FINAL REPORT

Performance Evaluation of a
State-of-the-Art Air/Fuel Ratio Control System
and an NSCR Catalyst on a Spark-Ignited
Natural Gas Fueled Engine Operating at
Fontana Wood Preserving
Fontana California

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1.0 Introduction and Background

Continental Controls Corporation (CCC) installed their EGC4 air/fuel ratio control system and a state-of-the-art three-way catalyst manufactured by DCL International, Inc. (DCL) on a spark-ignited, natural gas fueled engine at Fontana Wood Preserving in Fontana, California. Southern California Gas funded the project for demonstrating that through the implementation of emerging emissions control technologies for stationary gas engines, that engines of this type will be able to produce very low emissions of NOx, CO and VOC's on a continuous basis with minimal to no human intervention beyond routine maintenance. The CCC/SoCal Gas project team performed the installation in anticipation of implementing additional sensors and a catalyst monitoring system as part of a companion project the team is performing for the California Energy Commission.

The critical nature of the engine to the facility, the lack of back-up power from the utility grid and the large range of power output demanded on the engine throughout each day offered a unique opportunity to test this new system in an unusually demanding application.

1.1 Description of the Facility

Fontana Wood Preserving (FWP) uses the engine for generating electrical power to supply 100% of the electrical loads for the wood preserving and treating processes at the facility. In addition to supplying electrical power for process equipment, FWP recover the exhaust and jacket water heat, which is also used in the wood treating process. Specifically, the facility directly utilizes the exhaust in a large kiln for wood drying and Fontana personnel may fully or partially divert the exhaust to a hot water boiler system, which is also heated by the engine jacket water. The engine is not connected to and in fact has no provisions for interconnection with the electrical utility grid therefore the engine is required to respond to widely changing loads while maintaining frequency to within an acceptable range for plant equipment.

The engine operates exclusively on natural gas and the facility is a customer of Southern California Gas Company.

1.2 Description of Engine

The subject engine is a Model L-3711G series as manufactured by the Waukesha Engine Division of Dresser. The engine model series was originally designed and manufactured by the Climax Engine Company, which Waukesha acquired in 1957[1]. A number of variations of the engine were produced including an eight cylinder vee-type designated the H-2475 as well as the 12-cylinder L-3711 and a model L-3712. Production of major componentry ceased in 1998 although many spare parts are available from Waukesha as well as in the aftermarket.

[1] Note the 11-25-1992 permit to construct identified the engine as a model V-125, a Climax Engine designation. Waukesha changed this to their model numbering system which uses a letter of the alphabet to indicate the number of cylinders (e.g. 'L' is the 12th letter of the alphabet) followed by the engine displacement in cubic inches.

The engine is a 12-cylinder vee-type, four-stroke cycle, naturally aspirated, spark-ignited engine fueled by natural gas. The engine as originally equipped was fitted with one Impco 200 mechanical carburetor per bank of six-cylinders. Prior to the installation of new CCC fuel control equipment, the engine air/fuel ratio was controlled by an older electronic control system manufactured by Altronic which utilized signals from two narrow-band exhaust oxygen sensors and a single intake manifold sensor in a look-up table arrangement. The system controlled the gas supply to the carburetors by modulating a solenoid operated plug valve based on comparing the measured exhaust oxygen signals to a setpoint for the current manifold pressure. The air/fuel controller required regular and frequent adjustments to maintain emissions at optimal levels.

The engine and generator particulars appear in Table 1:

Table 1: Engine-Generator Data

Line	Parameter	Value
1	Engine Model	L-3711G
2	Serial No.	48257
3	Rated HP (permit)	463
4	Rated Speed (permit)	900
5	Bore (in)	7.5
6	Stroke (in)	7.0
7	BMEP (PSI)	110
8	Generator Manuf.	Electric Machinery Co
9	Generator S/N	374244611
10	Gen Rated Speed (RPM)	900
11	Generator Rated Output (kW)	400
12	Generator Type	Synchronous

1.3 Emissions Permit(s) and Levels

As shown in Table 2, the engine was permitted in 1992 and required to comply with the South Coast Air Quality Management District (SCAQMD) rule 1110.1. As of August 24, 2010, the engine received a revised permit requiring compliance with SCAQMD rule 1110.2, which also includes a further reduction in emissions of NOx and VOC emissions effective July 1, 2011.

Table 2: SCAQMD Air Permit Requirements

Permit Limits (PPMv Corrected to 15% O2)			
REF	CO	NOx	VOC
11/25/1992	2000	36	250
8/24/2010	250	45	250
7/1/2011	250	11	30

Historically, the engine has had little difficulty complying with the 2000/36 CO/NOx levels with the existing air/fuel ratio control system and catalytic converter although frequent; adjustments to the controller setpoints were required. However, with the original configuration the engine was unable to meet the 250/45 CO/NOx levels simultaneously.

2.0 Baseline Configuration

A description of the as-found engine condition follows.

2.1 Layout and Equipment

Figures 1-3 show the original configuration of the engine with the Altronic solenoid operated gas valves and the Impco 200 series mechanical, diaphragm-type carburetors. Currently, the generator is equipped with an Altronic EPC-150 Air/Fuel Ratio controller and a two-element Johnson-Mathey non-selective catalytic reduction (NSCR) catalyst. The project team created full-scale, three-dimensional drawings of the as-found set-up to facilitate the layout and of the proposed new equipment. These are shown in figures 4 and 5.

Drawings were also made of the exhaust system to permit design modifications to piping and supports for the catalytic converter since the newer unit was dimensional larger and configured somewhat differently. Figures 6 and 7 show the original catalyst and exhaust piping.

Figure 1: View of engine from free-end, original configuration

Figure 2: View of engine looking over right bank

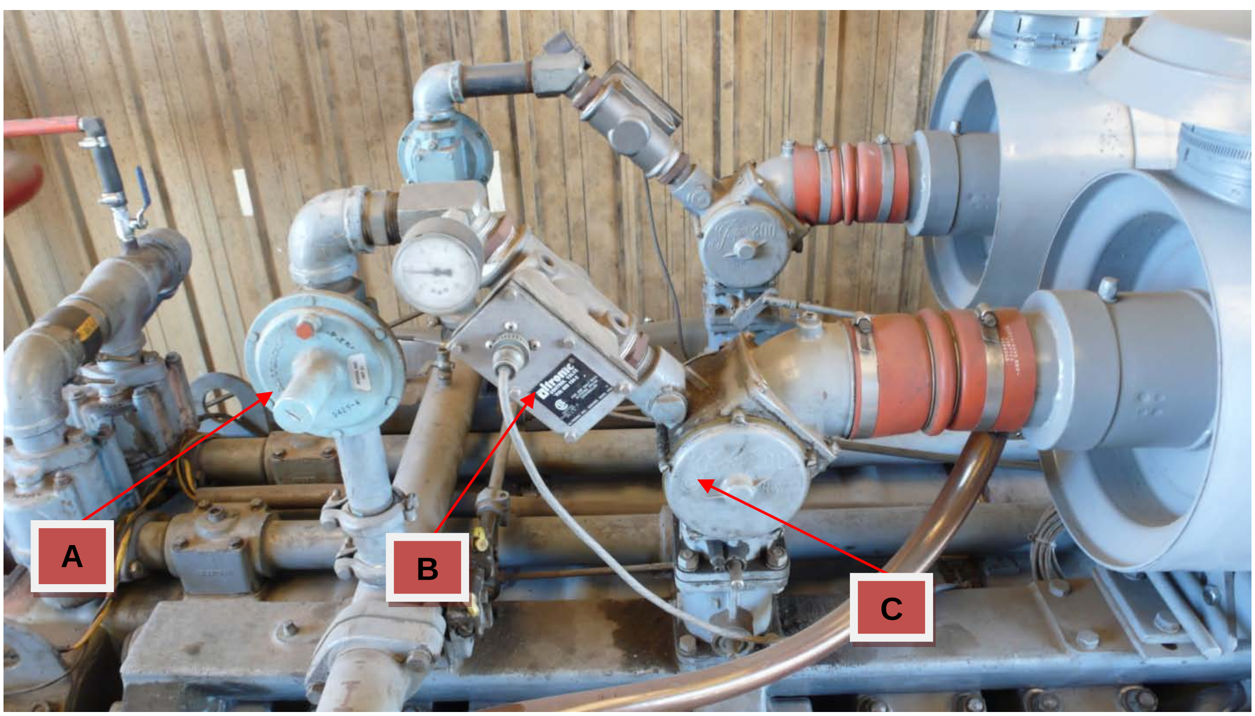


Figure 3: Regulators (A), solenoid operated gas control valves (B) and Impco Carburetors (C)

