Energy Research and Development Division
FINAL PROJECT REPORT

# ENGINE CHP EMISSION CONTROL TECHNOLOGY

Prepared for: California Energy Commission
Prepared by: DE Solutions, Inc.
Tecogen, Inc.

JUNE 2011
CEC-500-2013-087

**PREPARED BY:**

***Primary Author(s):***
Keith Davidson
Jean Roy
Ranson Roser

DE Solutions, Inc.
732 Val Sereno Dr
Encinitas, CA92024

Tecogen, Inc.
45 First Avenue
Waltham, MA 02451

***Contract Number: PNG-06-002***

***Prepared for:***

**California Energy Commission**

Rizaldo Aldas
***Project Manager***

Linda Spiegel
***Office Manager***
***Energy Generation Research Office***

Laurie ten Hope
***Deputy Director***
***ENERGY RESEARCH AND DEVELOPMENT DIVISION***

Robert P. Oglesby
***Executive Director***

# ACKNOWLEDGEMENTS

DE Solutions Inc. gratefully acknowledges the following participants:

- The Public Interest Energy Research (PIER) Program of the California Energy Commission, Contract # PNG-06-002, Rizaldo Aldas, Contract Manager, for financial support, technical guidance, and project oversight

- Southern California Gas Company, Steve Simons, Contract Manager, for financial support, technical guidance, project oversight, and commercialization assistance

- Tecogen, Inc., Jean Roy, Joe Gehret, Bob Panora, and John Freeman, for technical developments and management, laboratory and field testing, and commitment to successful market deployment

- Ranson Roser, for technical and project management support with the component evaluation, laboratory testing and field testing tasks

- University of California Irvine, Vince McDonell and Richard Hack, for the Rancho San Antonio Boys Home field test data analysis

- Rancho San Antonio Boys Home, Executive Director Brother John Crowe, for hosting the initial (robust traditional solution) field test

- City of San Fernando Regional Pool Facility, Public Works Director Ron Ruiz and Public Works Superintendent Nazri Hasbun, for hosting the two-stage catalyst field test

# PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

This is the Final Report for the *Engine CHP Emission Control Technology* project PNG-06-002. The information from this project contributes to Energy Research and Development Division's Environmentally Preferred Advanced Generation Program..

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

# ABSTRACT

This project successfully developed, designed and tested an ultra-low emission control system for rich burn internal combustion engines. The interest in this engine technology enhancement was driven by recent air criteria emission guidelines and requirements that have not yet been demonstrated on a sustainable basis. Cost-effective engine combined heat and power products are vital to achieving the California Air Resources Board targets for mitigating greenhouse gases.

The key innovation was a two-stage exhaust after-treatment catalyst that provided an elegant yet robust solution for achieving California Air Resources Board 2007 emission levels. The technology decouples nitrogen oxide control from carbon monoxide  and volatile organic compounds control in the respective catalyst sections. The first stage catalyst reduces nitrogen oxide to negligible levels at the expense of unacceptably high carbon monoxide by operating with a rich air/fuel ratio. Levels of carbon monoxide and volatile organic compounds can be attained that are considerably below California Air Resources Board 2007 guidelines with proper conditioning of the exhaust between the first stage and second stage catalyst. The system is also very tolerant of deviations in air/fuel ratio control.

The approach included a screening of emission control system components and software, laboratory testing, field testing, technology transfer and commercialization. Laboratory tests and field data demonstrated that the emission profile was well below California Air Resources Board 2007 levels and comparable to emissions from fuel cells.

Tecogen, Inc., a key subcontractor on the project team, is an established manufacturer of engine-driven combined heat and power and chiller products. Tecogen intends to incorporate this advanced emission system across its product line and also plans to make the technology available to non-Tecogen engine products.

Keywords:  Combined heat and power, CHP, reciprocating engines, rich burn engines, distributed generation

Please use the following citation for this report:

Davidson, Keith, Roy, Jean, and Ranson Roser (DE Solutions, Inc., Tecogen, Inc.). 2011. ***Engine CHP Emission Control Technology.*** California Energy Commission. Publication Number: CEC-500-2013-087.

