29 g/bhp-hr.
- Baseline PM values are at Tier 3 levels
- Revised NOx reductions are less than the Mark 5 threshold (at 73%).
- Revised PM reductions exceed the level 3 threshold (at 90%).
- As expected, the change in fuel flow does not affect the HP and ammonia values.

4. Fuel Flow Differences—Explanation and Corrective Action

Fuel flows are calculated by applying a transform value to the input analog voltage signal in order to obtain engineering units of fuel flow in grams per second (g/s). Typically, the transform is determined automatically by the SEMTECH in consort with the initial calibration of the Kral fuel flow meters. Regrettably, the transform value, while correct at the time of the fuel flow meter calibration, did not correctly transfer to the SEMTECH from the fuel flow software. This was determined to be a software glitch that Emisstar did not see upon our initial data analysis.

When it became clear that the fuel flow at maximum speed and load was unjustifiably high (≈160 vs. ≈22 GPH), a revisit to the transform function revealed the incorrect value. The correct value (0.00092 as opposed to 0.0065) was re-inputted and the raw data files were reprocessed.

Note that this was a software issue that was manually corrected by Emisstar staff, and not a Kral fuel flow meters issue. The Kral fuel flow meters were property calibrated, are mechanically sound, and produce accurate results. Figure 8, below, displays a screen shot of the correct VDC-to-GPH transform value.

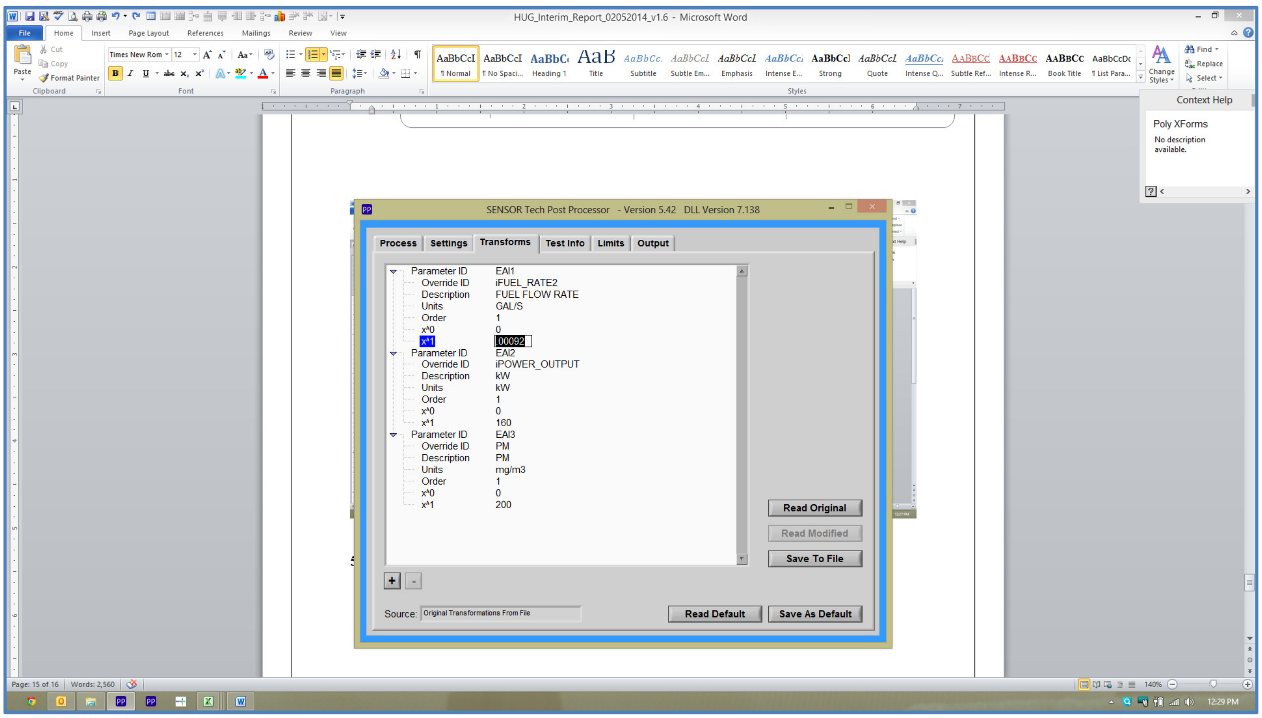


Figure 8 – Correct VDC → GPH Fuel Flow Transform Value

5. Gaseous Calibration

The fuel flow values influenced the brake-specific emissions resulting in the erroneous values in the initial analysis. The analyzers themselves were properly calibrated prior to testing.

As part of EPA 40 CFR regulation, the SEMTECH-DS system is designed to perform audit calibrations in field before and after each test to indicate that the SEMTECH-DS is operating properly. Results of the calibration for these tests is shown in Table 7:

Audit				
Date	10/10/2013			
Time	2:34:35 PM			
Audit Duration	30			
Idle Duration	15			
Audit Path	Span			
Idle Path	Zero			
Gas	Bottle	Tol	%Tol	
CO (ppm)	249.3	50	3	
CO2 (%)	4.2	0.25	3	
O2 (%)	0	0.5	3	
HC (ppmC3)	0	8	3	
NO (ppm)	244.5	15	3	
NO2 (ppm)	61.6	6	3	
CH4 (ppm)	0	0	0	
THC (ppmC3)	39.5	6	3	
Gas	Bottle	Mean Value	Std Dev	Result
CO(ppm)	249.3	260	0	Passed
CO2(%)	4.2	3.967333	0.004577	Passed
O2(%)	0	10	0	Not Selected
HC(ppmC3)	0	500	0	Not Selected
NO(ppm)	244.5	241.346667	2.166586	Passed
NO2(ppm)	61.6	58.066667	0.778888	Passed
CH4(ppm)	0	0	0	Not Selected
THC(ppmC)	39.5	39.873333	0.092753	Passed

Table 7 – Gaseous Instrumentation Calibration Results

Finally, the gaseous instrumentation was calibrated according to 40 CFR Part 1065 as shown in Figure 9:

Sensors, Inc.
6812 South State Road
Saline, Michigan 48176

Certificate No. 515
Issue date: 7/15/2013

Certificate of Compliance

This document certifies that the portable emissions measurement system (PEMS) listed below meets the audit requirements of CFR40 Part 1065 as indicated.
Some of these audits may need to be repeated as indicated or if major maintenance is performed to certain sub-systems of this PEMS.

PEMS Model:	SEMTECH-DS
PEMS S/N	H08-SDS01
Customer:	EMISSTAR
CO/CO_2 Analyzer S/N:	36882
NO/NO_2 Analyzer S/N:	272
THC Analyzer S/N:	211
NO_2 Chiller S/N:	996

1065 subpart	Description	Test date	Due date	Pass/Fail
307	Linearity of internal barometric pressure sensor	7/12/2013	370 days before testing	Pass
307	Linearity of external ambient temperature sensor		370 days before testing	
308	Continuous gas analyzer system response (1)	NA	NA	NA
309	Continuous gas analyzer uniform response (1)	NA	NA	NA
315	Pressure, temperature and dewpoint calibration		initial installation or major maintenance	
350	H_2O interference verification for CO_2 NDIR analyzers	7/12/2013	initial installation or major maintenance	Pass
355	H_2O and CO_2 interference verification for CO NDIR analyzers	7/12/2013	initial installation or major maintenance	Pass
360	FID optimization and verification	7/12/2013	185 days before testing	Pass
362	Non-stochiometric raw exhaust FID O_2 interference verification	7/12/2013	185 days before testing	Pass
372	NDUV analyzer HC and H_2O interference verification	7/15/2013	initial installation or major maintenance	Pass
376	Chiller NO_2 penetration	7/15/2013	initial installation or major maintenance	Pass

(1) See Notes page for explanation

Technician: Jeremy Palmer Date: 7-15-2013

Figure 9 – 1065 Calibration Documentation

ATTACHMENTS

Attachment One – Baseline data Sheets
Attachment Two – Degreen Data Sheets
Attachment Three – Summary Data Sheet

Appendix B

CE-CERT Test Report

Baseline and Degreened Emissions of Hug Nauticlean S SCR+ ADPF System

Emission Verification Testing of Hugfiltersystems Diesel Particulate Filter (DPF) Selective Catalytic Reduction (SCR) System on the Apache Tugboat

Prepared for:

Todd Jacobs

HugFiltersystems
123 Holmes Rd

Liberty Hill, TX 78642

281-900-5342

Todd.jacobs@hug-filtersystems.com

July 2014

Submitted by:

Dr. Robert L. Russell
Dr. John Pisano
Mr. Nicholas Gysel
Mr. William Welch

University of California, Riverside
CE-CERT
1084 Columbia Ave.
Riverside, CA 92507
951-781-5723

Disclaimer

This report was prepared as the result of work funded by the South Coast Air Quality Management District (SCAQMD) and carried out aboard the Sause Brothers Apache Tugboat operating in Long Beach Harbor. Todd Jacobs of Hugfiltersystems, the supplier of the Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) system retrofitted to the Apache engines, was there to help with preparing the engine and exhaust system for the test program and as observer of the testing. As such the report does not necessarily represent the views of Todd Jacobs, Hugfiltersystems or any other personnel present. Further the collective participants, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has neither been approved nor disapproved by the collective group of participants nor have they passed upon the accuracy or adequacy of the information in this report.

Acknowledgments

The authors express their gratitude to the SCAQMD for their financial support, Sause Brothers for operating their vessel according to the prescribed test conditions, and to all personnel who assisted in making any necessary modifications. Appreciation is extended to all the Apache crew members for their support and cooperative efforts during the emission testing. The authors are grateful to Mr. Kurt Bumiller for his help with the test preparations.

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Table A-1: Definitions Used Throughout ISO 8178-4 A-1

List of Figures

Acronyms and Abbreviations

°C..degree centigrade
C..carbon
CE-CERT..College of Engineering – Center for Environmental Research and Technology
CFO..critical flow orifice
CO..carbon monoxide
CO_2..carbon dioxide
DAF..dilution air filter
DT..dilution tunnel
EC..elemental carbon
ECE..Economic Commission for Europe
EFR..exhaust flow rate
EGA..exhaust gas analyzer
EP...exhaust pipe
EPA..Environmental Protection Agency
ETV..Environmental Technology Verification
F.S./day...full scale per day
g/kW-hr...grams per kilowatt-hour
gph...gallons per hour
HC..hydrocarbon
HCLD..heated chemiluminescence detector
HEPA..high efficiency particulate air
HFID...heated flame ionization detector
hp...horsepower
hr...hour
ID..internal diameter
IMO...International Maritime Organization
ISO..International Organization for Standardization
kg/m3..kilograms per cubic-meter
kPa..kilopascal
kW..kilowatt
lpm...liters per minute
lb..pound
MARPOL..International Convention for the Prevention of Pollution from Ships
min...minutes
mm...millimeter
NDIR..non-dispersive infrared
ng..nanogram
NIOSH..National Institute of Occupational Safety and Health
NO..nitric oxide
NO_x..oxides of nitrogen
NO_2..nitrogen dioxide
OC..organic carbon

O_2..oxygen
PM..particulate matter
PM2.5..particulate matter with a mean aerodynamic diameter less than 2.5 micron
PMD..paramagnetic detector
PTFE..polytetrafluoroethylene or Teflon Filter
ppm ....parts per million
ppmv ....parts per million by volume
psig..pound-force per square-inch gauge
QC/QA ....quality control/quality assurance
RH...relative humidity
RIC..reciprocal internal combustion
rpm ....revolutions per minute
scfm...standard cubic feet per minute
SMM ....simplified measurement method
SO_2 ....sulfur dioxide
SP ....sampling probe
VN...Venturi
T ....temperature
TC ....total carbon
TFE ....TeflonTM
TT..transfer tube
UCR ....University of California, Riverside
ULSD ....ultra low sulfur diesel
UN...United Nations
U.S. ....United States
EPA ....Environmental Protection Agency
ETV...Environmental Technology Verification
VN...Venturi
vol% ....volume %

Executive Summary

Hugfiltersystems installed a Nauticlean S, Diesel Particulate Filter/ Selective Catalytic Reduction (DPF/SCR) system on the diesel marine engines of a Sause Brothers Apache Tugboat. Per California Air Resources Board (CARB) regulation this system must be tested to confirm that it reduces Particulate Matter (PM) and Nitrogen Oxides (NO_x) by greater than 85% (CARB 2014). The regulation requires measuring the emissions of Particulate Matter (PM), Nitrogen Oxides (NO_x), Carbon Monoxide (CO), Carbon Dioxide (CO_2), and Total Hydrocarbons (THC), before and after the DPF/SCR system after 25 to 125 hours of operation and after the DPF/SCR system after 1000 hours of operation. When an SCR system is present the regulation also requires measurement of the ammonia (NH_3) concentration in the exhaust downstream of the SCR system. When a DPF system is present emissions must be measured during a DPF regeneration event.

Results The gaseous and PM emissions were measured before the DPF/SCR system in triplicate for each of the four modes of the ISO 8178-4 E3 test cycle (ISO 8178-4, 2007) during the morning and after the DPF/SCR system in the afternoon of April 14, 2014. For each test series the emission measurements began when the engine was in stable operation at its maximum load (~100%). The load was then progressively reduced to ~75%, ~50%, ~25%, and as stable operation was obtained the emissions were measured. This procedure was repeated until we had three emission measurements for each engine load. The goal of the project was to measure the baseline reduction in the engine exhaust emissions by the DPF/SCR system. Table ES-1 presents the weighted emissions for the baseline and Degreened catalyst without the inclusion of the DPF regeneration emissions and the percent reduction for each pollutant. Table ES-2 presents the weighted emissions with the inclusion of the DPF regeneration emissions.