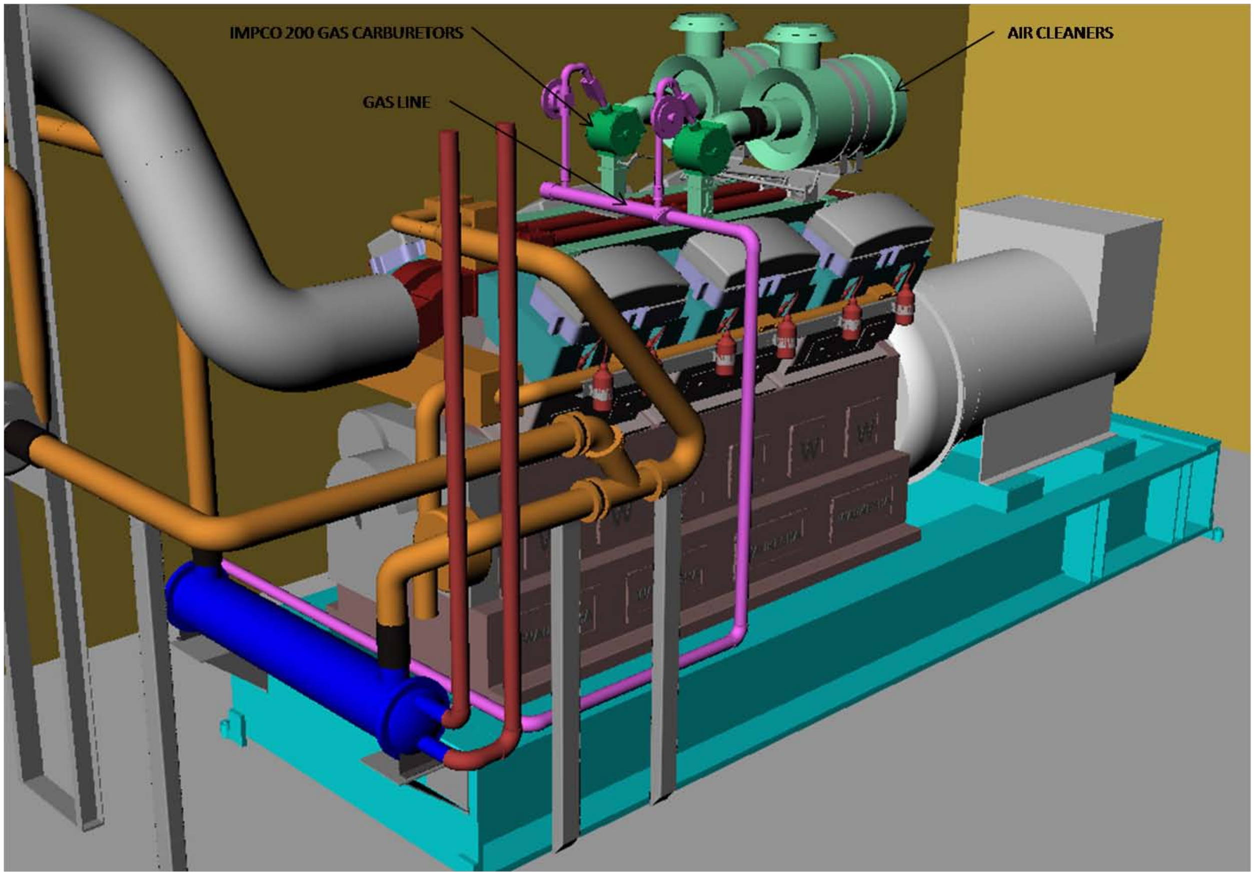


Figure 4: Solid Model of Engine Generated by the Project Team

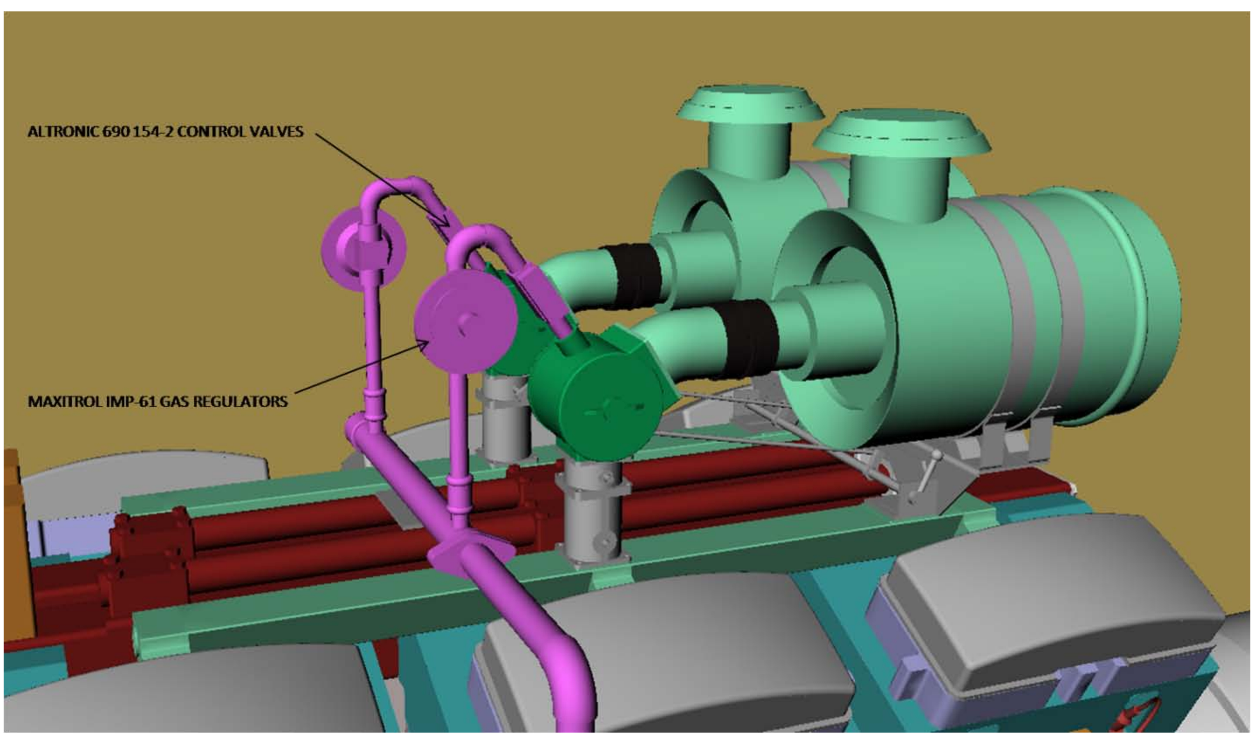


Figure 5: Detail of components to be modified. The two small pressure regulators were re-used

Figure 6: Original Catalyst and A-Frame Supports

Figure 7: Original exhaust piping viewed from engine toward catalyst (A).

2.2 Baseline Testing – Steady-State, December 15, 2009

To assess the performance of the engine, a test of the engine in the "as-found" baseline condition was conducted with data collected by CCC and the SoCal Gas mobile emissions laboratory. The testing consisted of acquiring both pre-catalyst (i.e. engine-out) emissions and post-catalyst emissions. In addition to determining the NOx, CO and VOC levels, the test data was also needed for use as input for sizing a new catalyst to comply with the new SCAQMD limits for this facility.

The results are summarized in Table 3. As can be seen the existing system was able to comply with the 1992 permit levels of NOx <36 PPM, CO < 2000 with substantial margin. However, as indicated in Figure 8, the engine would not be able to meet the newer standards.

Also, as shown in figure 9, even at steady-state conditions, the engine emissions were rather unstable, a result of the slow response of the air/fuel controller to small changes in engine torque and/or speed.

Table 3: Baseline Test of Engine December 15, 2009

Load (Kilowatt Output **)		as found (171 kW)	high load (245 kW)	low load (145 kW)
NO_X (ppm)	Upstream	2494	2600	2354
	Downstream	82.7	89.6	79.0
CO (ppm)	Upstream	7513	7909	7446
	Downstream	3175	3865	3312
Total HC (ppm)	Downstream	360	378	387
CO_2 (%)	Upstream	10.99	11.03	11.10
O_2 (%)	Downstream	0.05	0.05*	0.05*
NO_X @ 15% O_2 (ppm)	Downstream	23.5	26.1	23.3
CO @ 15% O_2 (ppm)	Downstream	898	1125	975
HC @ 15% O_2 (ppm)	Downstream	101	109	114

However, perhaps a bit of an aside, the permit levels of 2000 CO and 36 PPM of NOx corresponds to Best Available Retrofit Control Technology (BARCT) for stationary, non-emergency, natural gas fueled engines over 500 horsepower. References lines on Figure 8 indicate these levels.