# TABLE OF CONTENTS

# LIST OF FIGURES

## LIST OF TABLES

# EXECUTIVE SUMMARY

## Introduction

California has established strong policies and regulations that encourage the increased use of combined heat and power (CHP) systems. These include:

- The California Air Resources Board's (CARB) scoping plan implementing Assembly Bill 32, the Global Warming Solutions Act of 2006, which set into law goals to reduce greenhouse gas emissions in the state by 2020.
- Governor Edmund G. Brown Jr.'s energy strategy to boost CHP use by 6,500 megawatts (MW) over the next 20 years.
- Legislation to make fossil-fueled CHP systems eligible for the California Public Utilities Commission's Self-Generation Incentive Program (SGIP) and to allow users to sell excess power to the grid.

A 2009 California Energy Commission report, *Combined Heat and Power Market Assessment*[1] projected that by 2020 California would be able to produce 1,700 megawatts (MW) of electricity from CHP systems smaller than 5 MW. This market segment would primarily be served by engines projected to be the most cost-effective technology in that size range. The assessment assumed that these engines would be able to comply with the tightening emission regulations in California.

However, such engines have been unable to keep pace with the stringent air regulations, guidelines and legislation implemented over the last several years in California. These include:

- CARB guidelines to the local air districts requiring new distributed generation (DG) to achieve standards equal to the best available control performance from central station power plants.
- A South Coast Air Quality Management District (SCAQMD) rule requiring new DG engines to meet the CARB guidelines for nitrogen oxide (NOx) while appreciably lowering carbon monoxide (CO) and volatile organic compounds (VOC) limits from previous levels.
- A state-wide requirement that DG meet the CARB guideline for NOx to be eligible for the SGIP and to sell back excess electricity to the grid.

Complying with these new and expanding emission rules represents a formidable technology leap for reciprocating engines.

## Project Purpose

The project goal was to develop and test ultra-clean emission control technology for rich burn engines that surpasses CARB 2007 emission guidelines in a robust fashion and on a sustainable

---

[1] *Combined Heat and Power Market Assessment*, California Energy Commission Report CEC-500-209-094F, April 2010.

basis, without the need for frequent portable emission analyzer checks and field adjustments. A rich burn engine operates slightly rich in fuel so that the exhaust has low oxygen ($O_2$) content, enabling a three-way catalyst to reduce the NOx into nitrogen ($N_2$) and $O_2$, and have the $O_2$, react with CO and VOCs to produce inert gases. Rich burn engine technology with three-way catalysts (TWCs) has been employed in gasoline automobiles for decades. The cost premium for the advanced emission package was to be less than 10 percent of the cost of existing CHP systems.

In a conventional TWC, NOx is minimized in a rich air/fuel (A/F) mixture that uses more fuel than is optimal. CO emissions are minimized in a lean A/F mixture that uses less fuel than optimal. The A/F ratio (AFR) range where both NOx and CO are in compliance with CARB 2007 levels is very narrow. An $O_2$ sensor is used upstream of the catalyst to maintain the AFR at a preset control point. These levels have been temporarily achieved by using a robust catalyst, post catalyst $O_2$ sensor feedback and precise AFR control, but maintaining these levels over time has proven to be very difficult.

## Project Results

The project was divided into three tasks with various subtasks associated with design, development, laboratory testing, and field testing.

1. Control Software and Component Screening. State-of-the-art emission control software platforms and various technology components and methods were evaluated for their ability to meet program goals. The screening process covered TWCs, oxygen sensors, supplemental oxidation catalyst strategies, AFR controllers, control methodologies, high-energy ignition systems and exhaust gas recirculation.
2. Laboratory Performance Testing. Laboratory experiments targeted areas where Tecogen's current exhaust-after-treatment approaches could be enhanced to achieve compliance with CARB 2007 DG limits. Three-way catalysts were tested, as well as universal exhaust gas oxygen sensors, exhaust air injection with supplemental oxidation catalysts, dithering air/fuel ratio controls, capacitive discharge ignition, and exhaust gas recirculation.
3. Field Verification. Two existing Tecogen CHP sites were retrofitted with different advanced emission control systems. The Rancho San Antonio Boys Home CHP unit employed a more traditional emission treatment, but incorporated a robust TWC with a downstream $O_2$ sensor that provided active feedback to the upstream $O_2$ sensor to optimize the control set point. The City of San Fernando Regional Pool Facility CHP unit employed upstream and downstream $O_2$ sensors with a novel two-stage catalyst for the best control of NOx in the first stage and optimal control of CO and VOC in the second stage.