Table ES-1: Weighted Emission Factors Without Inclusion of DPF Emissions

	Weighted Emission Factors (g/kW-hr)										
Condition	NO_x	CO	THC	CO_2	PM	EC	OC	TC	FC	NH_3	H_20
Baseline	**8.35**	0.49	0.371	819.46	**0.169**	0.017	0.278	0.296	258.40	NM	NM
St. Dev.	**0.54**	0.03	0.015	0.06	**0.015**	0.005	0.172	0.176	0.02		
Degreened	**0.65**	0.15	0.392	818.16	**0.007**	0.000	0.025	0.025	257.99	0.24	1126
St. Dev.	**0.10**	0.01	0.003	0.20	**0.001**	0.000	0.001	0.001	0.06	0.05	12
% Reduction	**92.2%**	69.2%	-5.78%	0.16%	**95.7%**	100.0%	91.2%	91.7%	0.16%		
St. Dev.	**8.8%**	7.3%	-4.10%	0.03%	**12.2%**	37.7%	83.5%	81.0%	0.03%		
NM = Not Measured											

Table ES-2: Weighted Emission Factors With Inclusion of DPF Emissions

	Weighted Emission Factors (g/kW-hr)								
Condition	**NO_x**	CO	THC	CO_2	**PM**	EC	OC	TC	FC
Baseline	**8.32**	0.49	0.37	828.11	**0.17**	0.02	0.28	0.29	261.12
Degreened	**0.75**	0.16	0.40	826.84	**0.01**	0.00	0.03	0.03	260.72
% Reduction	**91.0%**	68.2%	-5.63%	0.15%	**94.1%**	99.6%	90.2%	90.8%	0.15%

Per the protocol, the ammonia and water concentration were measured in the raw exhaust after the DPF/SCR system during the emission measurements for the degreened catalyst . The weighted emission factors are 0.24 ±0.05 g/kW-hr for ammonia and 1126 ± 12 for water. Over the time of the DPF regeneration, which was forced immediately following the third measurement of mode 4, the ammonia emissions were 1.71 g/kW-hr and the water emissions were 1981 g/kW-hr.

Conclusion:

The HugFiltersystems DPF/SCR system reduces NO_x emission by greater than 90% and PM emissions by greater than 93%. The weighted ammonia emission after the DPF/SCR are 0.24 g/kW.hr.

1 Introduction

1.1 Marine Emission Regulations

Emissions from engines on marine vessels are among the largest sources of uncontrolled mobile sources and present a significant health hazard to those living near the ports. Emissions from these sources, operating on the oceans, are controlled by the US Environmental Protection Agency (EPA) and the International Maritime Organization (IMO) (EPA 2014), which is an agency of the United Nations. For marine vessels operating on United States inland waterways emission regulations are enacted by the EPA (EPA 2014). Commercial Harbor Craft vessels operating in Regulated California Waters (all ports, internal, estuarine and coastal waters within 24 nautical miles of the California coast) are subject to CARB regulations (CARB 2014a). Vessels having Tier 1 engines must reduce their exhaust emissions to Tier 2 or Tier 3 U. S. EPA marine emission standards according to a specific compliance schedule. Compliance can be obtained by replacing the engine with a complying engine or installing aftermarket emission control equipment.

The US EPA regulation for newly manufactured engines, divides marine engines into three categories based on displacement (swept volume) per cylinder, as shown in Table **1-1** (EPA 2014a). Categories 1 and 2 are further divided into subcategories, depending on displacement and net power output. The regulations are designed to substantially reduce nitrogen oxide (NO_X) and Particulate Matter (PM) emissions. Marine engines manufactured between 1973 and before the engines were subject to emission regulations may be subject to more stringent emission requirements when they are rebuilt.

Sause Brothers have chosen to bring the engines in their Apache and Arapahoe tugboats into compliance with the CARB regulation by installing a DPF/SCR emission control system. Once installed the regulation requires demonstrating that the installed emission control system complies with the emission reduction percentages after initial installation and is still in compliance after 1000 hours of engine operation (CARB 2014)

Table 1-1: Marine Engine Categories

Category	Displacement per Cylinder (D)	
	Tier 1-2	Tier 3-4
1	D < 5 dm^3†	D < 7 dm^3
2	5 $dm^3 \le$ D < dm^3	7 $dm^3 \le$ D < 30 dm^3
3	D ≥ 30 dm^3	

1.2 Project Objectives

The goal of the CE-CERT portion of the project is to measure the engine out emissions before the DPF/SCR system and after the DPF/SCR system to establish the baseline percentage of emission reductions by the DPF/SCR system. After 1000 hours of engine operation CE-CERT will measure the emissions after the DPF/SCR system to confirm the percentage of emission reductions. The approach is to measure the emissions using the ISO 8178 guidelines (ISO 8178-2:2008, ISO 8178-4:2007 and MARPOL Annex VI NO_X Technical Code for CO_2, CO, PM (2.5), NO_X, and SO_X emissions (MARPOL 1997).

CE-CERT carried out the baseline testing on Wednesday, April 9, 2014 as the Apache tugboat was operating in Long Beach Harbor with the engines being operated on CARB Ultra Low Sulfur Diesel (ULSD) fuel at the specified ISO 8178-4 E3 test condition.

2 Project Approach

2.1 Overview

The overall plan was designed to meet the requirements specified in the CARB regulation (CARB 2013) while the tugboat operated per the ISO 8178 E3 test cycle. The heart of the work was the measurement of the gaseous and particulate emissions, including: carbon oxides (CO, CO_2,), oxides of nitrogen (NO_X), particulate matter (PM), Total Hydrocarbons (THC), and for after the DPF/SCR system the Ammonia (NH_3) while the engine operated at the steady-state conditions specified in ISO 8178 E3. Measurement methods were IMO and ISO compliant for both the gases and PM. The following sections provide detailed information.

2.2 In-Use Emission Measurements Using IMO and ISO Methods

The project required simultaneous measurement of engine out NO_X, CO, CO_2, THC, and PM emissions using the in-use Simplified Measurement Methods (SMM) system that is compliant with the International Maritime Organization (IMO) NO_X Technical Code, followed by measuring the DPF/SCR system out emissions of NO_X, CO, CO_2, THC, PM, and NH_3 by the same method.

2.2.1 Test Vessel, Engine and Fuel

The project required simultaneous measurement of engine out NO_X, CO, CO_2, THC, and PM emissions using the in-use Simplified Measurement Methods (SMM) system that is compliant with the International Maritime Organization (IMO) NO_X Technical Code, followed by measuring the DPF/SCR system out emissions of NO_X, CO, CO_2, THC, PM, and NH_3 by the same method.

2.2.2 Operating Conditions of the Engine While Measuring Emissions

The engines on this vessel drive the propellers which propel the vessel. Therefore the appropriate test procedure for these engines is with the engine operating according to the 4-modes of the ISO-8178-4 E3 cycle shown in Table 2-1.

Table 2-1: Standard Cycle for Testing Heavy Duty Engines Driving Vessels Without Limitation of Length

Mode	1	2	3	4
Speed	Rated Speed			
Load (%)	100	75	50	25
Weighting Factor	0.2	0.5	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-E3. 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.

Typically engine speed,,boost pressure, and intake manifold temperature are measured which, along with the displacement of the engine, permits calculation of the gaseous exhaust flow rate. Emissions factors are calculated in terms of grams per kilowatt hour for each of the operating modes.

2.2.3 Engine Performance Measurements during Testing

Chapter 6 of the NO_X Technical Code (MEPC 2008), “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..

2.2.4 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 (ISO 2006) and detailed information is provided in Appendix B, “Measuring Gaseous & Particulate Emissions”.

Table 2-2: Engine Parameters Measured and Recorded

Parameter	Units
Load	kW
Engine Speed	RPM
Fuel supply	gph
Fuel return	gph
Air intake pressure	psi
Air intake temperature	°F

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. The signal output of the instrument is interfaced directly with a laptop computer through an RS-232C interface to record measured values continuously.

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" and the calibrations are provided in Appendix D, "Raw Data, Analysis, Analysis Equations, and Calibration Data". In addition to measuring criteria emissions, the project measured:

1. PM continuously with a monitor to check on whether the PM concentration was constant while the filters were being loaded.
2. PM mass fractionated into the elemental and organic fractions as an internal mass balance.
3. Ammonia (NH_3) and water (H_2O) when measuring emissions after the DPF/SCR system.

Details of the measurement method for NH_3 and H_2O is provided in Appendix C.

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. The raw data, post processed data, equations for the post processing, and calibration data are in Appendix D, “Raw Data, Analysis, Analysis Equations, and Calibration Data”

3.1 Calculation of Emission Factors

The emission factors at each mode are calculated from the measured gaseous concentration, the 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 8178-4 E3 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.

3.1.1 Calculation of the Exhaust Flow Rate by ISO 8178-2

The calculated emission factor is strongly dependent on the mass flow rate of the exhaust gas. Two methods for calculating the exhaust gas mass flow rate and/or the combustion air consumption are described in ISO 8178-2 Appendix A (ISO 2008). Both methods are based on the measured exhaust gas concentrations and fuel usage rate. The two ISO methods are described below.

Method 1, Carbon Balance, 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 method is only valid for fuels without oxygen and nitrogen content, based on procedures used for EPA and ECE calculations.

Method 2, Universal, Carbon/Oxygen-balance, is used for the calculation of the exhaust mass flow. This method can be used when the fuel usage is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, O, N in known proportions.

3.1.2 Calculation of the Exhaust Flow Rate Assuming the 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 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.

4 Results

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

4.1 Exhaust Flow Rate

We typically use the carbon balance method and the engine as an air pump to calculate the exhaust flow rate and have always obtained very good agreement between the two methods. For this program we were not able to use the engine as air pump method because we did not have measurement of the inlet air temperature or the boost pressure. The preferred method for calculating exhaust flow rate is the carbon balance method so not having the engine as an air pump has no effect on the final results or conclusions.

The carbon balance method requires knowing the fuel flow rate. For engines which have Electronic Control Modules (ECM) this information can be recorded every second. Since this engine did not have an ECM the fuel rate for each mode was read from a gauge in the wheelhouse. Since each mode is run at steady state conditions minor variations in the fuel rate over the course of the mode will not have a significant effect on the calculation of the exhaust flow rate.

4.2 Fuel

The engines were operated on CARB ULSD.

4.3 Calculation of Emission Factors

To determine the emission reduction percentages of the DPF/SCR system requires determining the emission factors before and after the DPF/SCR system, which will be called Before Catalyst and After Catalyst, respectively, from this point on.

4.3.1 Operating Loads for the Engine when Emissions are Measured

During the emission measurements, the engine was operated at load points close to those specified in ISO 8178-4 E3. The actual loads in Table 4-3 are typical of the type of deviation from the specified loads when trying to hit the set points while operating at sea.

Table 4-1: Actual Load Points During Testing Compared to Specified Load Percentage

ISO 8178-4 E3 Mode	1	2	3	4
Specified Load (%)	100	75	50	25
Before Catalyst, Load (kW)	188	133	78.2	51.5
Before Catalyst, Load (%)	100	70.8	41.6	27.4
After Catalyst, Load (kW)	189	135	78.6	51.2
After Catalyst, Load (%)	100	71.4	41.4	27.0

Hug personnel had installed a strain gauge on the engine shaft to provide a measurement of the load. Unfortunately it did not work. The load was calculated during the analysis of the data based upon the rpm, which had been recorded from a gauge in the wheelhouse for each mode, and an available lug curve for an equivalent engine (Johnson 2010).

4.3.2 Carbon Dioxide Emissions

Carbon dioxide (CO2) 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 repeatable and accurate when compared with the measured fuel consumption (FC). Values for before and after the catalyst are plotted in Figure 4-1 and are nearly linear, as expected, and the CO_2 emissions are the same before and after the catalyst as expected since the fuel is exactly the same.

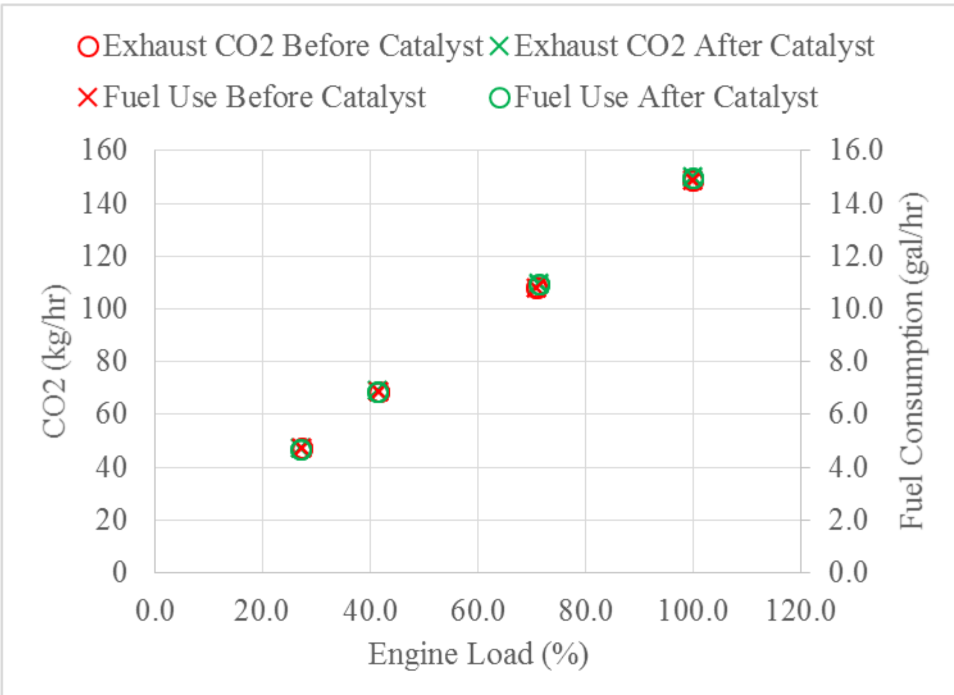

Figure 4-1: Engine Gaseous Emission Rate for CO2 versus Engine Load

The CO2 emission factors are provided in Figure 4-2. Values obtained during this project, ~ 800 g/kW-hr, are about the expected values for a medium speed diesel engine. The emission factor increases as the power decreases from the 50% load point. In previous studies an ~25% increase in fuel consumption has been observed when going from 50% to 25%.power, whereas in this study the increase is only ~17%. Figure 4-3 presents these emission factors at different engine loads and includes the overall average weighted emission factor. There are no statistically significant differences in the emissions of CO_2 for before and after the DPF/SCR system at any mode.