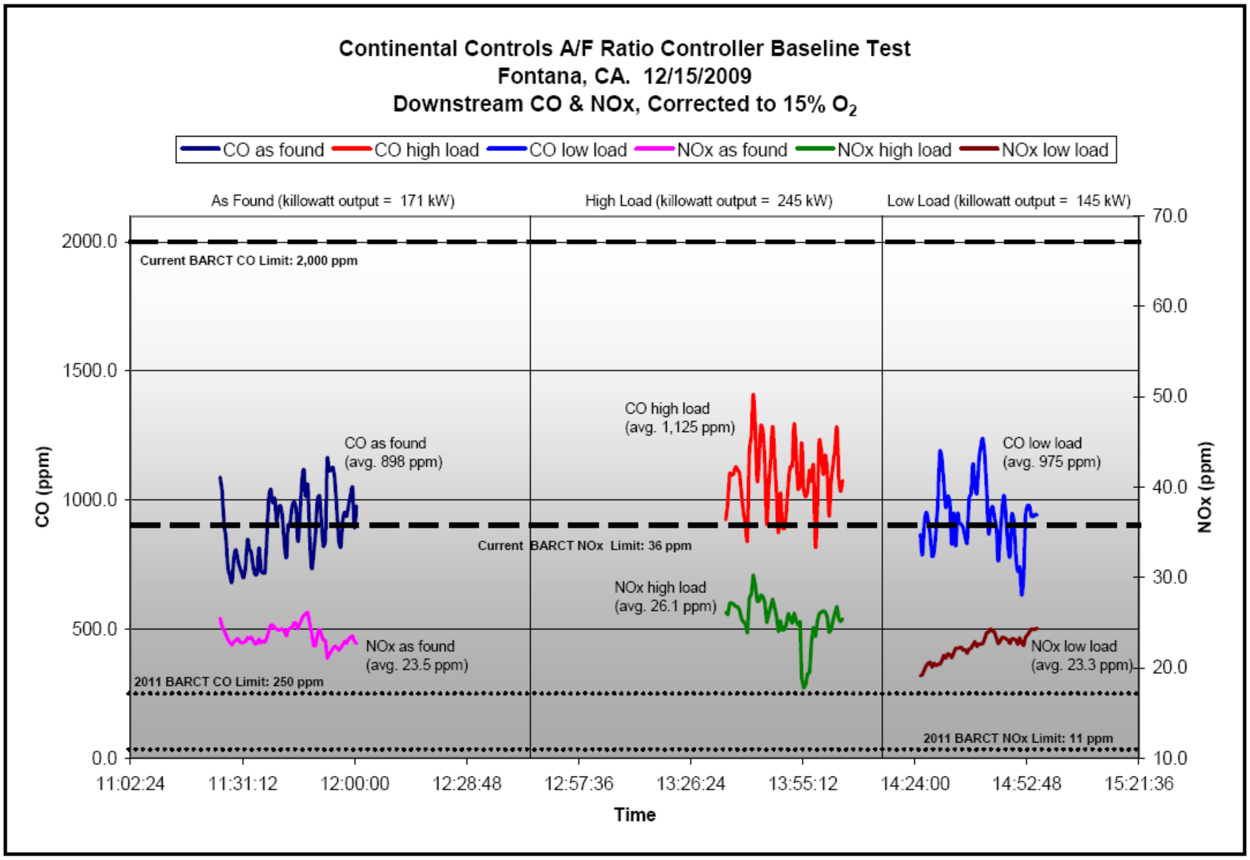
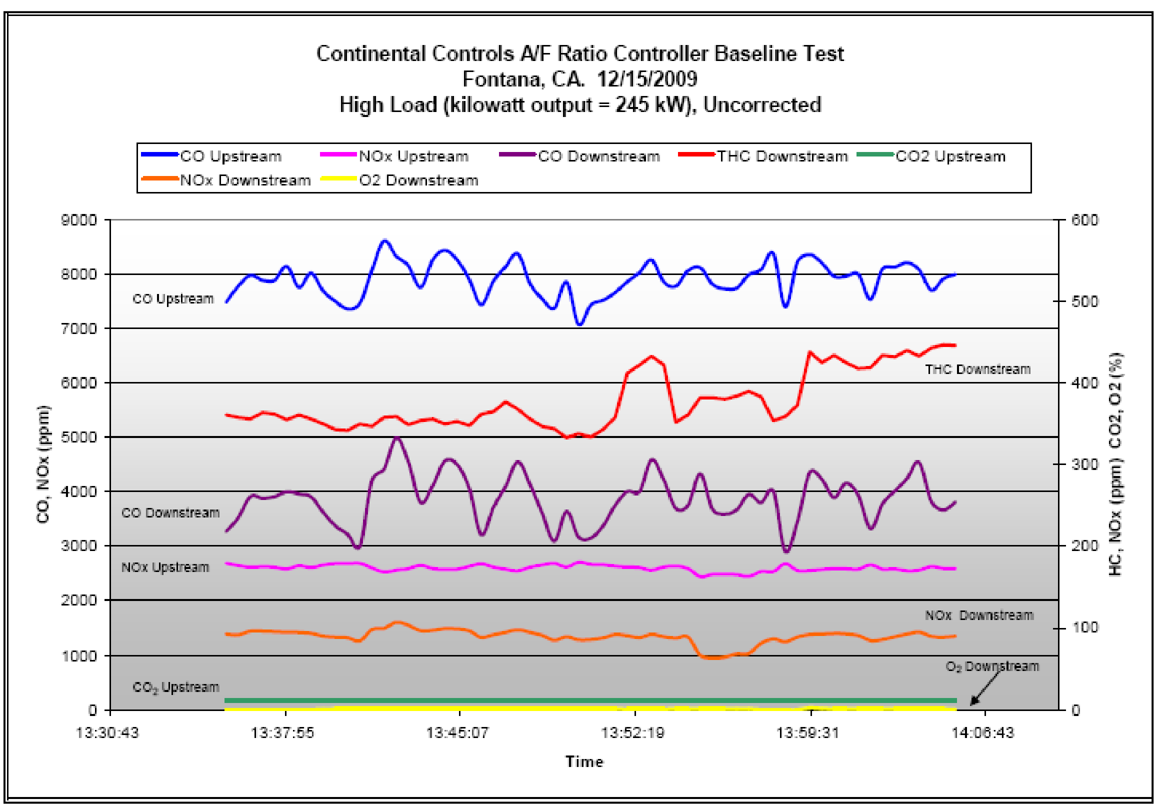


Figure 8 (above) and 9 (below): Baseline Emissions Data. Note fluctuations in the "steady-state data"



3.0 Upgrades to Emissions Controls

Following the evaluation of the engine, careful measurements of the dimensions and consideration of owner and site requirements, the project team developed installation drawings and specifications for the new air/fuel ratio control system and a new, NSCR catalyst sized to meet the July 1, 2011 SCAQMD permit limits with adequate margin for deterioration with a long service interval estimated at 4,000 operating hours.

3.1 Air/Fuel Ratio Controller Installation

The new air/fuel control system replaced the Altronic solenoid operated valves and the Impco 200 carburetors serving each bank of engine cylinders with Continental's EGC-4, Electronic Gas Carburetors. The EGC4 is a unitized electronic pressure regulator coupled and integral with a specially designed venturi-type mixer. CCC also provided a freestanding control cabinet to house a large flat panel display unit. Continental's Valve Viewer graphical HMI software is used to continuously monitor the performance of each of the two EGC4's permitting adjustment to any tunable parameters necessary if authorized. The system is also remotely accessible via the internet allowing remote monitoring and implementation of system parameters if needed without having to conduct a visit to FWP from CCC's offices in San Diego.

CCC was able to install the two new EGC4's with minimal downtime to the facility. The controllers were installed first and baseline testing with the original Johnson-Mathey catalyst was conducted. Following the completion of this testing, the engine was secured and the new catalyst was installed.

Following the installation of the new controllers, monitoring equipment and the catalyst, CCC commenced weekly checks of the system for the purposes of optimizing performance and trending any changes during the catalyst "de-greening period". CCC will continue these weekly checks throughout the coming months.

3.2 EGC4 Principle of Operation

The EGC4 operates by using an internal, high precision, pressure sensor to measure the gas injection pressure into the integral venturi mixer. Taking advantage of the physical characteristics of a venturi (a convergent-divergent nozzle), one of which is that if the gas pressure admitted to the throat of the venturi remains at a constant pressure (near zero) regardless of the combustion air drawn through the main body, the mass air/fuel ratio will remain constant over a wide range of air flows. Since this simple pressure control loop does not depend on an exhaust gas measurement and the delays resulting from transport and sensor response, it can respond to both minute and large changes in load extremely fast making changes as often as 30 times each second.

Once the engine warms up, the EGC4 reads the value of the pre-catalyst exhaust gas oxygen concentration from the wide band oxygen sensors and in a slower, outer control loop biases the value of the pressure setpoint slightly. In this way, the controller is able to maintain the optimal inlet chemistry to the catalytic converter. The wide range oxygen sensors are extremely robust and have the advantage over the narrow band sensors they replaced that they can be calibrated in air while the engine is shutdown. Adding further robustness to this system, each time the engine is shutdown, the EGC4 re-zeroes its internal pressure sensor assuring accurate fuel pressure for engine starting and consistent performance. The figures on the following pages show the installation of the final system.