The two-stage catalyst technology provided an elegant yet robust solution to achieving CARB 2007 emission levels. The technology decoupled NOx control from CO control in the respective catalyst sections. The first stage catalyst reduced NOx to negligible levels at the expense of unacceptably high CO by operating with a rich AFR.

A key innovation coupled proper conditioning of the exhaust from the first stage catalyst into a second stage catalyst, resulting in a system that produced CO and VOC emission levels considerably below CARB 2007 guidelines. Furthermore, the system was very tolerant to deviations in A/F ratio. Laboratory tests and field data demonstrated that the emission profile is well below CARB 2007 levels and comparable to emissions from fuel cells.

The project reviewed various AFR control strategies and hardware control systems, along with wide-band oxygen sensors or universal exhaust gas oxygen sensors (UEGO) and their controllers and catalysts. A UEGO sensor measures oxygen content in an exhaust stream. Its signal has a linear relationship with $O_2$ concentration. An initial screening process obtained information through literature searches and inquiries to manufacturers and their vendors, which team members considered in light of Tecogen product characteristics. The project team then agreed on a technical direction and created a preliminary laboratory test plan that was followed with some deviations as tests proceeded.

The project team conducted a series of experiments in the Tecogen test cell. From this work, the following results were obtained:

- Tecogen's standard Süd-Chemie catalyst for commercial applications did not comply with the CARB 2007 DG limits.
- DCL International's (DCL) robust TWC produced compliant engine emissions and was selected for field testing where longer-term emissions characteristics could be observed.
- The two-stage after-treatment approach demonstrated a significant reduction in emissions below the CARB-2007 levels and showed increased tolerance to changes that occur with AFR set-point. This after-treatment process was also selected for field testing.
- AFR dithering did not demonstrate emissions benefits in comparison to the standard steady-state fuel control process.
- Three different UEGO controllers using two different UEGO sensors failed to provide Tecogen's AFR controller with signals stable enough for precise closed-loop fuel control, presumably due to noise interference from the inverter.
- Exhaust gas recirculation (EGR) lowered engine efficiency on the Tecogen engine and increased post-catalyst CO without any offsetting benefit. Tecogen's naturally aspirated engine is not conducive to EGR operation, which would necessitate reducing the power output.
- No changes were observed when operating the engine with a high-energy capacitive discharge ignition system, even when tested with EGR. The stock ignition system and the capacitive discharge system produced similar results during efficiency and emission testing.

The project team performed long-term field monitoring of the emissions from two CHP customer host sites retrofitted with enhanced exhaust after-treatment equipment designed and laboratory tested to achieve CARB 2007 DG limits. The Rancho San Antonio Boys Home field test demonstrated the capabilities of a traditional but robust TWC assembly in a test period that lasted from July to November 2009. The San Fernando Municipal Pools (SFP) field test began collecting data from a two-stage after treatment approach in June 2010 and continued to demonstrate positive results through May 2011. The results from the field test program are summarized below.

- The traditional three-way catalyst approach using a 50 percent oversized catalyst manufactured by DCL could not produce CARB compliant emissions for more than a few months of engine operation, even if the maximum CHP thermal credit were taken.
- The two-stage after-treatment approach with proper exhaust conditioning and supplemental air injection prior to the second stage catalyst complied with CARB DG requirements on Tecogen's CHP unit at SFP. Figures ES-1 and ES-2 show the daily results over the course of the field test period.