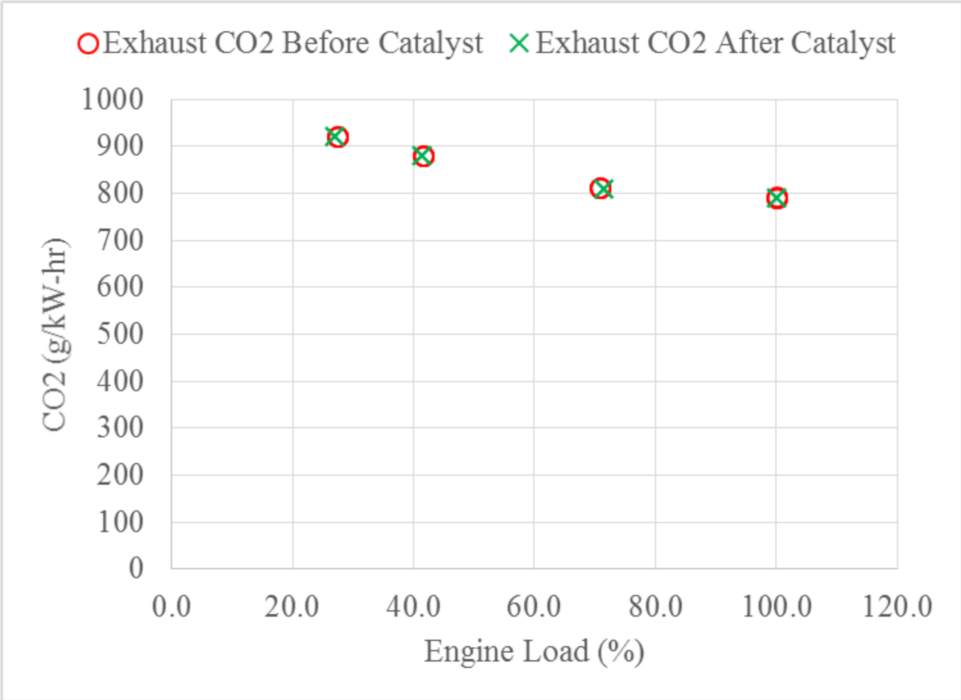

Figure 4-2: Engine Emission Factor for CO_2 versus Load

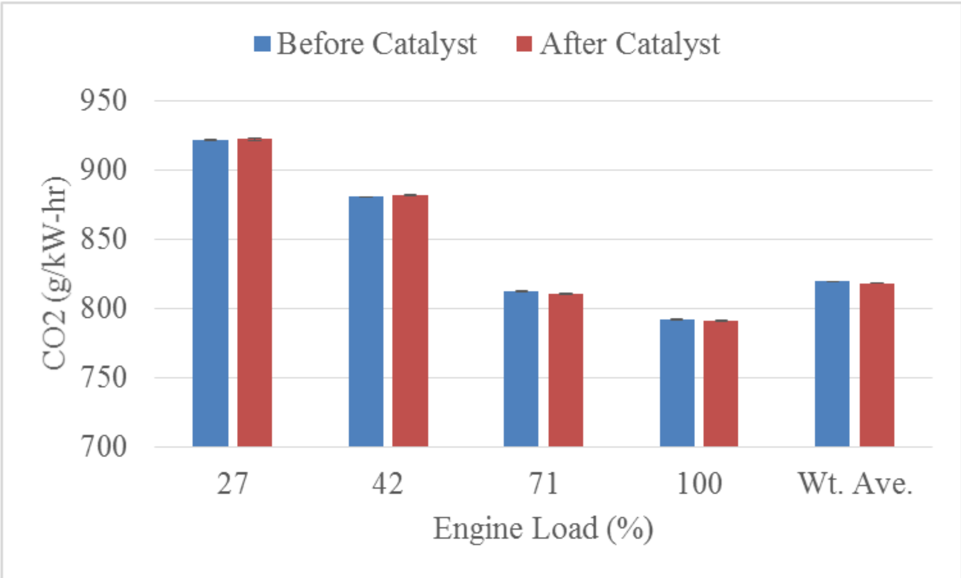

Figure 4-3: Average CO_2 Emission Factors for each mode and Overall Weighted Emission Factor

4.3.3 Quality Checks: Carbon Mass Balance: Fuel vs. Exhaust

As part of CE-CERT's QA/QC, the carbon mass balance is checked by comparing the carbon flow from the fuel with the measured carbon in the exhaust gases. The fuel flow and engine rpm was recorded once for each mode from a readout in the wheelhouse after stable operation was achieved. The fuel rate in gal/hr was converted to kg/hr by multiplying the gal/hr times (3.785 l/gal)(0.8289 kg/l)(0.8655gC/gfuel), where 0.8289 is a typical density of CARB ULSD, and 0.8655 is a typical carbon content of CARB ULSD. Figure 4-4 shows that there is essentially a one to one comparison thus confirming the QA/QC. When forced through zero, the carbon balance was within less than 1% of the carbon flow from the fuel for both fuels.

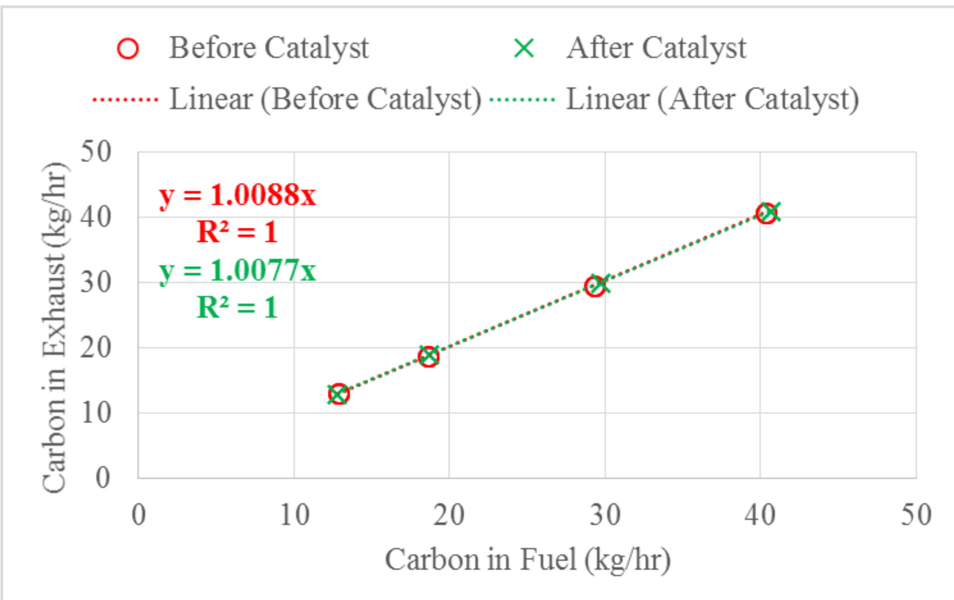

Figure 4-4: Carbon in the Exhaust versus Carbon in the Fuel

4.3.4 NO_x Emissions

NO_X emission rates and factors are the second parameters of interest in air basins that are environmentally sensitive. The gaseous emission factors for NO_X are presented in g/kW-hr in Figure 4-5. Overall the SCR catalyst reduces the NO_X emissions by 92.2%.

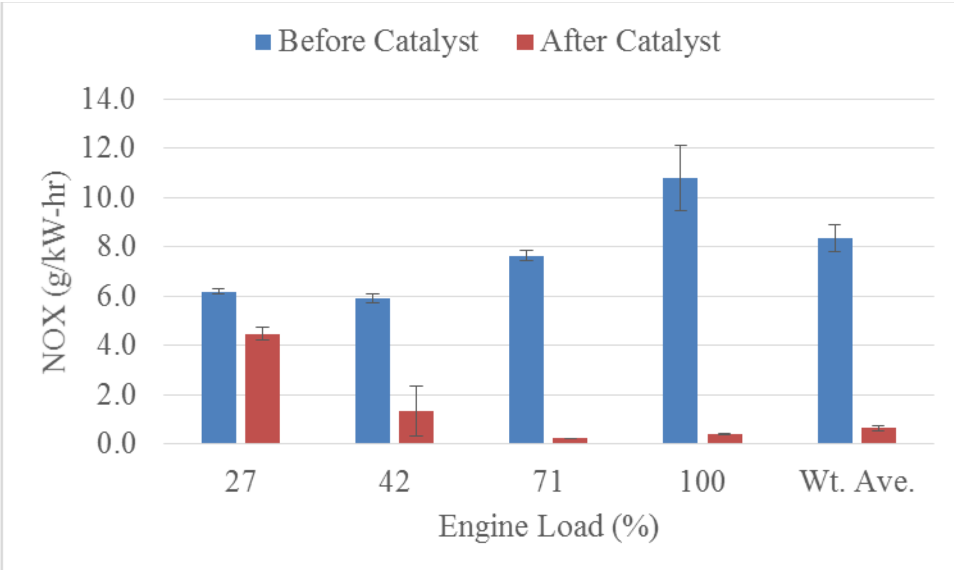

Figure 4-5: Average NO_X Emission Factors for each test mode and Overall Weighted Emission Factor

4.3.5 CO Emissions

CO emission rates and factors are presented in g/kW-hr in Figure 4-6. CO emissions were low across all load points which is typical of diesel engines. Overall the SCR catalyst reduced the CO emissions by 69.2%.

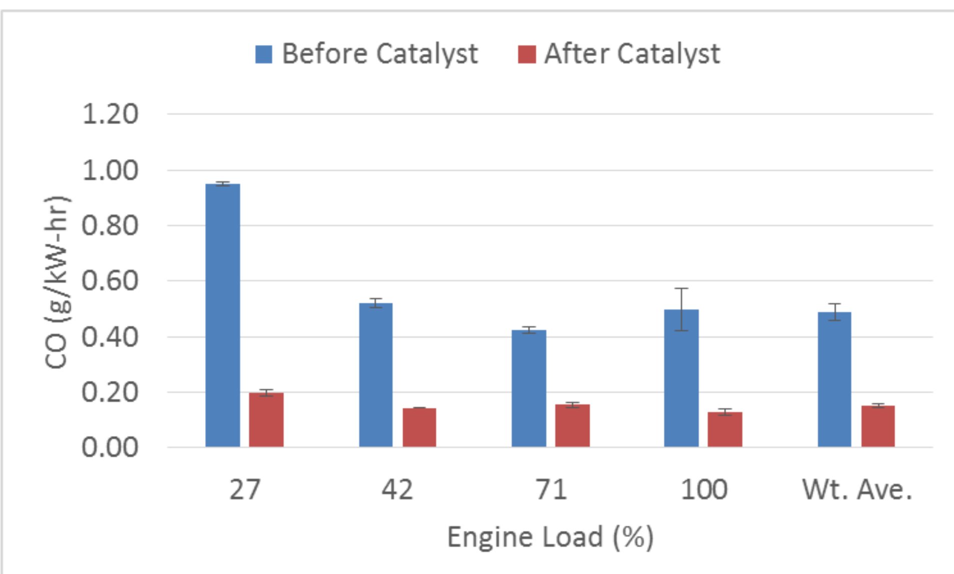

Figure 4-6: Average CO Emission Factors for each test mode and Overall Weighted Emission Factor

4.3.1 Particulate Matter $PM_{2.5}$ Mass Emissions

In addition to the gaseous emissions, the test program measured emissions of the PM2.5 mass and PM2.5 emissions fractionated into elemental and organic carbon. Total PM2.5 mass emissions are presented in g/kW-hr for all the test modes is plotted in Figure 4-7. The DPF catalyst reduced the PM2.5 emissions by97.3%.