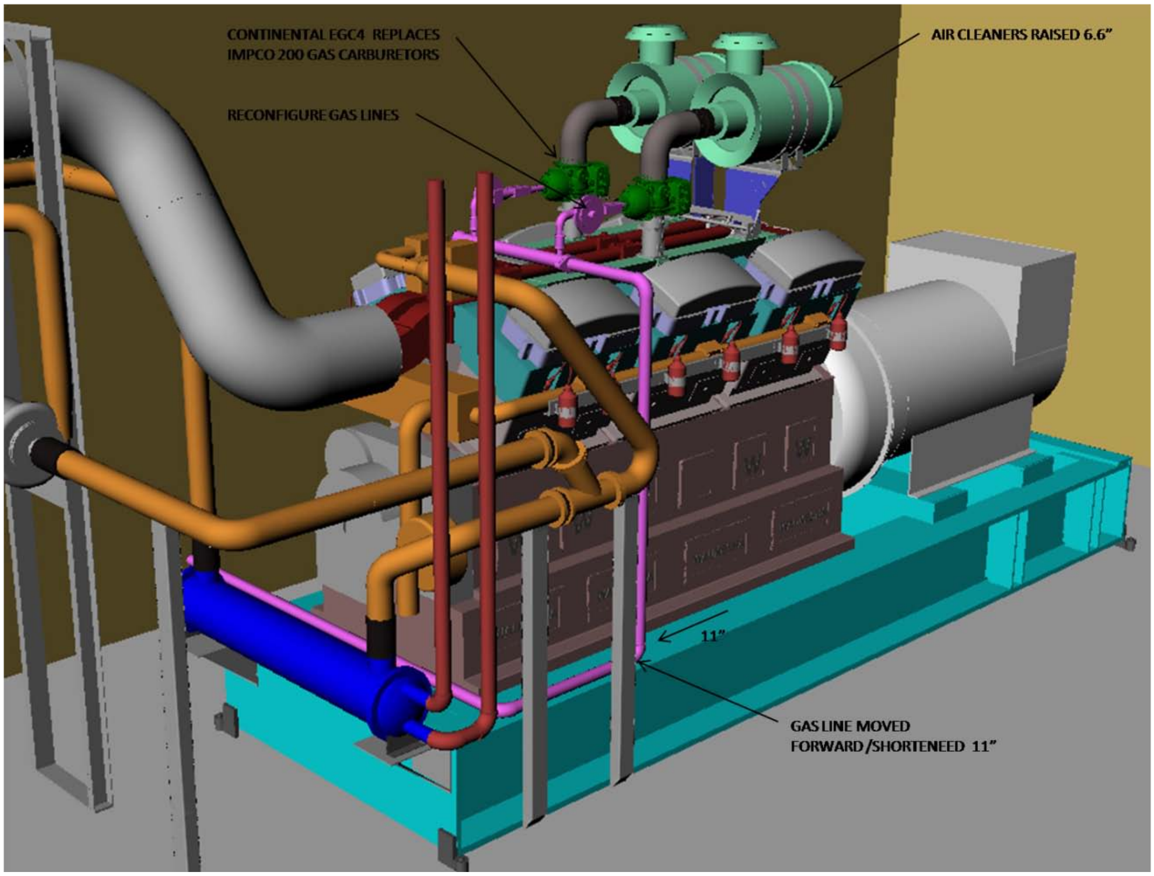
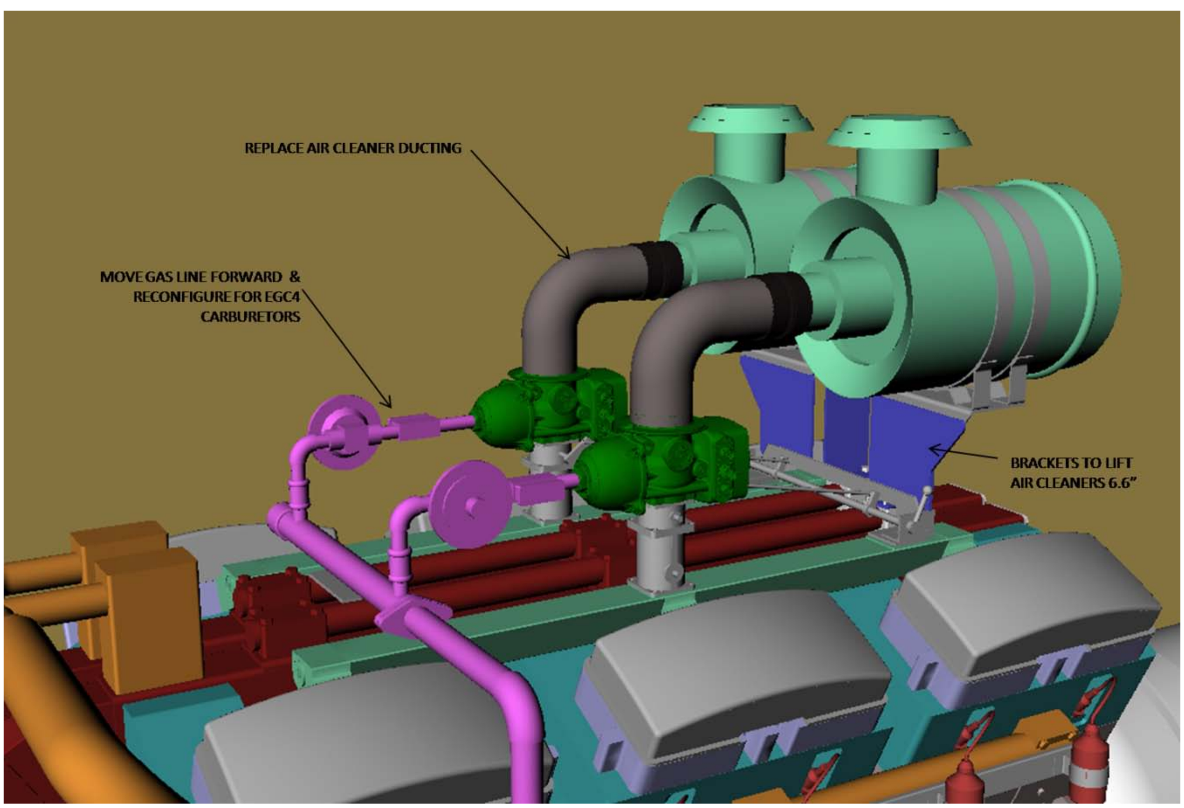


Figure 10 (above) and 11 (below): Preliminary Installation Drawings



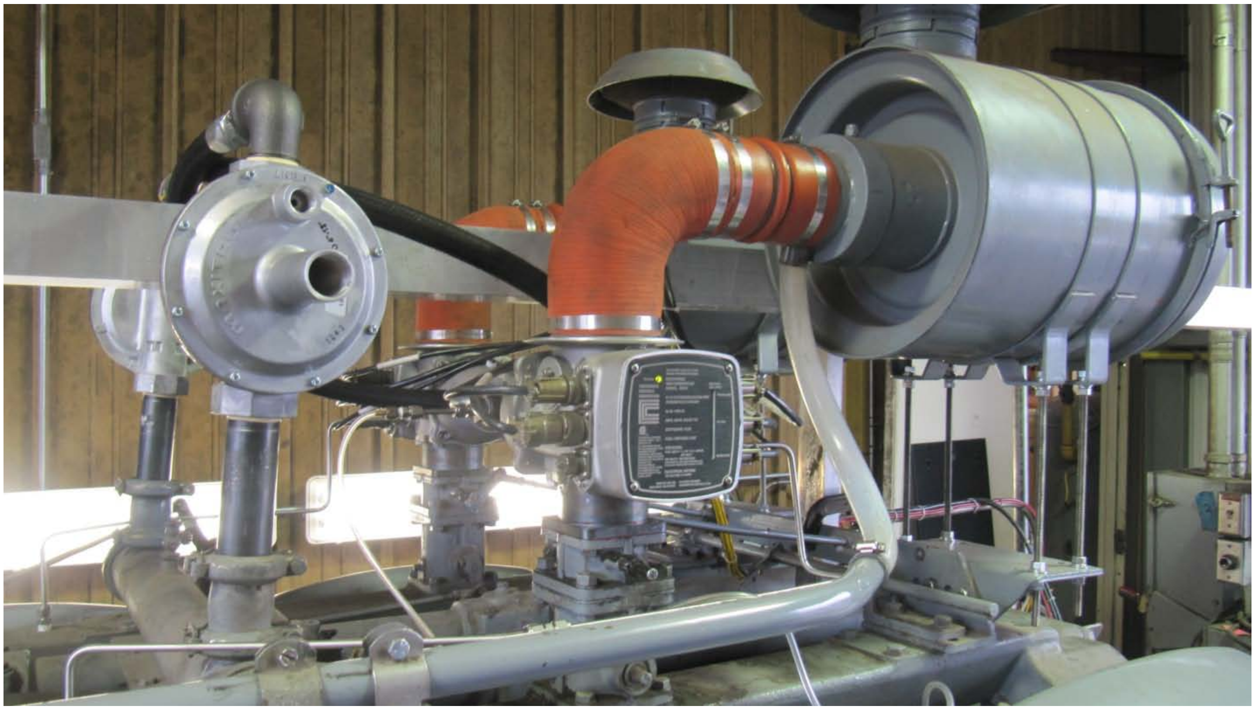


Figure 12: View of reconfigured Fuel System and EGC4 installation.

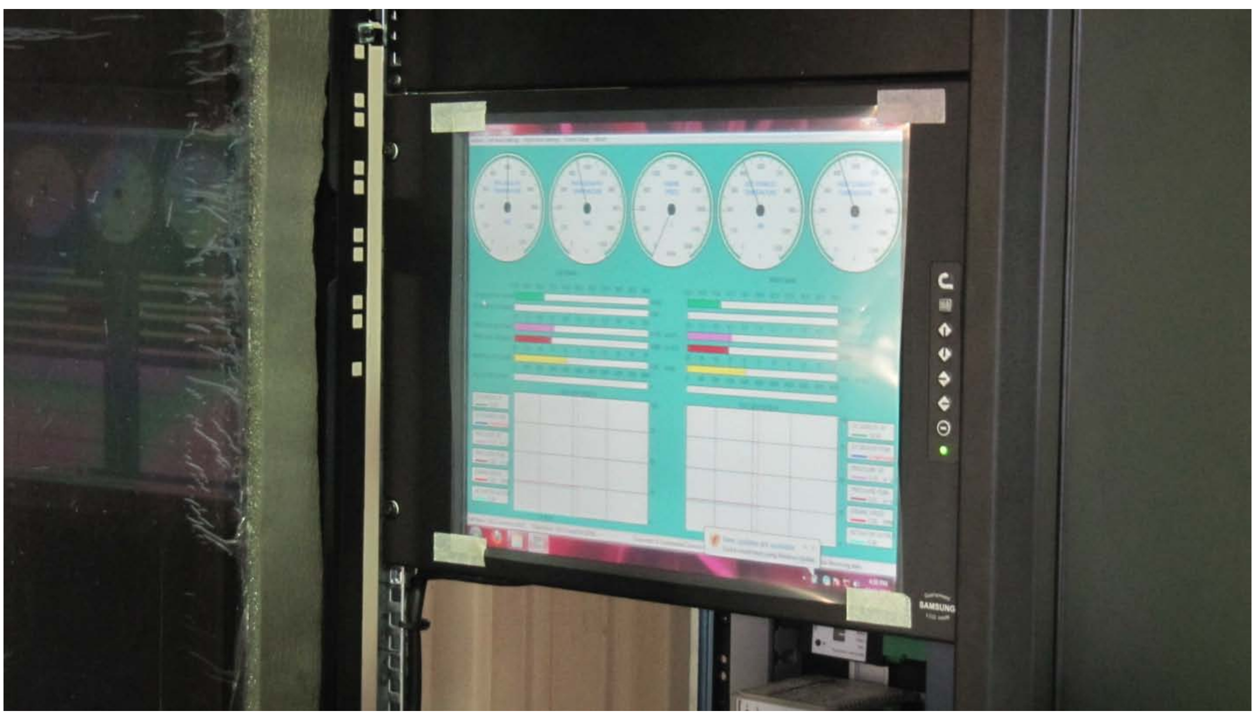


Figure 13: Large, flat panel display allows monitoring of the position, settings and inputs to both valves. The software also logs data for later retrieval and analysis if needed. Data is presented numerically as well as graphically via dials, bar charts and a strip-chart like display