**Figure ES- 1: Daily CO Averages from SFP Field Test**

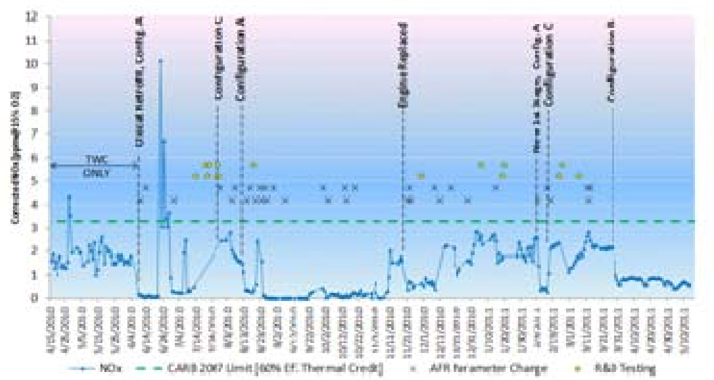
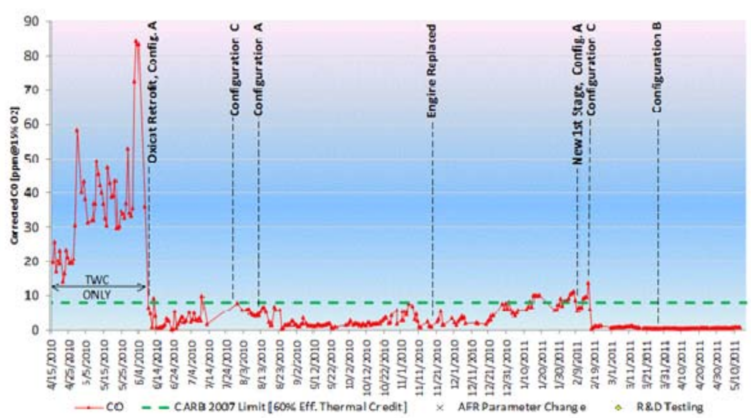



**Figure ES- 2: Daily CO Averages from SFP Field Test**




- Performance results were most appropriately described for the time period starting March 28, 2011, after which no corrective or investigative modifications were made. The first stage TWC was replaced in February 2011.

- Over 3,900 two-minute emissions samples were recorded since March 28, 2011, and 99.9 percent of the $NO_x$/CO samples were compliant with CARB 2007 DG limits, even without the CHP thermal credit.

The project met its objective and future Tecogen product offerings will incorporate the advanced emission feature. The authors formed the following conclusions:

- The robust traditional approach with a single catalyst did not demonstrate sufficient degradation margin, control tolerance, or sustainability to warrant a commercial offering where continuous emissions compliance with CARB 2007 is required.
- The two-stage catalyst approach widened the tight AFR compliance window. This approach coupled with Tecogen's AFR control algorithms demonstrated superb and sustainable performance once the optimal exhaust conditioning levels were established.
- The confidence developed in the two-stage catalyst solution for ultra-low emission air districts and for maintaining compliance in less stringent air districts led to Tecogen's commitment to integrate this advanced emission technology into its product line. Three 100-kilowatt (kW) INV-100 units containing the advanced emission control system were delivered to the Sacramento Municipal Utility District for start-up in late 2011 as part of a microgrid demonstration project.
- The project met its economic target of a 10 percent or less cost premium over the baseline product. The current cost estimate is for a cost premium of three percent or less.

The authors' recommendations included:

- Continue monitoring the San Fernando Pools field test unit to gain additional field experience, to fine-tune control and performance, to develop a maintenance schedule and to gauge the life of the advanced components.
- Demonstrate the two-stage concept with the second stage configured with a true oxidation catalyst. To date, the two-stage after-treatment concept has been demonstrated using TWC products in both stages. Cost savings without performance degradation are expected.
- Develop and deploy retrofit kits for non-CHP Tecogen products. This process would demonstrate the performance versus cost implications of the two-stage strategy over a broader array of Tecogen engine products.
- Demonstrate the efficacy of this technology to non-Tecogen stationary engine products used in CHP and mechanical drive systems.

## Project Benefits

Combined heat and power provides numerous benefits to California ratepayers. CHP provides ultra-high natural gas use efficiencies that conserve natural gas resources on California's gas distribution system and can achieve combined electric and thermal efficiencies of 80 percent or more. CHP also reduces greenhouse gas emissions from conventional fossil energy sources, eliminates transmission and distribution losses, and reduces or eliminates grid congestion. In addition, CHP provides commercial, institutional, industrial and multi-family residential energy users with an option to curb energy costs and boosts power reliability for business adopters.