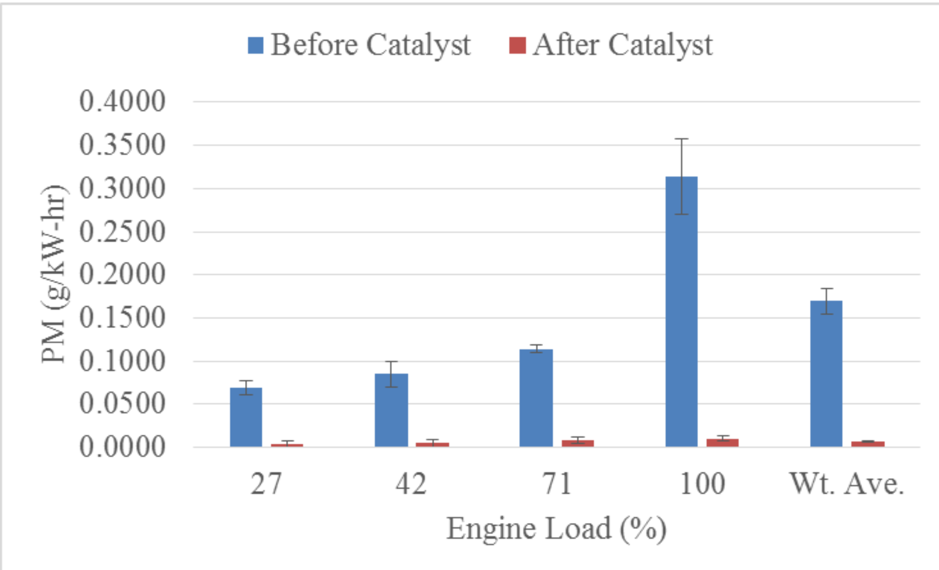

Figure 4-7: PM2.5 Emission Factors

4.3.2 PM Mass Fractionated into Elemental Carbon (EC) plus Organic Carbon (OC)

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. Figure 4-8 represents EC/OC measurements across all loads for before and after the catalyst. The OC fraction accounts for 85 to 96% of the total PM mass for before the catalyst,, depending on the mode, and for over 99% of the total PM mass for after the catalyst. As described in – "Measuring Gaseous & Particulate Emissions", PM2.5 in the raw exhaust was sampled using a partial dilution system and the PM was collected on filter media. The total and speciated PM2.5 mass emissions and percent reduction in elemental and organic carbon are presented in Appendix C, "Raw Data, Analysis, Analysis Equations, and Calibration Data"

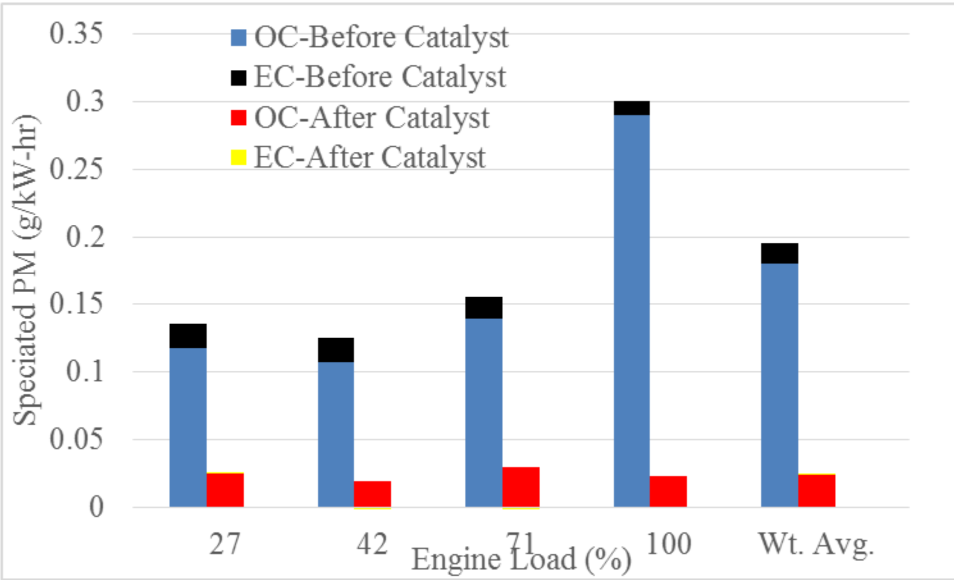

Figure 4-8: PM Mass Fractioned into Elemental & Organic Carbon

4.3.3 Quality Check: Conservation of $PM_{2.5}$ Mass Emissions

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 carbon. To account for hydrogen and oxygen in the organic carbon, the organic carbon is multiplied by a factor of 1.2 (Shah, et. al, 2004). The plot showing the parity and the cumulative mass is provided below as Figure 4-9. In prior work we have observed approximately a 1 to 1 correlation for a trendline forced through the intercept with an R^2 value greater than 0.95. However in those cases there were more data points above 0.15 g/kW-hr than for the present before catalyst case. The after catalyst case has extremely low emissions and therefore greater variability in the data points.

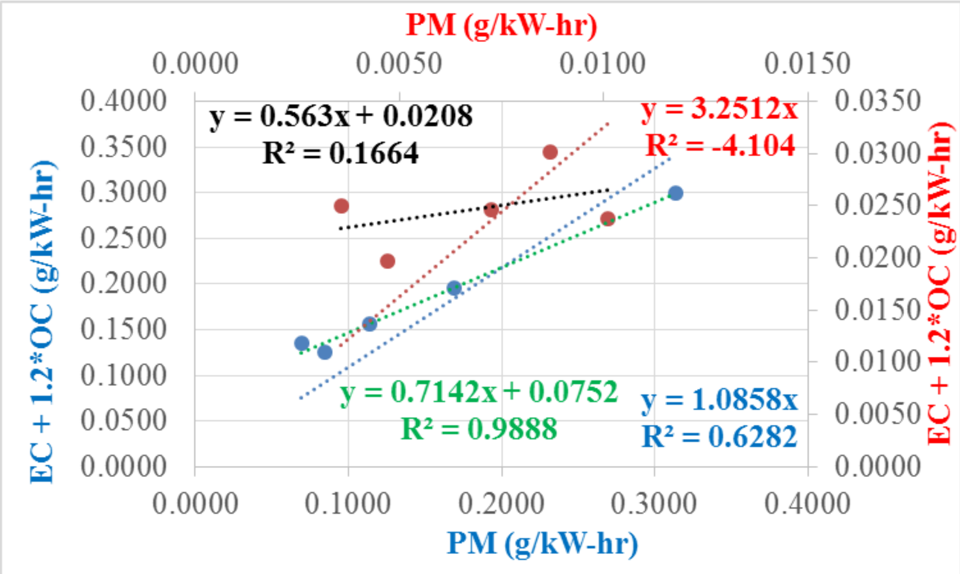

Figure 4-9: Comparison of Mass on Teflon Filter & Cumulative Mass from Quartz Filter

4.3.4 Fuel consumption by Carbon Balance

Since 99+% of the carbon in the fuel is converted to CO_2 the grams of CO_2 can be used to calculate fuel consumption in g/kW-hr by multiplying the grams of CO_2 by the ratio of molecular weight of C to molecular weight of CO_2 and by 100 divided by the % of C in the fuel. The fuel consumption across all loads is shown in Figure 4-10. Fuel consumption depends upon the engine load but is independent of the presence of the catalyst.

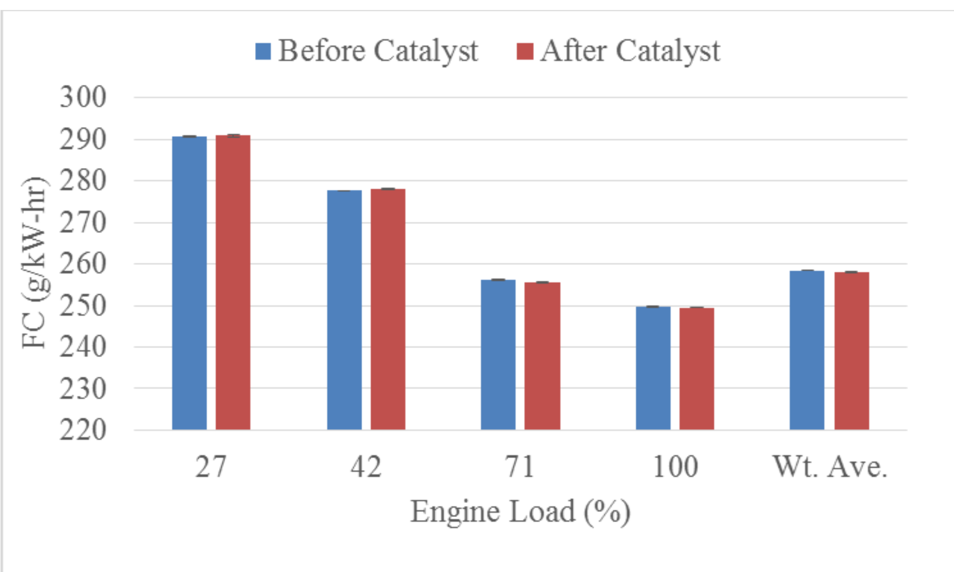

Figure 4-10: Fuel Consumption as a Function of Engine Load

4.4 Summary of Emission Factors

Table 4-2 presents all the measured emission factors by mode and the weighted emission factors and Table 4-3 presents the emission factors for the two regenerations. During the baseline testing an unforced regeneration occurred near the end of the third test of mode 1. It was not known at the time that a regeneration had occurred and the regeneration may not have been complete when the decision was made to change the conditions to mode 2. Therefore the emission factors for the unforced regeneration in Table 4-3 may be underestimated. The THC were not available as the FID flame was out. The forced regeneration was run after the conclusion of the third test of the degreened emissions for mode 4 while maintaining the mode 4 conditions. The PM emission factor is not available as the filter weighed less after the test than before the test.

Table 4-2: Emission Factors by Mode and Weighted Emission Factors

		Emissions (g/kW-hr)										
Mode	Load (kW	NO_x	CO	THC	CO_2	PM	EC	OC	TC	FC	NH_3	H_20
Before Catalyst												
4	52	**6.19**	0.95	0.44	922	**0.0692**	0.0175	0.1180	0.1355	291	NM	NM
3	78	**5.92**	0.52	0.33	880	**0.0848**	0.0183	0.1071	0.1255	278	NM	NM
2	133	**7.65**	0.42	0.36	812	**0.1142**	0.0166	0.1391	0.1557	256	NM	NM
1	188	**10.81**	0.50	0.39	792	**0.3135**	0.0107	0.2894	0.3002	250	NM	NM
Weighted		**8.35**	0.49	0.37	819	**0.1692**	0.0150	0.1805	0.1955	258	NM	NM
After Catalyst												
4	51	**4.48**	0.20	0.31	922	**0.0036**	0.0001	0.0249	0.0250	291	1.66	1417
3	79	**1.35**	0.14	0.52	882	**0.0047**	0.0000	0.0197	0.0197	278	0.50	1610
2	135	**0.24**	0.16	0.50	811	**0.0087**	0.0000	0.0302	0.0302	256	0.09	1100
1	190	**0.40**	0.13	0.21	791	**0.0101**	0.0000	0.0237	0.0237	249	0.15	977
Weighted		**0.65**	0.15	0.39	818	**0.0072**	0.0000	0.0246	0.0246	258	0.24	1126
NM = Not Measured												

Table 4-3: Emission Factors During Regenerations

Condition	Mode	NOx	CO	THC	CO2	PM	EC	OC	FC	NH3	Water
Forced	4	4.61	0.43	0.59	1683	NA	0.0007	0.0421	531	1.71	1991
Unforced	1	8.13	0.46	NM	994	0.4715	0.0103	0.4605	313	NM	NM
	Avg	6.37	0.44	0.59	1338	0.4715	0.0055	0.2513	422	1.71	1991

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A Appendix A: Test Cycles and Fuels for Different Engine Applications

A.1 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 (ISO 8178-4, 2007) 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 8178-4.

Table A-1: Definitions Used Throughout ISO 8178-4

Test cycle	A sequence of engine test modes each with defined speed, torque and weighting factor, where the weighting factors only apply if the test results are expressed in g/kWh.
Preconditioning the engine	1) Warming the engine at the rated power to stabilize the engine parameters and protect the 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 8178-4 clause 6.

A.2 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 (ISO 8528-5, 2005).

A.3 Modes and Weighting Factors for Test Cycles

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.

A.4 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.

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

B-Type mode number	1	2	3	4	5	6	7	8	9	10	11
Torque	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Off-road vehicles											
Cycle C1	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15
Cycle C2				0,06		0,02	0,05	0,32	0,3	0,1	0,15
Constant speed											
Cycle D1	0,3	0,5	0,2								
Cycle D2	0,05	0,25	0,3	0,3	0,1						
Locomotives											
Cycle F	0,25							0,15			0,6
Utility, lawn and garden											
Cycle G1						0,09	0,2	0,29	0,3	0,07	0,05
Cycle G2	0,09	0,2	0,29	0,3	0,07						0,05
Cycle G3	0,9										0,1
Marine application											
Cycle E1	0,08	0,11					0,19	0,32			0,3
Cycle E2	0,2	0,5	0,15	0,15							

Marine application propeller law					
Mode number E3	**1**	**2**	**3**	**4**	
Power (%)	100	75	50	25	
Speed (%)	100	91	80	63	
Weighting factor	0,2	0,5	0,15	0,15	
Mode number E4	**1**	**2**	**3**	**4**	**5**
Speed (%)	100	80	60	40	Idle
Torque (%)	100	71,6	46,5	25,3	0
Weighting factor	0,06	0,14	0,15	0,25	0,4
Mode number E5	**1**	**2**	**3**	**4**	**5**
Power (%)	100	75	50	25	0
Speed (%)	100	91	80	63	Idle
Weighting factor	0,08	0,13	0,17	0,32	0,3

Table A-3: Fuel Selection Criteria

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

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

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

B Appendix B: Measuring Gaseous & Particulate Emissions

B.1 Scope

ISO 8178-1 (ISO 8178-1,2006) and ISO 8178-2 (ISO 8178-2, 2008) specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in IS0 8178-4 (ISO 8178-4, 2007). 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 (MARPOL 73/78, 1997), 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.

B.2 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**.