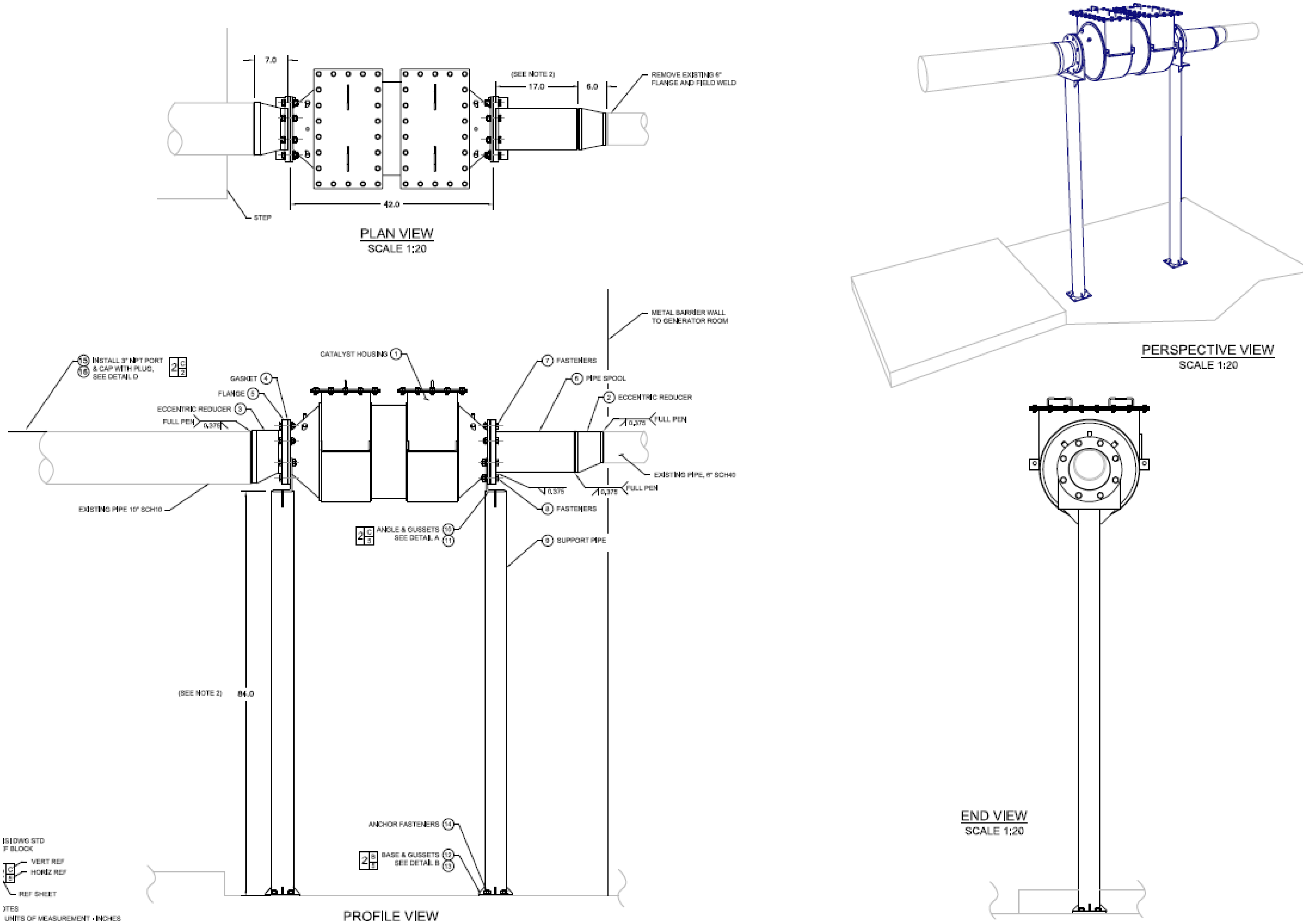


Figure 14: Installation Drawings for New Catalyst

Figure 15:
New Catalyst Installed, prior to reinsulation of piping and wrapping catalyst with the manufacturer's furnished removable insulating blankets.

4.0 Results - Evaluation of Modifications

The following section contains a comparison of the performance of the new, Continental Controller and old air/fuel controller an Altronic EPC-100 and the combination of the new controllers and old, Johnson Mathew catalyst and the new DCL catalysts. The base line data is presented in section 4.1, section 4.2 shows the initial performance with the new AFRC system with the original Johnson Mathew catalyst, section 4.3 shows the final performance with the new DCL catalyst and the CCC AFRC and finally section 4.4 shows the performance achieved with after de-greening of the catalyst and fine tuning of the controller setpoint.

4.1 Results Presentation – Base-line Condition

Figure 16 shows the original controller and catalyst in the as-found condition following optimization of the AFRC control curve by the facility. Both steady-state and transient emissions varied widely and were in excess of the project targets.

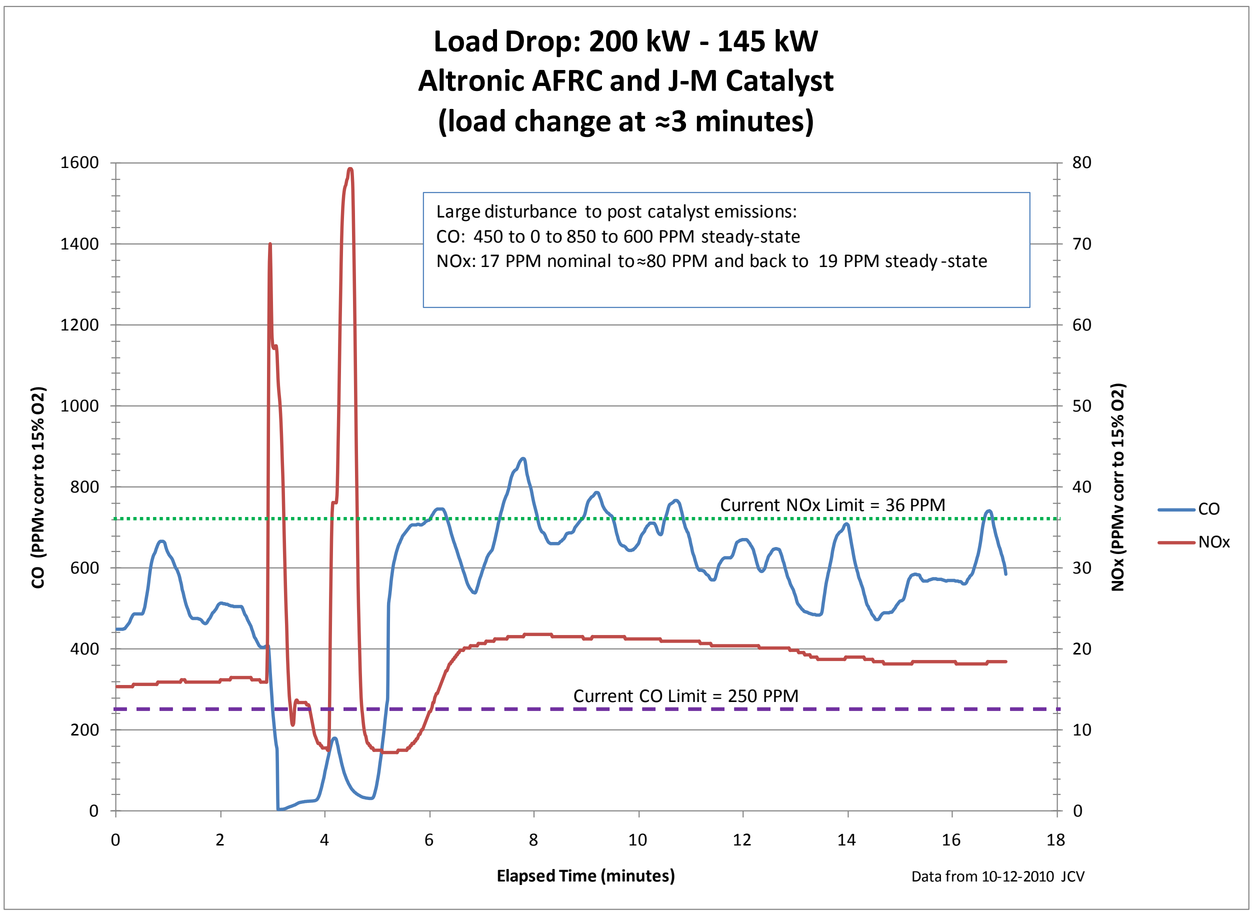


Figure 16: Original Controller and Catalyst showing large upset to emissions from a load change

4.2 Results Presentation – New Continental Controller, Original Catalyst

In order to assess the improvements of the new Continental AFRC independently from the catalyst, the new controls were commissioned and prior to “de-greening” of the catalyst or final optimization of the AFRC system. These results are summarized in Figure 17 below.

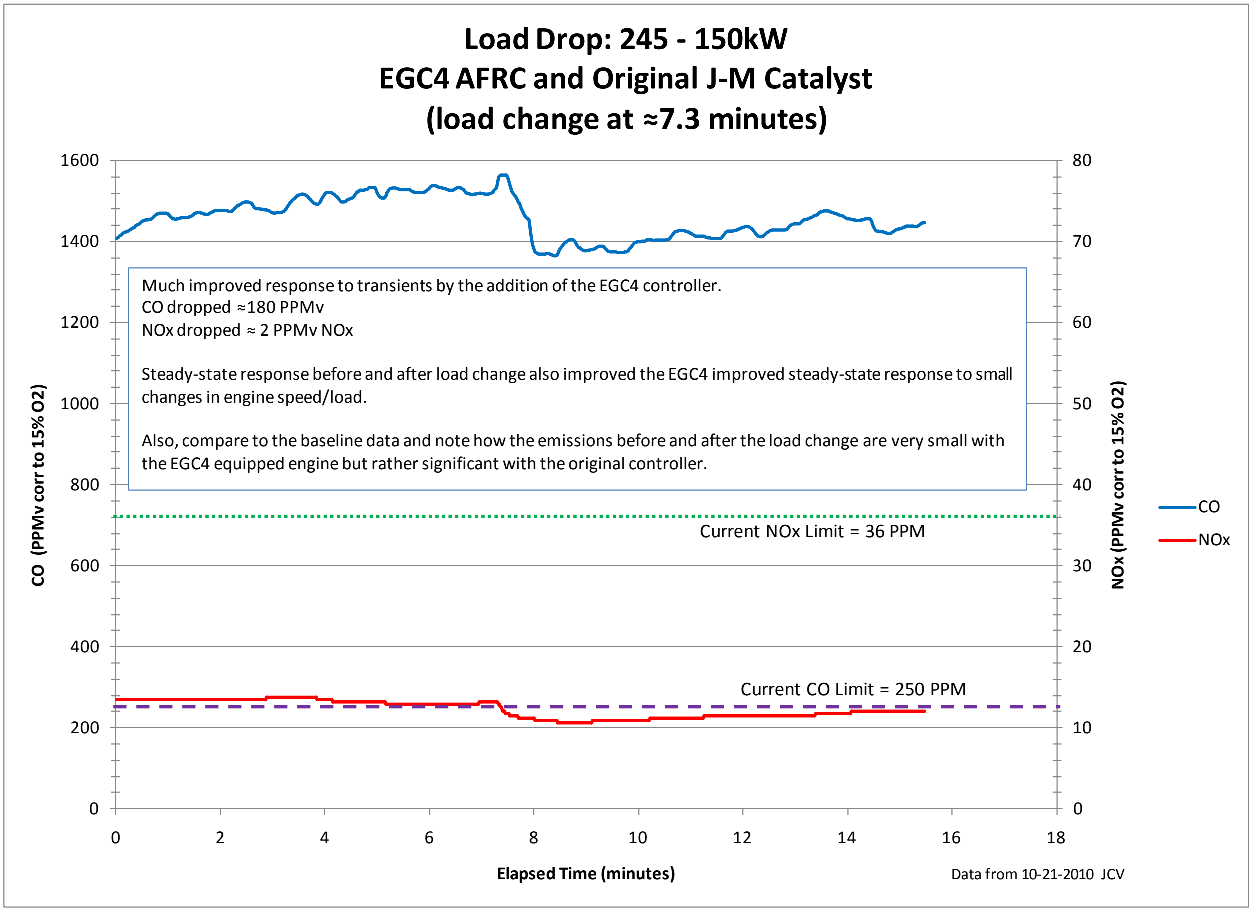


Figure 17:
New EGC4 Controller and Old Catalyst showing reduced upset to emissions from a load change and steadier performance overall

4.3 Results Presentation – New Continental Controller, new DCL Catalysts

The overall performance of the new controller and catalyst are shown in Figure 18, which shows steady-state performance with a large transient a 4-minutes but at the same scale as the previously presented data, and in Figure 19, which shows a close-up view of the performance during the load transient.