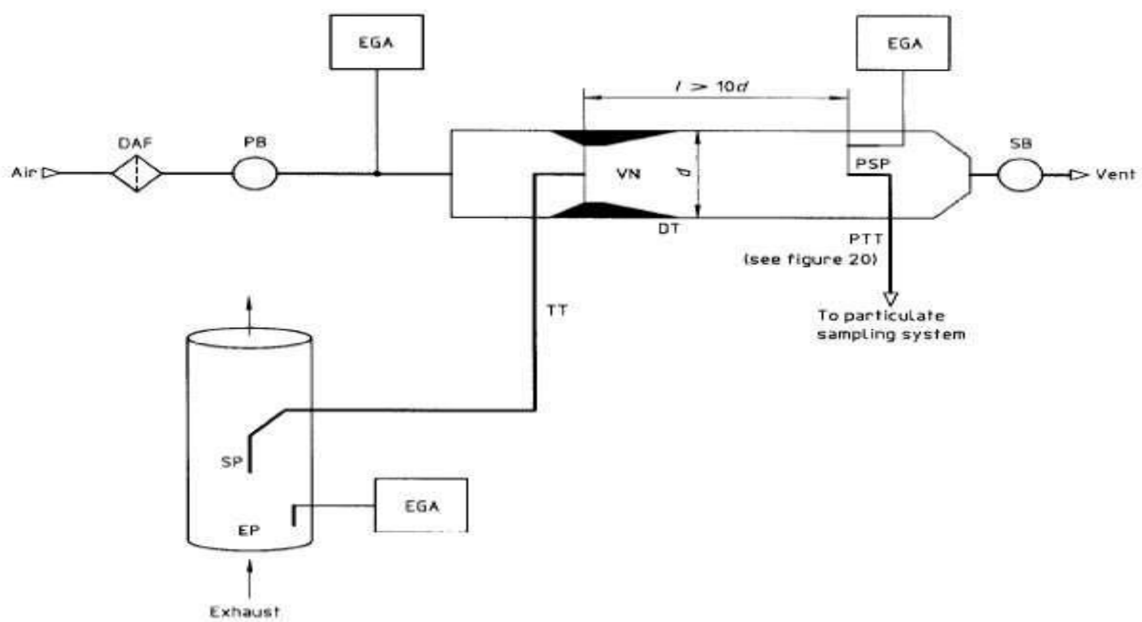

Figure B-1: Partial Flow Dilution System with Single Venturi, Concentration Measurement and Fractional Sampling

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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 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

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

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; Equal to/greater than probe diameter & < 25 mm diameter; TTs insulated. For TTs > 1m, heat wall temperature to a minimum of 250°C or set for < 5% thermophoretic losses of PM.	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; 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

B.3 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%. In the current study, for the before catalyst results the values were within 6 to 12% depending on the mode. For the after catalyst results, where NO_x emissions are very low, the dilution ratios were within 4 to 57%. The CO_2 dilution ratio was used to convert the measured pollutant concentrations to the concentration in the raw exhaust. According to ISO, dilution air is set to obtain a maximum filter face temperature of <52°C and the dilution ratio shall be > 4.The minimum dilution ratio was 4.14 and the maximum dilution ratio was 5.70.

B.4 Dilution System Integrity Check

ISO describes the necessity of measuring all flows accurately with traceable methods and provides a path and metric to quantifying the leakage in the analyzer circuits. 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.

B.5 Measuring the Gaseous Emissions: CO, CO2, HC, NOx, O2, SO2

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.

B.5.1 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.

B.5.2 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 (Kelly, et. al, 1999) under the U.S. EPA Environmental Technology Verification (ETV) 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

. Note that the Horiba instrument measures sulfur oxides (SO_2); however, 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.

Table B-2: Detector Method and Concentration Ranges for Horiba PG-250

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%

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 **Error! Reference source not found.**. The PG-250 meets the analyzer specifications in ISO 8178-1 Section 7.4 for repeatability, accuracy, noise, span drift, zero drift and gas drying.

Table B-3: Quality Specifications for the Horiba PG-250

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

B.7 *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-4.

Table B-4: Measuring Particulate by ISO and CE-CERT Methods

	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

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.

B.7.1 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 streams leaving the dilution tunnel; the major flow vented outside the tunnel and the minor flow directed to a cyclone separator, sized to remove particles >2.5um. The line leaving the cyclone separator is split into two lines; each line has a 47 mm 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.

B.7.2 *Measuring Non-Regulated Particulate Emissions*

B.7.2.1 *Measuring the Elemental and Organic Carbon Emissions*

CE-CERT collected simultaneous Teflo™ 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.

B.7.2.2 Measuring Real-Time Particulate Matter (PM) Emissions-DustTrak

In addition to the filter-based PM mass measurements, CE-CERT takes continuous readings with a Nephelometer (TSI DustTrak 8520, **Figure 0-1**) 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 0-1: Picture of TSI DustTrak

B.8 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 are 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.

C Appendix C: Ammonia Slip and Water Measurement with Tunable Diode Laser

C.1 Introduction

With the broad based deployment of post combustion NO_x control technologies, continuous measurement of associated ammonia slip levels has gained increased importance with respect to potential balance of SCR impacts, as well as applications for direct process control.

The current project used a tunable diode laser specifically tuned to measure both NH_3 and H_2O to report dry values of NH_3 slip.

The system used a one-meter heated sample cell, heated to the exact exhaust gas temperature to minimize thermal perturbations and integrity of the sample. Heated lines were used to transport the sample gas from the exhaust line to the quartz line sample cell.

The sample cell optics were configured for dual pass operation.

The objective is to quantify to sub-ppmV levels continuous ammonia slip measurements from the tugboat engine having a DPF/SCR emission control system.

C.2 Technology Description

C.2.1 Tunable Diode Lasers

Tunable Diode Lasers are fabricated on a tiny piece of semiconductor material typically only 0.5 mm square. The diode lasers themselves produce laser light at specific wavelengths that can be continuously tuned over narrow wavelength intervals. Adjusting the device temperature enables tuning of the laser output, and even finer tuning can be achieved by adjustment of the laser operating current. The development of diode lasers themselves has been rapid over the past decade, especially for application in communications transmission. Diode lasers with outputs ranging from visible to mid-infrared wavelengths are commercially available at competitive pricing levels for use in analytical instrumentation.

Laser-based spectroscopic techniques to detect trace gases sensitively and selectively in real time in the infrared spectral region have been the focus of considerable research and instrumentation development over the last few years. The principal optical gas sensor technologies are based on absorption spectroscopy of fundamental bands in the 3–25-µm spectral region and near-IR vibrational overtone and combination bands from 1–3 µm. Common radiation sources include continuous wave diode lasers and telecommunication distributed-feedback (DFB) diode lasers. These GaAs-based, diode lasers are ideally suited for overtone spectroscopy of molecules with chemical bonds such as C-H, O-H, and N-H in the near-IR region ~0.78–2.5 µm. Figure C-1 shows the dynamics of a NH_3 molecule which has a rich spectrum in the near-IR region. These spectral absorption features are from the vibrational and rotational characteristics of this molecule as it absorbs energy of a specific wavelength. In just the spectral range from 1450 to 1560 nm ~;6400–6900 cm^{-1}, Lundsberg-Nielsen et al. identified 1710 ammonia absorption lines and assigned 381 of them to rotational–vibrational transitions in the combination band n1 to n3 and the overtone band at 2n3. Webber et al. examined these lines for interferences, specifically moisture, and pointed out the best lines for monitoring purposes with near IR ammonia measurements are the lines at 1512.3, 1514.1 and 1531.7 nm. At these wavelengths, low-noise In GaAs detectors are available that operate with quantum efficiencies close to unity and require little cooling (ambient temperature levels) and minimal temperature control. Overtone spectroscopy exhibits absorption line strengths that are typically one to two orders of magnitude weaker than those of the fundamental vibrations in the mid-IR. To obtain the required sensitivity in the near IR, longer absorption path lengths and optimal balancing of laser noise are required.

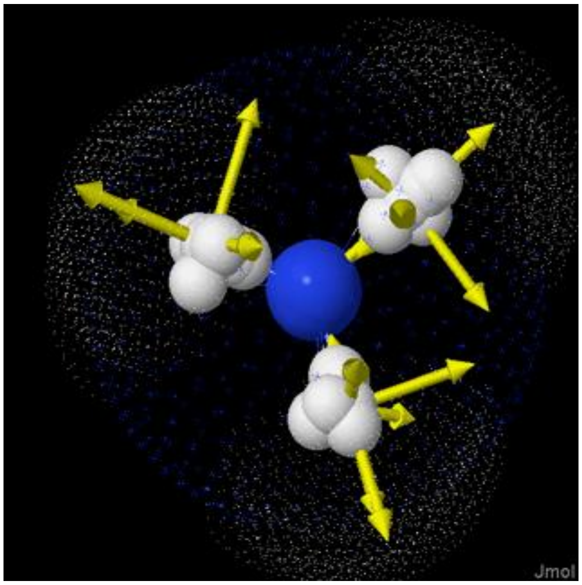

Figure C-1: Diagram of an NH3 Molecule Showing Degrees of Freedom of Excitation Which Correlate to Energy Absorptions at Specific Wavelengths

C.2.2 Tunable Diode Laser Spectroscopy

TDLs offer significant advantages when applied to spectroscopic systems. As a light source, they provide the highest available power density in a spectrally narrow window. The fundamental, vibrational absorption bands in the infrared region contain a number of discrete rotational lines, the width and shape depending on temperature and pressure. For some gases the lines are well separated; for others, pressure broadening results in overlapping lines. Larger molecules often possess so many closely spaced lines that thermal or Doppler broadening is sufficient to cause line overlapping. This inhibits most conventional forms of infrared spectroscopy. However, TDLs have spectral resolutions smaller than Doppler line widths and advantage can be taken of this inherent property. The fraction of light intensity transmitted through a gas is given by the Beer-Lambert law:

$$P/P_0 = \exp(-\sigma(\psi)NL) \tag{C-1}$$

Where P and P_o are the transmitted and incident laser power, L is the absorption path length in centimeters and N is the concentration of the absorbing molecules in number of molecules per cubic centimeter. $\sigma(\psi)$ is the wavenumber dependent absorption cross section in square centimeters per molecule which is typically a function of temperature.

C.3 Instrument Description

Unisearch has manufactured and marketed worldwide the LasIR^{TM} line of gas analyzers based on near-infrared tunable diode laser spectroscopy since 1995 when they pioneered the NIR tunable diode laser measurement technique for HF measurements in the aluminum industry. They introduced their next generation S-Series of gas analyzers (Figure C-2) 6 years later using the direct absorption technique. Their instrumentation has been found to be the best available technology (BAT) for NH_3 measurements by The Electric Power Research Institute (EPRI).

The Unisearch S Series LasIR consists of a control unit containing the laser, central power supply, and signal processing electronics, plus multiple sets of remote optics depending on application. In the "SM series, the light is optically multiplexed so that it can supply 100% of the available power sequentially to each location. The analyzer is typically housed in a control or instrument room and coupled to the remote optics by means of fibre optical cables for transmitting the laser light and co-axial cables for signal return. All signal processing, data reporting, and data storage functionality is incorporated in the analyzer, with an external computer for set-up and supplementary external data logging. Direct absorption signal processing, where quantification is based on Beer's law, as in the current analyzers, is a direct measurement of the absorption feature.

Unisearch has also developed a computer controlled gain adjust feature. This feature is necessary to compensate for changes in power specifically in environments where dust loadings can change rapidly and over a large range. The gain adjust feature increases the dynamic range of the instrument and reduces noise by keeping the amplified signal within the optimum range.

In certain circumstances, it is desirable to measure ammonia concentrations at temperatures above ambient. From Beer's law, the strength of the absorbance depends on the number of absorbing species. The LasIR is normally calibrated assuming T_{cal} = 298 K (25 °C) and P_{cal} = 1013 mbar (1 atm). Mixing ratios reported in ppm, ppb, or % by volume are independent of temperature and pressure, as they are simply a ratio and do not change as the gas expands or contracts. The absolute absorbance responds to the actual number density of absorbing molecules, which does change with T or P. Thus to obtain an accurate mixing ratio at temperatures or pressures other than T_{cal}, P_{cal} , it is necessary to apply a correction factor based on the ideal gas law (PV = nRT). These corrections are calculated automatically by the LasIR analyzer if the process temperature and pressure are known. This may be achieved either by entering fixed values for process temperature and pressure upon initial set-up, or by connecting an external sensor which communicates with the LasIR via a 0-10 V analog input.

The strength of a given absorption feature can vary with temperature. This can be corrected for if the relationship is known. The peak height at calibration temperature (usually 298 K) is defined to be one. Unisearch has measured the appropriate correction factors at different temperatures. Automatic correction for this effect is included in the system software.

The laser contained in this analyzer is tuned thermally across the spectral feature selected to monitor the gas. It is mounted on a thermoelectric cooler (Laser Head Assembly) that monitors and controls the coarse temperature of the laser. Fine-tuning is achieved by a cyclic current ramp that facilitates repetitive scanning of a given laser frequency range. Multi-scan averaging improves the sensitivity of the system. The laser diode is mounted on a thermoelectric cooler to maintain a stable temperature environment. The laser is coupled to a fiber-optic cable, which is in turn coupled to a fiber-optic beam splitter where the beam is divided into equal outputs in the ‘Multiplexer’ mode of operation.

Figure C-2: The front panel of an eight channel multiplexed S-Series LasIR

The outputs using an optical multiplexer from the fiber-optic beam splitter are sent to the fiber outputs of the analyzer where they provide the laser emission for the signal measurements for each of the measurement targets. One output from the beam splitter provides the laser emission for the reference channel. The laser emission on the reference channel passes through a small cell (Reference Cell) containing a high concentration of the target gas that is used to lock the laser wavelength onto the absorption feature and also serves as a secondary calibration standard.

For these measurements we propose a dual pass system, (refer to Figure C-3) with a transmitter/receiving assembly on one side and a retro-reflector on the other side. This monostatic setup effectively doubles the optical path length and yields double the sensitivity of the measurements undertaken. The optics will be mounted on the sample cell.

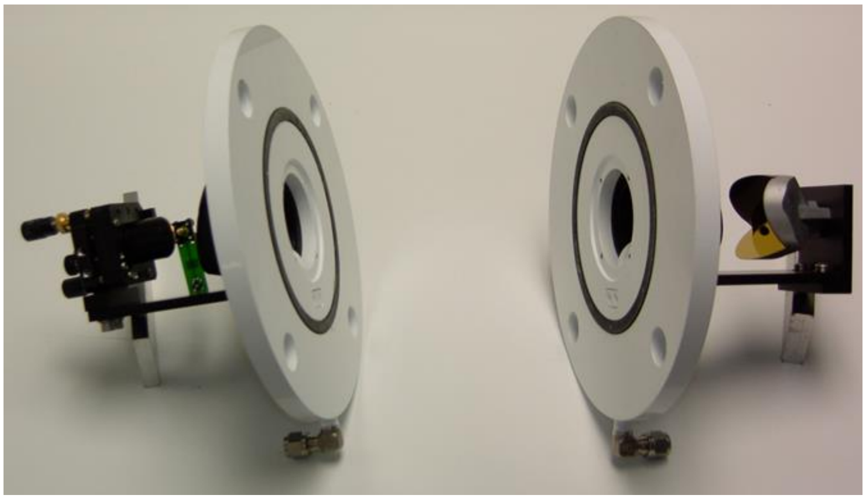

Figure C-3: Optics with a transmitter/receiving assembly on one side and a retro-reflector on the other side.

The optical heads are totally passive and only require the fiber optic and coaxial cable hookup.

C.4 System Installation

The system installation will use an extractive heated one meter sample cell.

C.4.1 Sample Cell

The cell is 1.0 meters long and has an ID of 5.0 cm. This sample cell is typical of those commonly used to facilitate flue gas TDL measurements for NH_3. Each end of the sample cell is equipped with 4" standard flanges; thus the operational path length of the cell is 1 meter but with dual pass optics the path length will be 2 meters.

Specifications

- Material: The sample cell is made of 314 electro-polished stainless steel and is quartz lined
- Pressure: The sample cell is maintained at atmospheric pressure
- Path length: 1.00 m for single pass optics, 2.00 m for dual pass optics
- Temperature Range: 300K-700K
- Uncertainties:

Pressure - .01 atm

Path length .025 m

Temperature +/- 5C

Refer to Figure C-4 which shows the sample cell which has a radiative heater and white insulation. It is mounted on a rigid assembly and is easily transportable for many point monitoring.

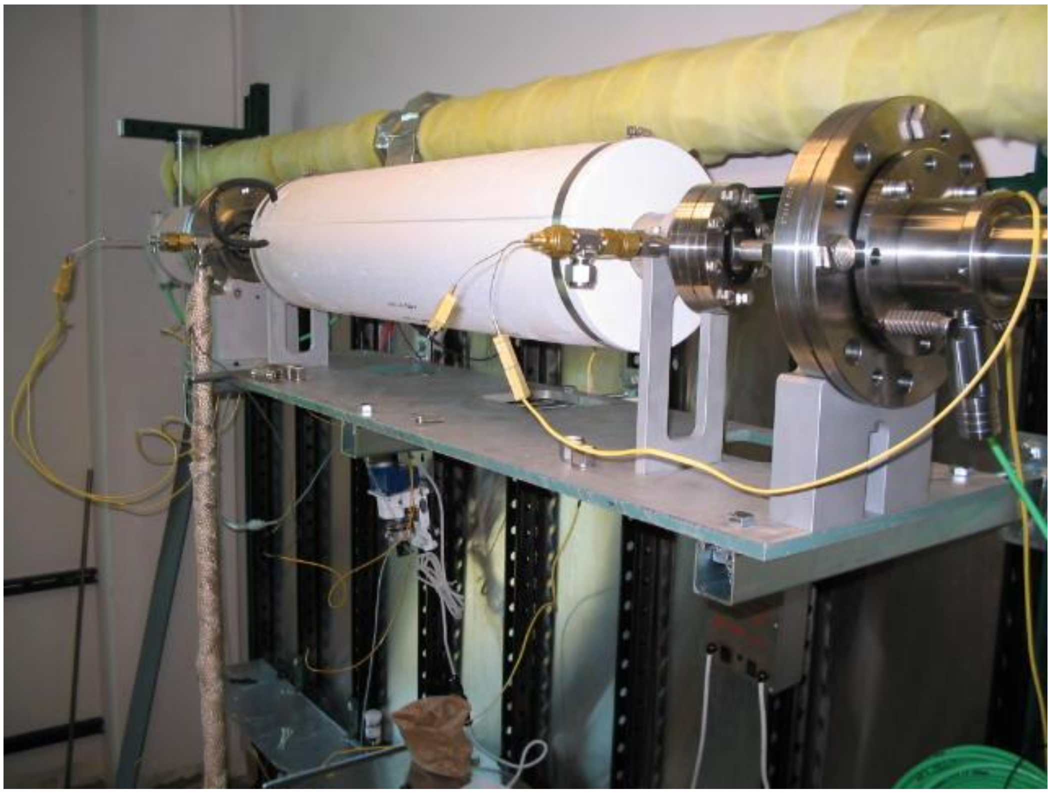

Figure C-4: Sample Cell with light path flanges, shows gas ports, radiative heating assembly and thermocouple locations, also the radiative heater encircling the sample tube.

C.4.2 Temperature Control System

The sample cell is a 1.0 meter by 2.50 inch outside diameter stainless steel tube that can be heated to maintain a desired gas temperature up to 700º F within the cell path. A single radiative heater was custom ordered and fitted over the cell. The heater comes with its own insulation.

The heater operates on 120 VAC and can deliver over 25 watt/inch^2 to the apparatus.

Temperature in the cell is regulated by thermocouple feedback to a PID temperature controller coupled to solid-state relays (SSR) as shown in Figure C-5**.**

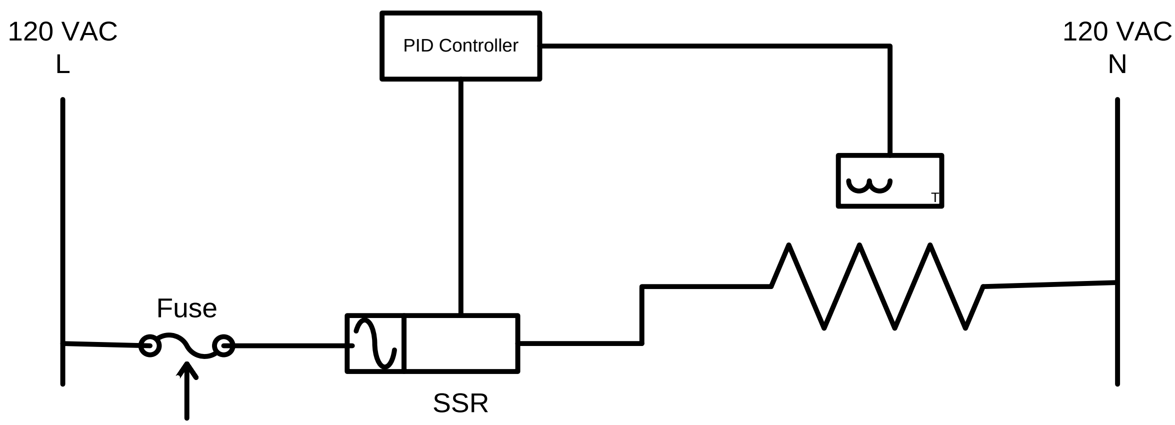

Figure C-5: Cell Temperature Control System Schematic

C.4.3 System Temperature Measurements

Type K Thermocouples (TCs) are used for all temperature measurements in the system. All TCs are 0.0625 inch diameter, ungrounded junction in a stainless steel sheath and have a response time of approximately 0.25 seconds.

Standard wire type K thermocouples have a range from –200º C to 1250º C with an accuracy of ±0.75% or ±2.2º C (whichever is greater) above 0º C. Type K extension wire has an accuracy of ±2.2º C up to 277º C and ±0.75% above 277º C.

The temperature controllers used in the system are from Omega Engineering. These controllers have an input accuracy of ± 0.5º C and have cold-junction compensation with temperature stability of ±0.05º C.

An error analysis [Eq. 4-2] shows an overall system accuracy for temperature measurement of ± 3.15º C up to 277º C and ± 3.27º C at 315º C.

$$Accy_{Total} = \sqrt{Accy_{TC} + Accy_{Ext.} + Accy_{CNi} + Stby_{CJC}} \quad \text{(C-2)}$$

C.5 Field Verification of Accuracy

An in-line audit module (Unisearch Model: LAS-AM-NH_3) will be used on the project to conduct on-site verification of calibration. The audit module was designed to allow the user to check the sensitivity of the analyzer without the need for calibration gas cylinders and flowing gas streams. The audit module concentration was warranted to be within +/- 5% of the stated value for a period of at least one year from date of shipment. The cell was expected to be stable for a minimum of five years for ammonia.

As shown in Figure C-6, the audit module has two FC/APC ports on the front panel. In order to perform an in-line audit of the system the laser beam was directed through both the audit module and the measurement path in series. The ammonia concentration measured on the monitor display represents both the ammonia concentration in the measurement path plus the ammonia in the audit cell. Thus, the audit module introduces an ammonia 'spike' to the measurement path, which can then be compared against a known response based on measurement and audit cell temperature, pressure, measurement path length, and ammonia concentration within the audit cell.

Figure C-6: Audit cell Linked in Series with LasIR Ammonia Monitor

The specification for the audit cell used in this example was 125 ppmV-m at 660°F (350°C) at 0.95 atm (965 mbar). To determine the equivalent concentration of the gas in the audit cell for this application it is necessary to correct for the following parameters:

- Measurement path, L_p in meters (5 meters)
- Sample gas temperature was 730° F, T_p in Kelvin (387.8° C ; 661.1 K)
- Sample gas pressure, P_p in mbar (960 mbar)
- Audit cell temperature, T_a in Kelvin (350° C ; 623.3 K)
- Audit cell pressure, P_a in mbar (965 mbar)

An absorption line-strength factor 'F' must also be obtained from the target gas temperature-factor plot, and represents the difference in the molecular absorption from an ammonia molecule at 660° F (350° C) compared to one at 730° F (387.8° C), which was approximately 1.11. In brief, this value indicates that an ammonia molecule will absorb 1.11 times greater energy at the lower temperature.

An example is given below from data taken for a similar type project.

For this project, with a stated ammonia concentration of [Y] of 125 ppmv at 350° C and 965 mbar for a one meter path length (L_a), the audit cell equivalent mixing ratio [X] for the gas conditions in the measurement path would be:

[X] = [Y] x [(Tp)/(Ta)] x [(Pa)/(Pp)] x (F) x [(La/Lp)]

[X] = 125 x [(661.1 K)/(623.3 K)] x [(965 mbar)/(960 mbar)] x (1.11) x [(1 m)/(5 m)]

[X] = 29.6 ppmv

The ammonia concentration value displayed on the ammonia monitor with the audit cell inserted in series with the measurement path will then be the sum of the concentration of the gas in the flue gas stream plus the audit cell value, corrected to the same temperature, pressure, and path length. Thus, if the flue gas ammonia concentration was 1 ppmv, the total ammonia concentration displayed with the audit cell inserted would be 30.6 ppmv.

Audits were conducted on January 25th with a signal to noise of about 3 to 1 (Figure C-7), which shows the green (signal) versus blue (noise) horizontal bar graph.

A background was taken prior to insertion of the audit cell (Figure C-7) with background subtraction used to correct resultant ammonia slip readings with measured ammonia slip values of 0.40 ppm. Also note in Figure 5-2 that the background varied from -0.13 to a high of 0.82. These are actually real measurements of the ammonia slip and when averaged over the previous five hours of sampling yielded a value of 0.49 ppm.

The insertion of the audit cell showed high confidence in the calibration of the system, as it went to a value of 29.43 ppm (Figure C-7), which means the audit cell added 29.03 ppm of NH_3. This is well within the 5% stated accuracy value of the audit cell, which was calculated to add 29.6 ppm of NH_3.