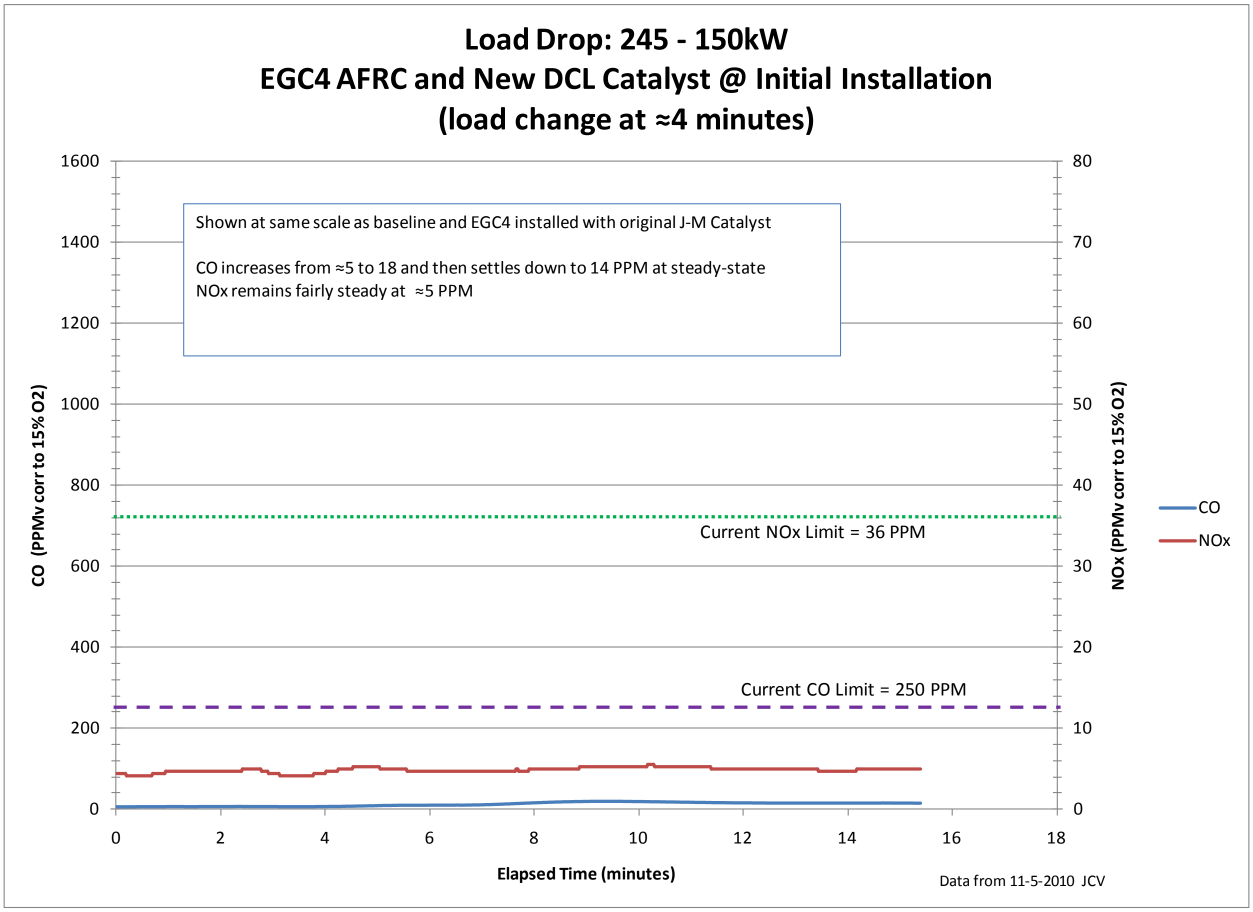


Figure 18: New EGC4 Controller and New DCL Catalyst showing initial performance

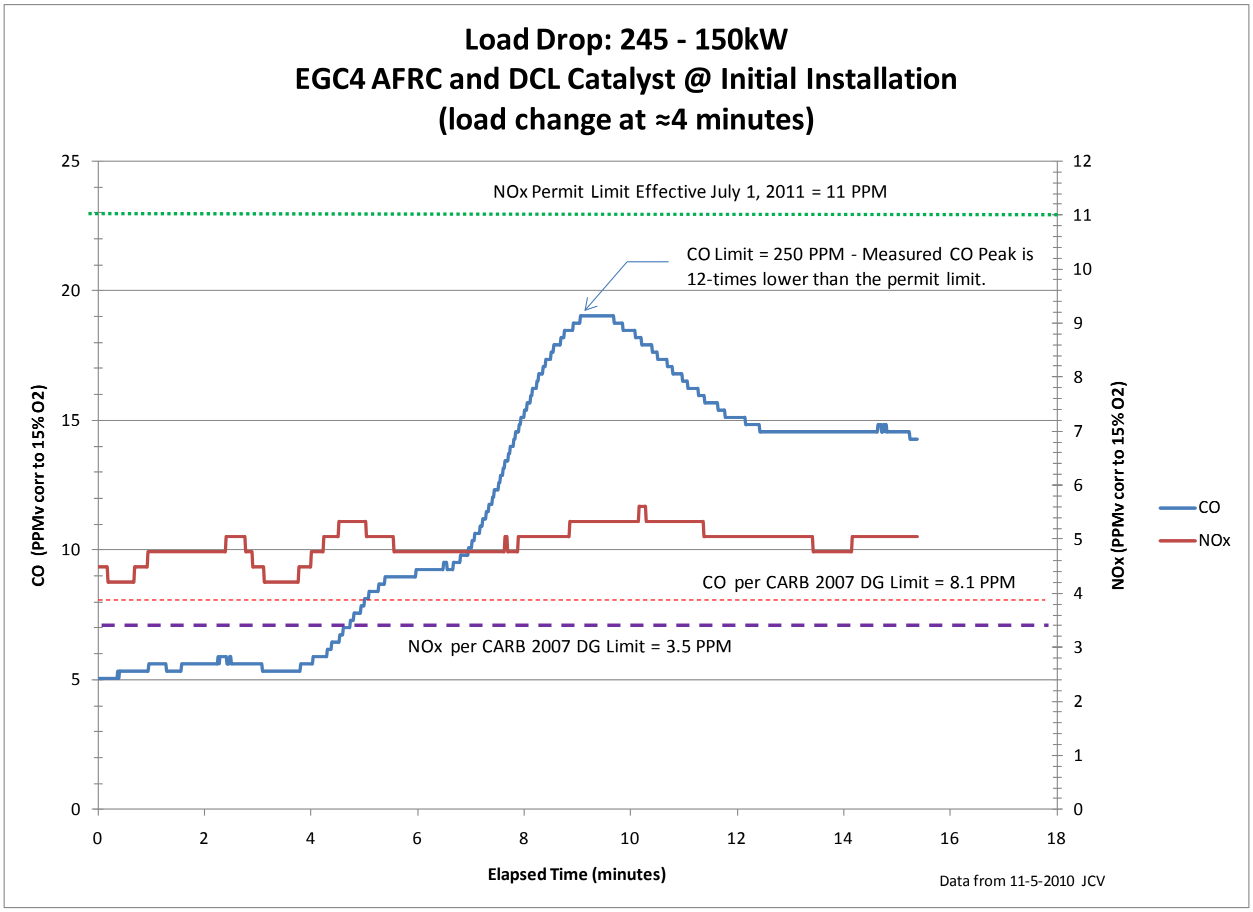


Figure 19: Close-up view of data shown in Figure 18

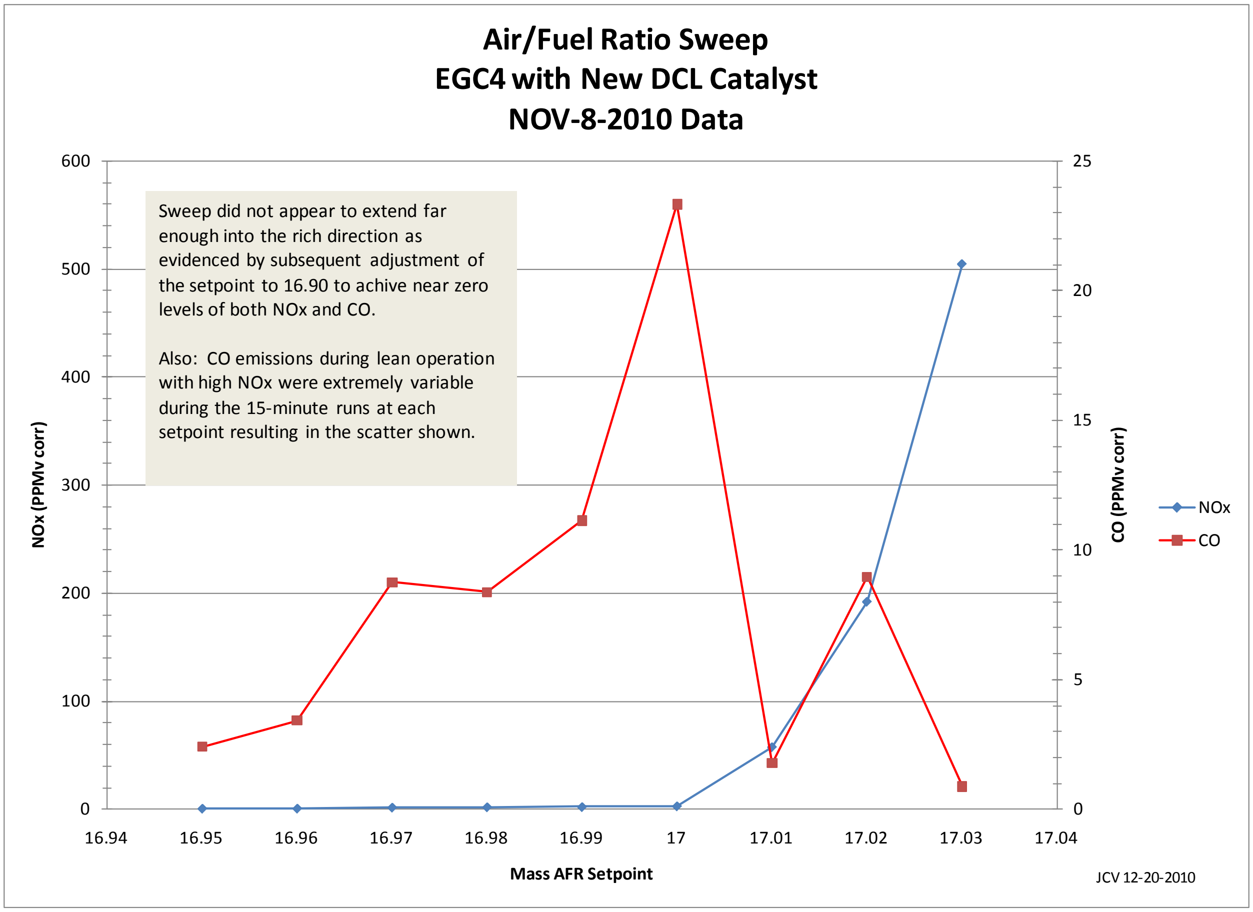


Figure 20:
Sweep of Air/Fuel Ratio Setpoint from November 8, 2010. Approximately 100 hours later, a setpoint of 16.90 ultimately resulted in both NOx and CO stabilizing at approximately zero PPMv corrected. See Figure 21 on the following page.

Now that the catalyst has stabilized and the system is insulated, the test team will repeat this sweep over a wider range of air/fuel ratios.

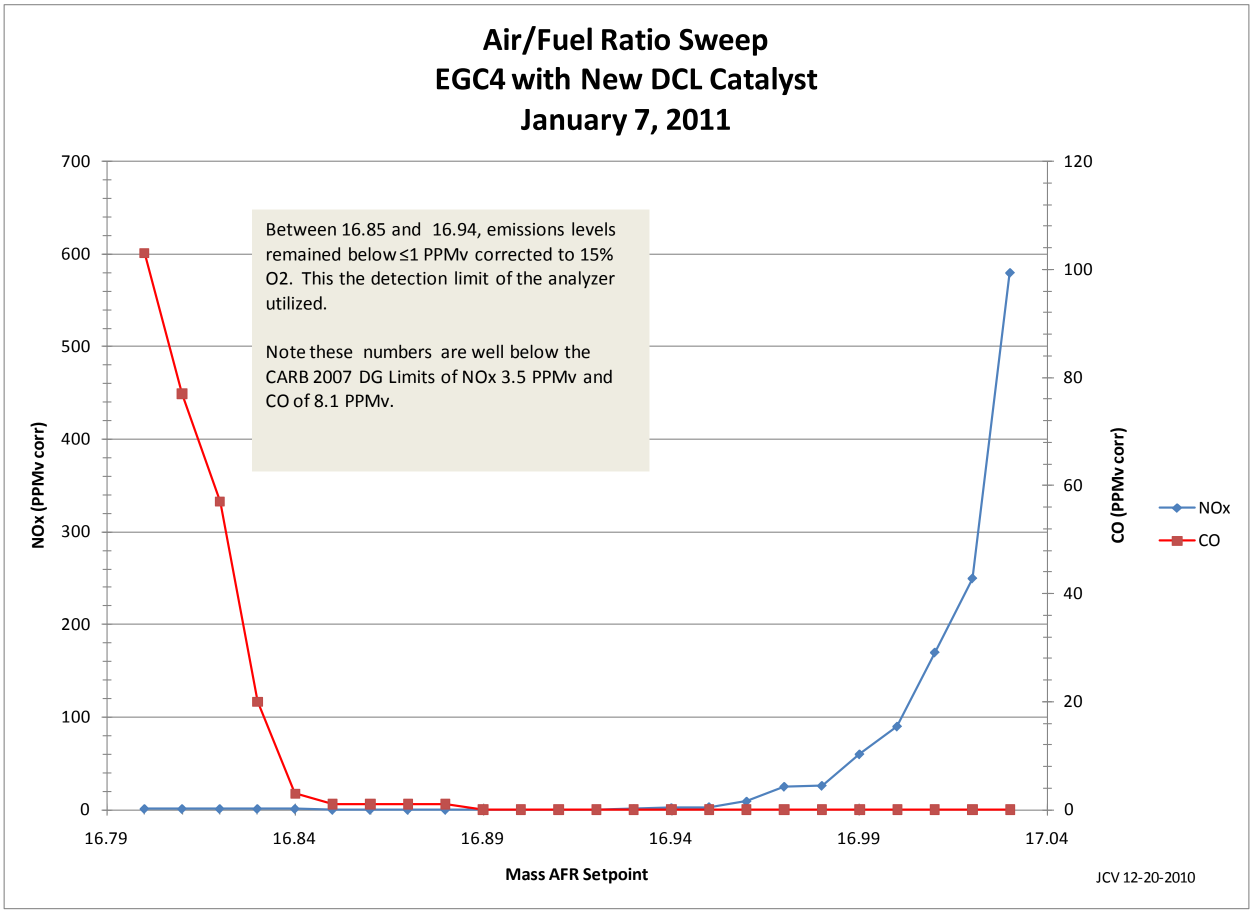


Figure 21:
Sweep of Air/Fuel Ratio Setpoint from January 7, 2011 after apparent breaking-in or "de-greening" of the catalyst.