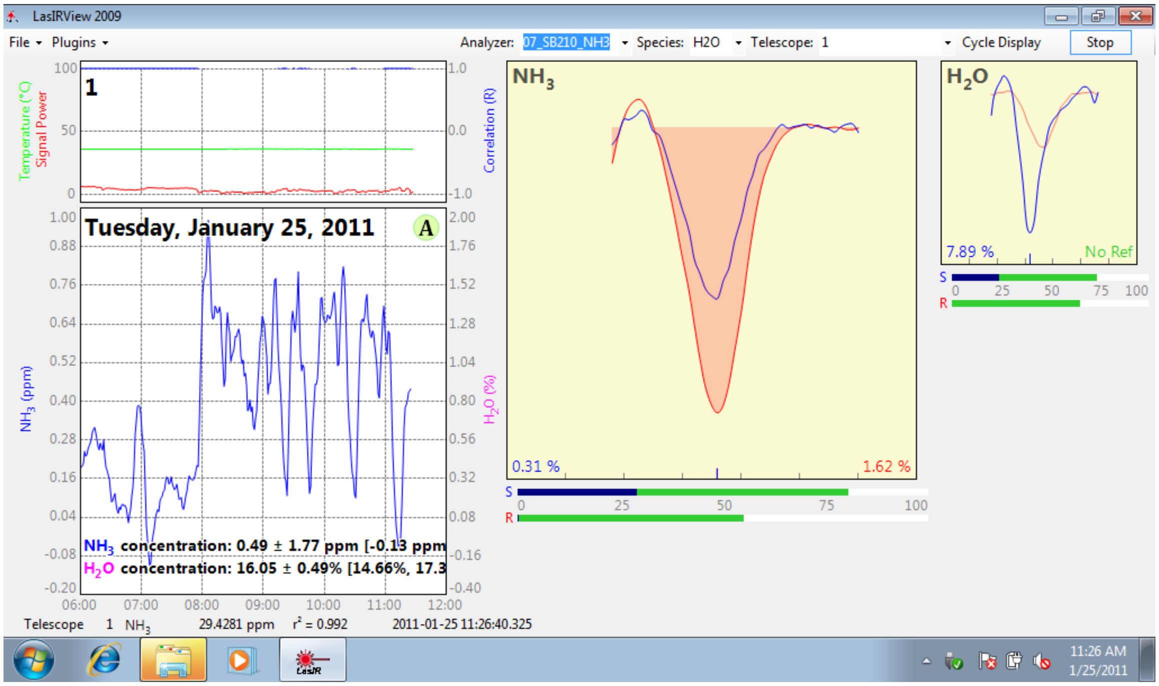

Figure C-7: Audit Cell Verification of Ammonia Monitor Response

C.6 Specifications

Table C-1: Pre, Post, and Average Calibration for NOx, CO, and CO2

Parameter	**Results**	**Notes**
Percent Difference with Respect to Moisture	2.61 %	○ Moisture effect at 16%-m
Percent Difference with Respect to Temperature	2.931%	○ Range 77 °F -752 °F
Maximum Percent Difference	11.90%	○ @ 752°F at 2.5 ppmv-m
Minimum Percent Difference	0.02%	○ @ 392°F at 25.0 ppmv-m
Linearity	○ Regression slope y = 1.0242x-.3256 ○ R^2=0.991	○ Calculated over entire dynamic range
Precision	2.35%	○ Average precision for all temperature ranges
Zero Drift	2.23%	○ Average zero drift for all temperature ranges
2-Meter OPL Minimum Detection Limit	○ @ 77°F (20°C) 0.41 ppmv/m ○ @ 392°F (200°C) 0.63 ppmv/m ○ @ 572°F (300°C) 0.74 ppmv/m ○ @ 752°F (400°C) 0.83 ppmv/m	○ Averaged for 5 tests ○ Averaged for 3 tests ○ Averaged for 3 tests ○ Averaged for 3 tests

At 700 °F we will be able to measure better than 0.50 ppmV with a 15-second integration time at levels up to 10% moisture.

We will also report moisture to within 0.1% concurrently.

D Appendix D: Raw Data, Analysis, Analysis Equations, and Calibration Data

Table D-1: Gas Phase raw data and Calculated Emissions

									Dilute Concentration			Raw Concentration				Dil. Ratio			Emissions (g/hr)				Emissions (g/kWhr)				Fuel Use	
Date	Loc.	Specified Test Mode		Actual Test Conditions					NO_x	CO	CO_2	NO_x	CO	CO_2	THC	NO_x	CO_2	Exh. Flow	NO_x	CO	THC	CO_2	NO_x	CO	THC	CO_2	(g/hr)	(g/kWhr)
		Load %	Speed %	RPM	Fuel Use (gal/hr) #	HP	(kW)	Load %	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(%)	(ppm)			(scfm)										
4/9/2014	BC	100	100	1723	14.86	252	188	100.0	99.0	5.11	0.62	564	29.11	3.56	49.7	5.06	5.70	1312	2311	110	73	149029	12.3	0.58	0.39	792	46992	250
4/9/2014	BC	100	100	1723	14.86	252	188	100.0	91.7	4.57	0.68	522	26.02	3.90	FO	5.06	5.70	1193	1946	89	FO	148920	10.3	0.47	FO	792	46958	250
4/9/2014	BC	100	100	1723	14.86	252	188	100.0	92.6	4.53	0.73	527	25.80	4.15	FO	5.06	5.70	1119	1842	83	FO	148852	9.8	0.44	FO	791	46936	250
4/9/2014	BC	75	91	1586	10.80	179	133	70.8	81.4	4.86	0.82	376	22.48	3.80	52.6	5.39	4.63	891	1050	58	52	108225	7.9	0.43	0.39	812	34126	256
4/9/2014	BC	75	91	1586	10.80	179	133	70.8	77.3	4.53	0.81	358	20.97	3.75	46.9	5.39	4.63	903	1011	55	47	108237	7.6	0.41	0.35	812	34129	256
4/9/2014	BC	75	91	1586	10.80	179	133	70.8	72.7	4.52	0.78	336	20.92	3.60	42.9	5.39	4.63	943	994	57	45	108273	7.5	0.43	0.34	813	34141	256
4/9/2014	BC	50	80	1398	6.86	105	78	41.6	48.9	4.74	0.70	241	23.34	3.43	37.3	6.33	4.93	630	478	42	26	68855	6.1	0.54	0.33	881	21712	278
4/9/2014	BC	50	80	1398	6.86	105	78	41.6	47.5	4.60	0.71	234	22.66	3.47	37.5	6.33	4.93	621	458	40	26	68847	5.9	0.52	0.33	881	21709	278
4/9/2014	BC	50	80	1398	6.86	105	78	41.6	47.7	4.58	0.71	235	22.56	3.52	36.5	6.33	4.93	612	453	40	25	68839	5.8	0.51	0.32	880	21707	278
4/9/2014	BC	25	63	1106	4.72	69	52	27.4	40.8	6.79	0.59	194	32.32	2.83	37.8	6.06	4.76	530	325	49	22	47483	6.3	0.96	0.43	922	14973	291
4/9/2014	BC	25	63	1106	4.72	69	52	27.4	38.1	6.47	0.57	181	30.81	2.72	37.5	6.06	4.76	553	317	49	23	47505	6.2	0.95	0.45	922	14979	291
4/9/2014	BC	25	63	1106	4.72	69	52	27.4	37.7	6.39	0.57	180	30.44	2.71	37.0	6.06	4.76	554	315	49	23	47506	6.1	0.94	0.44	922	14980	291
4/9/2014	BCR	100	100	1723	18.76	252	188	100.0	264.6	16.1	3.07	1507	91.91	17.47	FO	5.06	5.70	326	1529	86	FO	186929	8.1	0.46	FO	994	58943	313
4/9/2014	AC	100	100	1726	14.97	254	190	100.0	5.10	2.19	1.08	21.1	9.08	4.47	22.9	15.1	4.14	1043	80	27	27	149942	0.42	0.14	0.14	791	47280	249
4/9/2014	AC	100	100	1726	14.97	254	190	100.0	4.33	1.83	1.04	17.9	7.58	4.31	30.4	15.1	4.14	1083	72	23	37	149980	0.38	0.12	0.19	791	47292	249
4/9/2014	AC	100	100	1726	14.97	254	190	100.0	4.48	1.81	1.00	18.6	7.48	4.16	43.1	15.1	4.14	1124	77	24	54	150017	0.41	0.12	0.28	791	47304	250
4/9/2014	AC	75	91	1592	10.94	181	135	71.4	1.94	2.12	0.83	9.6	10.43	4.07	73.0	10.4	4.93	841	34	22	68	109662	0.25	0.16	0.51	810	34579	256
4/9/2014	AC	75	91	1592	10.94	181	135	71.4	1.63	1.81	0.78	8.0	8.91	3.82	71.3	10.4	4.93	896	32	21	71	109713	0.24	0.16	0.53	811	34595	256
4/9/2014	AC	75	91	1592	10.94	181	135	71.4	1.51	1.67	0.79	7.5	8.22	3.88	63.2	10.4	4.93	884	30	20	62	109702	0.22	0.15	0.46	811	34591	256
4/9/2014	AC	50	80	1402	6.89	105	79	41.4	1.49	0.39	0.69	6.5	1.70	3.00	56.3	3.01	4.38	726	23	7	46	69235	0.29	0.09	0.58	881	21831	278
4/9/2014	AC	50	80	1402	6.89	105	79	41.4	10.1	1.02	0.64	44.1	4.48	2.82	50.4	3.01	4.38	775	115	12	44	69280	1.46	0.15	0.55	882	21846	278
4/9/2014	AC	50	80	1402	6.89	105	79	41.4	16.0	1.39	0.63	69.9	6.09	2.76	37.5	3.01	4.38	794	181	15	33	69297	2.30	0.19	0.42	882	21851	278
4/9/2014	AC	25	63	1102	4.69	69	51	27.0	26.1	1.47	0.58	122	6.87	2.71	31.8	5.08	4.68	551	215	11	19	47211	4.20	0.21	0.38	923	14887	291
4/9/2014	AC	25	63	1102	4.69	69	51	27.0	30.6	1.38	0.63	143	6.48	2.93	26.1	5.08	4.68	508	231	10	15	47172	4.52	0.19	0.29	922	14874	291
4/9/2014	AC	25	63	1102	4.69	69	51	27.0	33.3	1.50	0.65	156	7.04	3.04	23.5	5.08	4.68	488	241	10	13	47154	4.72	0.19	0.25	922	14869	291
4/9/2014	ACR	25	63	1102	8.59	69	51	27.0	24.3	3.07	0.89	114	14.39	4.14	42.1	5.08	4.68	648	236	22	30	86104	4.61	0.43	0.59	1683	27150	531

BC = Before Catalyst; BCR = Before Catalyst Regeneration (Unforced near end of third run of 100% load, not recognized at time of testing); AC = After Catalsyt; ACR = After Catalyst Regeneration (Forced after conclusion of third run of 25% load); FO = Flame out of FID

For regeneration add 3.9 gal/hr from the regeneration burner

Gaseous emissions for third run of BC 100% taken from 3 minutes before the beginning of the regeneration instead of for last 3 minutes of the run.

Table D-2: Particulate Matter raw data and Calculated Emissions

										Teflon	Quatrz Mass		
Date	Loc.	Specified Test Mode		Actual Test Conditions					PM CT	Mass	EC	OC	TC
		Load %	Speed %	RPM	Fuel Use (gal/hr)#	HP	(kW)	Load %	min	mg	mg	mg	mg
4/9/2014	BC	100	100	1723	14.86	252	188	100.0	5	0.4227	0.0134	0.3278	0.4068
4/9/2014	BC	100	100	1723	14.86	252	188	100.0	7	0.4938	0.0204	0.4201	0.5245
4/9/2014##	BC	100	100	1723	14.86	252	188	100.0	7	0.4582	0.0169	0.3739	0.4656
4/9/2014	BC	75	91	1586	10.80	179	133	70.8	7	0.2526	0.0360	0.2667	0.3560
4/9/2014	BC	75	91	1586	10.80	179	133	70.8	7	0.2505	0.0321	0.2331	0.3118
4/9/2014	BC	75	91	1586	10.80	179	133	70.8	8	0.2738	0.0456	0.2923	0.3964
4/9/2014	BC	50	80	1398	6.86	105	78	41.6	7	0.1585	0.0336	0.1660	0.2328
4/9/2014	BC	50	80	1398	6.86	105	78	41.6	7	0.1622	0.0350	0.1667	0.2351
4/9/2014	BC	50	80	1398	6.86	105	78	41.6	9	0.1623	0.0362	0.1771	0.2487
4/9/2014	BC	25	63	1106	4.72	69	52	27.4	7	0.0917	0.0244	0.1407	0.1932
4/9/2014	BC	25	63	1106	4.72	69	52	27.4	7	0.1073	0.0248	0.1451	0.1990
4/9/2014	BC	25	63	1106	4.72	69	52	27.4	7	0.0872	0.0224	0.1171	0.1629
4/9/2014	BCR	100	100	1723	18.76	252	188	100.0	4.6	2.2423	0.0476	1.7753	2.1779
4/9/2014	AC	100	100	1726	14.97	254	190	100.0	10	0.0531	0.0000	0.0887	0.1065
4/9/2014	AC	100	100	1726	14.97	254	190	100.0	10	0.0416	0.0000	0.0787	0.0945
4/9/2014	AC	100	100	1726	14.97	254	190	100.0	10	0.0294	0.0000	0.0808	0.0970
4/9/2014	AC	75	91	1592	10.94	181	135	71.4	10	0.0168	0.0000	0.0614	0.0737
4/9/2014	AC	75	91	1592	10.94	181	135	71.4	6	0.0229	0.0000	0.0594	0.0712
4/9/2014	AC	75	91	1592	10.94	181	135	71.4	10	0.0251	0.0000	0.0717	0.0861
4/9/2014	AC	50	80	1402	6.89	105	79	41.4	10.3	0.0238	NS	NS	NS
4/9/2014	AC	50	80	1402	6.89	105	79	41.4	10	0.0081	0.0000	0.0404	0.0485
4/9/2014	AC	50	80	1402	6.89	105	79	41.4	10	0.0014	0.0000	0.0334	0.0401
4/9/2014	AC	25	63	1102	4.69	69	51	27.0	10	0.0044	0.0006	0.0556	0.0672
4/9/2014	AC	25	63	1102	4.69	69	51	27.0	10	0.0173	0.0000	0.0369	0.0443
4/9/2014	AC	25	63	1102	4.69	69	51	27.0	10	0.0009	0.0000	0.0359	0.0431
4/9/2014	ACR	25	63	1102	8.59	69	51	27.0	25.5	-0.023	0.0029	0.1487	0.1814

BC = Before Catalyst; BCR = Before Catalyst, Regeneration (Unforced near end of third run of 100% load, not recognized at time of testing); AC = After Catalsyt; ACR = After Catalyst, Regeneration (Forced after conclusion of third run of 25% load); OC corr = 1.2 (OC) to account for hydrogen and oxygen in organic carbon; TC = EC + OC corr

PMCT = Particulate Matter and EC/OC sampling time

NS = No Sample

For regeneration add 3.9 gal/hr from the regeneration burner

@ Don't know what happened with this sample, assumed TC corr is a reasonable value for PM2.5

The total PM mass was 2.7005 mg, total EC was 0.0645 mg, and total OC was 2.149 mg, all of which include the regeneration emissions. Estimated the PM, EC, and OC emissions for this third run as the average of the equivalent emissions from runs 1 and 2. The emissions from the regeneration are estimated as the difference between the total emissions and the estimated emissions without regeneration.

D.1 Analysis Equations

Equations for calculations.

1. Load (kW) = 0.745699872(HP)

Where: HP = Horsepower

2. Load (%) = 100(Load (kW) / Load at 100% (kW)

3. Dilute Concentrations, DC_x (Based on Calibration Curves, see 9.2)
   a. DC_{NOx} = 0.9709(Measured Dilute NO_x) + 3.5093
   b. DC_{CO} = 1.4775(Measured Dilute CO) + 0.0552
   c. DC_{CO2} = 1.0804(Measured Dilute CO_2) – 0.1265

4. Raw Concentrations, RC_x (Based on Calibration Curves)
   a. RC_{NOx} = 0.9709(Measured Raw NO_x) + 3.5093
   b. RC_{CO} = 1.4775(Measured Raw CO) + 0.0552
   c. RC_{CO2} = 1.0804(Measured Raw CO_2) – 0.0367

5. Dilution Ratios
   a. Based on CO_2 = RC_{CO2} / DC_{CO2} = DR
   b. Based on NO_x = RC_{NOx} / DC_{NOx}

6. Exhaust Flow Rate in scfm
   a. EFR I= $C_F(24.4715)F_C(3.785)\rho_F(1000)(0.03531)(0.001) / (12.0107(C_{CO2} - 0.03)(60))$

Where: By Carbon Balance

C_F = Carbon content of fuel = 100 – measured Hydrogen content of fuel

24.4715 = Volume in liters of 1 mole of gas F_C = Fuel consumption in gal/hr

3.785 = liters/gal

ρ_F = density of fuel in kg/m^3

1000 = g/kg

0.03531 = ft^3/l

0.001 = m^3/l

12 = molecular weight of carbon in g

C_{CO2} = Measured concentration of CO_2 in the exhaust

0.03 = Background concentration of CO_2

60 = minutes per hour

7. Emissions (E_{gx}) in g/hr
   a. $E_{gNOx} = (C_{NOx})(DR)\ (10^{-6})(46.0055)\ /\ 24.4715(EFR\ I)(60)\ /\ (0.035325)$
   b. $E_{gCO} = (C_{CO})(DR)\ (10^{-6})(28.0101)\ /\ 24.4715(EFR\ I)(60)\ /\ (0.035325)$
   c. $E_{gCO2} = (C_{CO2})(DR)(10^{-2})(44.0095)\ /\ 24.4715(EFR\ I)(60)\ /\ (0.035325)$
   d. $E_{gPM2.5} = (mg/filter)(DR)(EFR\ I)(0.028)(60)/(T_t)/(T_f)$
   e. $E_{gEC} = (\mu g/filter)(DR)(EFR\ I)(0.028)(60)/(Q_t)/(Q_f)/1000$
   f. $E_{gOC} = (\mu g/filter)(DR)(EFR\ I)(0.028)(60)/(Q_t)/(Q_f)/1000$

Where: 10^{-6} for C_{NOx} and C_{CO} converts ppm to moles

10^{-2} for C_{CO2} converts % to moles

46.0055, 28.0101, 44.0095 = g/mole for NO_x, CO, and CO_2, respectively

60 = min/hr

.035325 = ft^3/l

mg/filter = Teflon final weight

T_t = sampling duration for Teflon filter

T_f = flow through the Teflon filter in l/min

ug/filter = EC/OC mass collected on Quartz filter Q_t = sampling duration of Quartz filter

Q_f = flow through the Quartz filter in l/min

0.028 = m^3/ft^3

1000 = mg/ug

8. Emissions (E_x) in g/kW-hr
   a. $E_{NOx} = E_{gNOx}$ / Load
   b. $E_{CO} = E_{gCO}$ / Load
   c. $E_{CO2} = E_{gCO2}$ / Load
   d. $E_{PM2.5} = E_{gPM2.5}$/ Load
   e. $E_{EC} = E_{gEC}$/ Load
   f. $E_{OC} = E_{gOC}$/ Load

9. Fuel Consumption (FC) in g/kW-hr
   a. FC = [CO_2 (g/hr)][(MW C)/MW CO_2][100/%C in fuel]

b. MW C = Molecular weight of C = 12.0107
c. MW CO_2 = Molecular weight of CO_2 = 44.0095
d. %C in fuel = % carbon in fuel

D.2 Calibration Data

Table D-3 presents the pre and post calibration data for the Horiba PG-250 and Figures D-1 through D-3 presents the plots of the calibration data and the regression equations for the calibration data

Table D-3: Pre, Post, and Average Calibration for NOx, CO, and CO2

Pre	Zero	Bottle	Low	Bottle	High	Bottle
NOx	0.578813559	0	147.4809524	154	957	918
CO	0.046892655	0	19.0547619	27.4	136.3783	202
CO2	-0.164915254	0	1.225	1.55	9.140723	9.83
Post	Zero	Bottle	Low	Bottle	High	Bottle
NOx	0.789552239	0	152.2955224	154	928.3509	918
CO	0.130845771	0	17.66865672	27.4	137.0193	202
CO2	0.336517413	0	1.953134328	1.55	9.277544	9.83
Avg	Zero	Bottle	Low	Bottle	High	Bottle
Nox	0.684182899	0	149.8882374	154	942.6754	918
CO	0.088869213	0	18.36170931	27.4	136.6988	202
CO2	0.085801079	0	1.589067164	1.55	9.209133	9.83

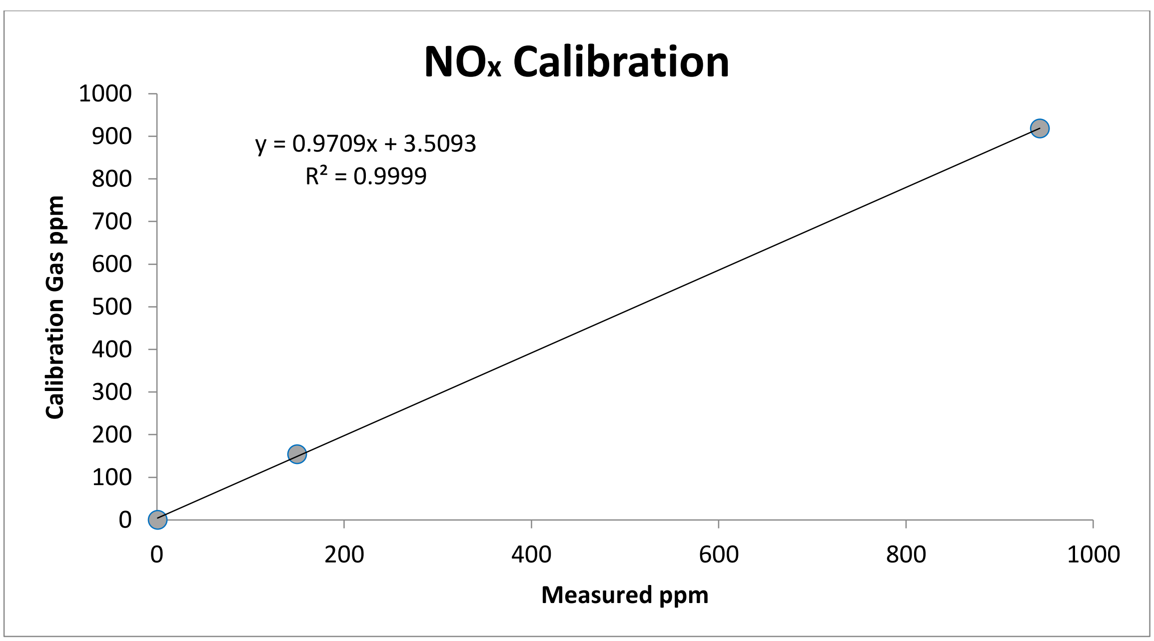

Figure D-1: NO_x Calibration gas ppm versus NO_x Measured ppm

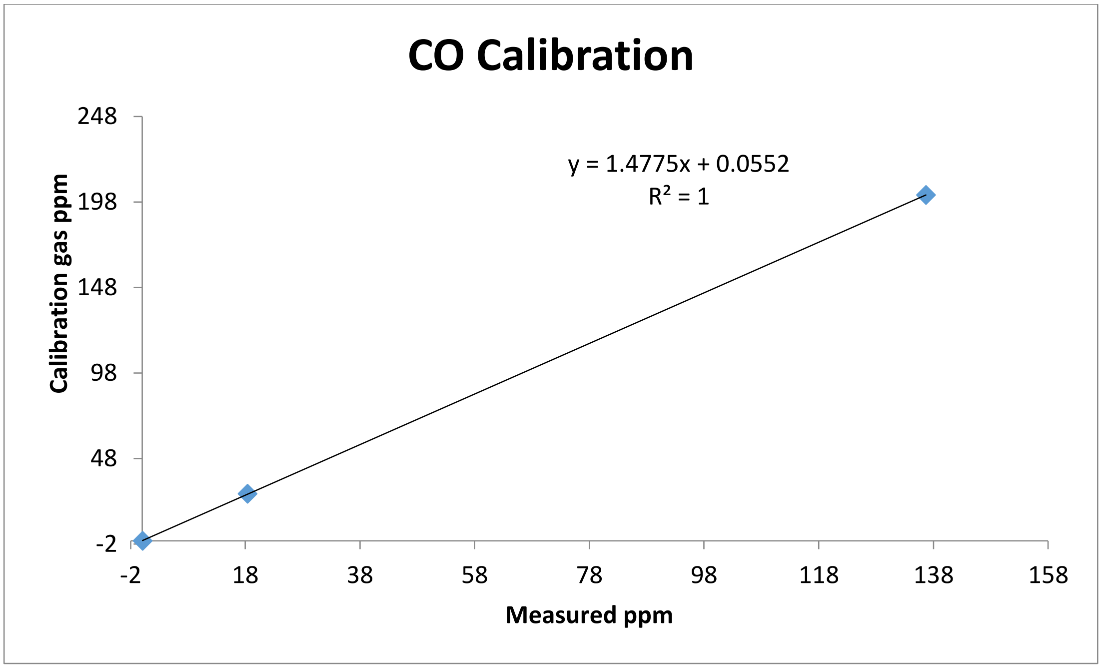

Figure D-2: CO Calibration gas ppm versus CO Measured ppm

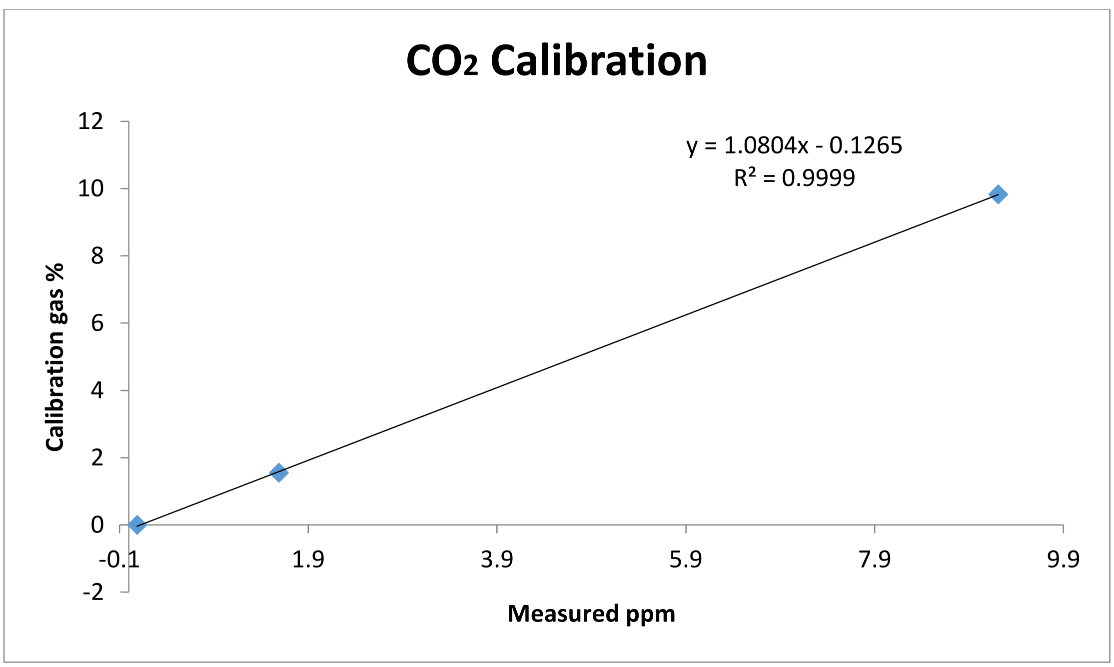

Figure D-3: CO_2 Calibration gas ppm versus CO_2 Measured ppm