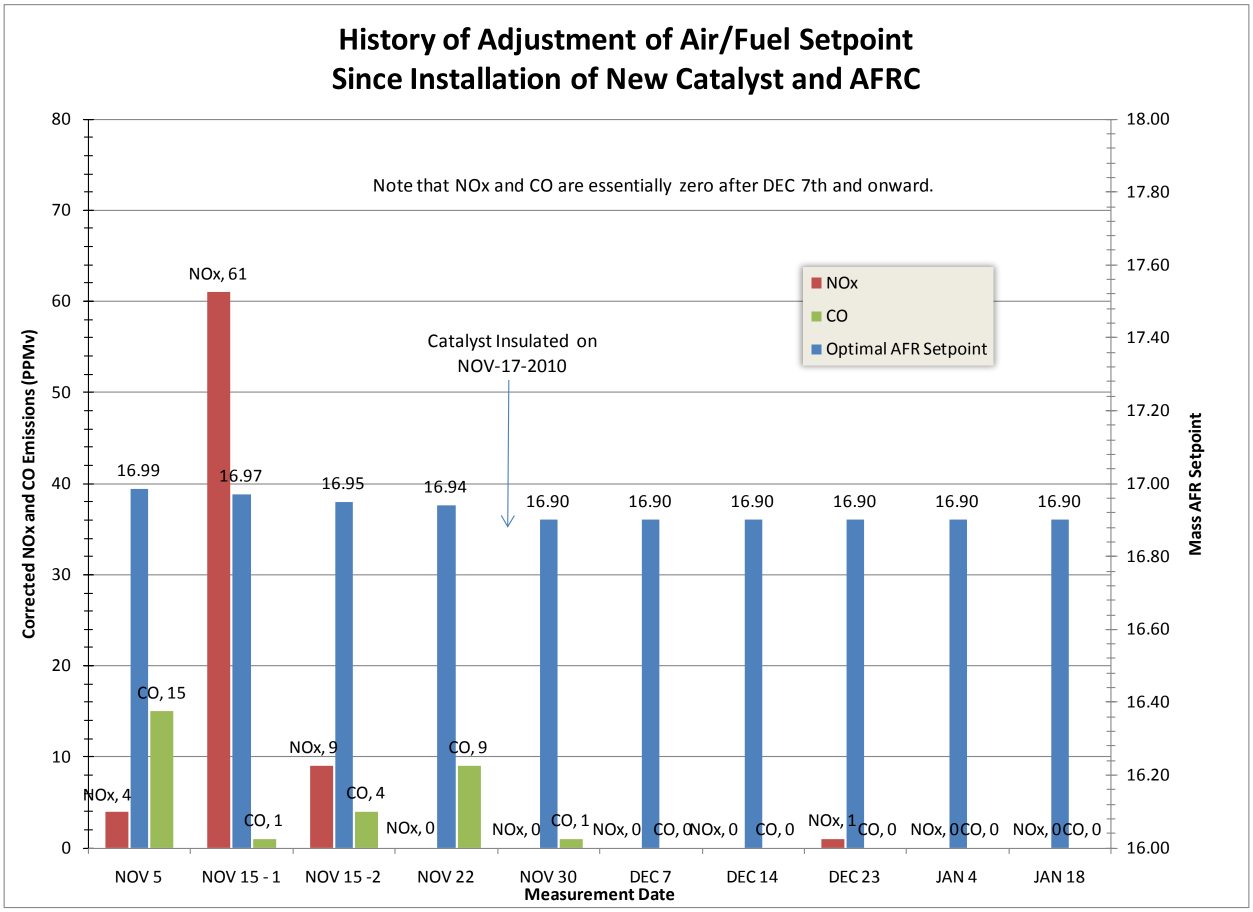


Figure 22:

Minor changes to the setpoint required during the initial few weeks of catalyst operation. Catalyst meets all emissions established in the project goals. Continued weekly monitoring will determine deterioration rates of the catalyst and performance degradation of the wide band oxygen sensors.

		CONDITIONS	
Line No.		***As Found***	***Max Load***
1	Load (kWe):	60 Kw (100 AMPS)	175 KW (260 AMPS)
2	Date:	12/14/2010	12/14/2010
3	Time:	7:55 AM	9:15 AM
4	Data Recorded by:	DL Campbell	DL Campbell
5	Engine Hours:	3241.3	3242.6
6	NOx Pre-catalyst (PPM):	888 PPMv (Corr)	1467 PPMv (Corr)
7	CO Pre-catalyst (PPM):	1440 PPMv (Corr)	982 PPMv (Corr)
8	O2 Pre-catalyst (%):	0.4%	0.4%
9	CO2 Pre-catalyst (%):	11.5%	11.5%
10	Exhaust Temperature Pre-Cat (deg F):	831	944
11	Exhaust Back Pressure at engine (in wc):	1.1	2.35
12	NOx Post-catalyst (PPM):	1 PPMv (Corr)	0 PPMv (Corr)
13	CO Post-catalyst (PPM):	1 PPMv (Corr)	0 PPMv (Corr)
14	O2 Post-catalyst (%):	0.1%	0.0%
15	CO2 Post-catalyst (%):	11.6%	11.7%
16	Exhaust Temperature Post-Cat (deg F):	875	965
17	Exhaust Back Pressure post cat (in wc):	0.2	0.4
18	Right Bank O2 Sensor Setpoint (AFR):	16.9	16.9
19	Right Bank O2 Sensor Reading (AFR):	16.9	16.9
20			
21	Left Bank O2 Sensor Setpoint (AFR):	16.9	16.9
22	Left Bank O2 Sensor Reading (AFR):	16.9	16.9
23			
25	Left Bank Exhaust Temperature (deg F)	855	965
24	Right Bank Exhaust Temperature (deg F)	848	967
25	Manifold Pressure Right Bank (inches HG vacuum):	-18.27	-9.76
26	Manifold Pressure Left Bank (inches HG vacuum):	-17.52	-10.75
27	Engine Speed (RPM):	879	874
28	Ignition Timing (deg BTDC):	24.26	24.27
29	Voltage (VAC):	505	500
30	Amperage:	100	260
31	Frequency (Hz):	58.75	58.75
32	Power (kWe)	60	175

Figure 23: Sample Weekly Log Sheet
All emissions readings are 15-minute averages @ 1-second intervals

4.4 Comments - Old Versus New Air/Fuel Controller – Original Catalyst

CCC recorded data prior to and after the installation of the new controller but prior to replacement of the original catalyst. This data appears in figures 16 and 17 from which it is evident that the engine performance is considerably steadier during both constant load and transient conditions. During the load transient event in particular, even with the old catalyst the EGC4 controller recovers much more quickly. The lower NOx and higher CO indicate the new and old controllers were controlling at different setpoints the new controller adjusted richer than the old unit was.

4.5 Comments - New Air/Fuel Controller and New Catalyst

Figures 18 and 19 display the performance during the same conditions indicated in the previous plots except now the team had completed the installation of the new DCL catalyst. As shown, the improvement in performance required a change in the vertical scaling of the graph such that the small magnitude of the disturbance can be observed.

Once the catalyst had accumulated a few weeks of operation, the optimal value of the setpoint settled out and the post-catalyst emissions dropped to the limits of detection of the analyzer (≤ 1 PPMv raw).

4.6 Comments - Weekly Performance Monitoring

The test team recommends that follow-on work, planned to commence is February, include recording weekly engine performance and emissions readings and/or continuous readings. This consists of obtaining data in the “as-found” condition and then after adding certain plant loads such that the engine produces a repeatable “high load” point of approximately 200 kW. The actual value of the high load data is dependent on the operational requirements of FWP and varies from 175-245 kW on average. A typical data sheet appears in Figure 23.

In addition to the engine-system and emissions data, CCC also completes a check of the controller setpoints to ensure there have been no changes to any of the tunable parameters. A sample of this checklist appears in Figure 24 on the following page.

Figure 24: CCC Valve Parameters Log sheet.

5.0 Discussion

To date, the project has met or exceeded the hoped for performance goals with regard to post-catalyst emissions and reliability. These permitted emissions remain at or near zero and the engine is responding well over a wide range of loads including periods during and after load changes. The on-going weekly data collection, planned to be performed under a separate research program will quantify any further changes required to the air/fuel ratio setpoint and as these become necessary. The emissions data and engine operating data will help to determine if the change is due to the performance of the catalyst, to degradation in engine performance or a result of drift of the oxygen sensors.

The Test Team found that at very low loads (near zero kW) operating conditions; the CO emissions would exceed the CARB 2007 limits. To remedy this, the team implemented a setpoint scheduled on engine load using air manifold pressure as an additional input. This solved the problem entirely even though the change in setpoint required was only from 16.90 to 16.94 or a change of 0.04 AFR. The team had hoped that the magnitude of the setpoint changes and the variations in emissions could be correlated and this data used as input for an adaptive control strategy based on post-catalyst NOx emissions. Clearly, the team realized this goal. What is particularly noteworthy is that an air/fuel ratio dither of ±0.04 AFR would probably accomplish the same goals. Based upon on going testing Continental Controls has underway, dithering of this magnitude will also provide much improved catalyst performance during large load transients.

As mentioned, based on previous work, CCC is aware that implementing a dithering strategy will greatly stabilize post catalyst carbon emissions as well as the already very stable NOx emissions. Contemporaneously, dithering will provide better catalyst performance during load transients. Examining the high and variable CO values, which occurred at idle conditions prior to the load scheduling of the air/fuel setpoint and during large load transients, it is clear to the project team that dithering would enable improved control even though currently averaged emissions over a 10-15 minute period yields emissions concentrations of ≤ 1PPMv corrected to 15% O2. Some of the lowest reported for this engine type.

An additional and somewhat unexpected finding was the length of time it took to “de-green” the new catalyst. It is somewhat unclear how much this effect had to do with when the catalyst was insulated, but clearly, there appears to have been a period of more than 100 operating hours during which the optimal air/fuel ratio setpoint changed. From an initial setpoint of 16.99 at commissioning to the current setpoint of 16.90 with some unpredicted increases in emissions early on. The emissions out of the catalyst also continued to drop after this period. As of this writing, the catalyst is providing reductions of NOx, CO and VOC’s of 99.99%.

As shown in Figure 21, the Continental Controls Test Team conducted an additional air/fuel ratio sweep. The sweep covered the range of 16.80 to 17.03 at .01 increments of AFR. Each measurement point consisted of the result of 15-minute averages of 0.1 second sampled data. Approximately 15-minutes elapsed between setpoint changes to permit the system to stabilize. Keep in mind that some load changes occur even during stead-state operation so the consistent performance shown in Figure 21 also contains averages having significant minor transients as plant loads automatically cycle on and off (e.g. air compressors).

6.0 Conclusions

- The EGC4 system is providing the improved performance required as testing the EGC4 with the original catalyst showed, the benefits of the pressure control system, venturi mixer and a very fast acting control valve add measurable benefit.
- The catalyst provided by DCL has performed according to specifications.
- At the present time, the catalyst is achieving a 99.9% reduction in both NOx, CO and VOC's.
- A dithering strategy, if implemented, is expected to further stabilize post-catalyst emissions and provide better performance during changes in load.
- Based on the small amount of changes required to the air/fuel ratio setpoint to achieve sub-1 PPMv emissions through the load range, a modest amount of dithering would eliminate the need for this additional input.
- The results of the analysis of the weekly data during the next several months provided valuable information on the degradation characteristics of NSCR equipped engines.

7.0 Recommendations

While the period of performance for this project is concluding, the work will carry-on under a companion project funded by the California Energy Commission and Southern California Gas Company. To that end, the Continental Controls Test Team offers the following recommendations:

- Continue to acquire and analyze weekly and/or continuous engine operating data and emissions readings.
- Continue to perform periodic air/fuel ratio sweeps to track the optimal O2 setpoint. Replacements of O2 sensors and catalyst elements shall help distinguish between changes in the air/fuel ratio setpoint necessitated by degradation of these sensors or the catalyst material.
- Implement a dithering strategy and re-test the effect of transient emissions performance.