Engines are the most cost-effective CHP technology that is less than 5 MW in size. Engines are expected to account for approximately 1,500 MW of new CHP in California over the next twenty years, assuming a cost effective emission-control solution for engines and proactive state policies toward CHP[2]. This equates to avoided $CO_2$ emissions of about 1.6 million metric tons and natural gas consumption of 23 trillion British thermal units (BTUs) in 2029.

[2] Estimate based on *Combined Heat and Power Market Assessment*, California Energy Commission Report CEC-500-209-094F, April 2010.

# CHAPTER 1: Introduction

## 1.1 Background and Overview

### 1.1.1 State Policy and Regulatory Drivers

Combined Heat and Power (CHP) has become an important element of California's energy and environmental policy. Significant policy and regulatory drivers exist to increase the use of Combined Heat and Power (CHP) in California:

- The 2008 California Air resources Board (CARB) Scoping Plan[3], implementing AB 32, identified CHP as an important contributor to meeting California's Greenhouse Gas (GHG) reduction targets. CARB targeted CHP for 6.7 metric tonnes (MT) of reduction by 2020 corresponding to 4,000 MW of new CHP capacity.
- The 2009 California Energy Commission CHP Market Assessment[4] examined the remaining technical potential for CHP in California and assessed market penetration for various regulatory scenarios.
    - The assessed scenarios included $CO_2$ offset payments, incentives and electricity export to the grid. Of the various scenarios considered, the mid-range projection matched up with the CARB 2020 target.
    - For the case with incentives and $CO_2$ offset payments, the projected new CHP implementation is 1,700 MW for CHP systems < 5 MW. This market segment would primarily be served by engines which are projected to be the most cost-effective technology in that size range. The assessment assumes that engines will be able to comply with the tightening emission regulations in California.
- One of the steps in Governor Brown's eight point energy strategy is to increase the use of CHP in the State by 6,500 MW over the next twenty years.
- Recent legislation has been enacted to promote greater adoption of CHP.
    - AB 1613 allows for sellback of excess electricity generated from CHP systems designed to match the thermal load.
    - SB 412 enables fossil CHP to be eligible for the Self-Generation Incentive Program (SGIP)

### 1.1.2 Air Quality Regulations

On November 15, 2001, the California Air Resources Board (CARB) adopted a regulation that established a distributed generation (DG) certification program as required by Senate Bill 1298 (chaptered September 2000). The DG certification program requires manufacturers of electrical generation technologies that are exempt from district permit requirements to certify their

---

[3] *Climate Change Scoping Plan – a Framework for Change,* prepared by the California Air Resources Board for the State of California, December 2008

[4] Combined Heat and Power Market Assessment, prepared by ICF International for the California energy Commission, October 2009

technologies to specific emission standards before they can be sold in California. These technologies include micro turbines and fuel cells. The standards were phased in over time with non-permitted DG required to achieve standards equal to the best available control performance from existing central station power plants by 2007. CARB issued like guidance to the local air districts for permitted DG which generally includes reciprocating engines and gas turbines. The recommended DG thresholds also include a thermal credit for CHP systems that operate in the field with at least 60 percent combined electric and thermal efficiency (HHV). Whereas, gas turbine Best Available Control Technology (BACT) was already at or near the CARB Guideline, these emission control levels represented a formidable technology leap for reciprocating engines.

These limits, which have become known as the CARB 2007 DG standard, have been partially adopted by The South Coast Air Quality Management District (SCAQMD) for DG. SCAQMD Rule 1110.2, as amended in 2010, lowered the emission limit for new DG engines and instituted a requirement for more frequent emission measurements to better ensure continuous compliance. For typical rich burn engine CHP systems meeting the 60 percent total efficiency criteria, the CARB 2007 and SQAQMD requirements are shown in Table 1-1 along with the best Available Control Technology (BACT) levels applicable to non-DG engines, DG engines outside SCAQMD and DG engines that existed prior to the amended Rule 1110.2. As shown, the new emission thresholds require a threefold reduction in $NO_x$ and a nine fold reduction in CO for CARB 07 (factor of four reduction in CO for SCAQMD).

**Table 1-1: Emission Regulations**

| | Lb/MW-hr | | ppm @ 15% O | |
|---|---|---|---|---|
| | NOx | CO | NOx | CO |
| CARB 07 Limit* | 0.07 | 0.1 | 3.3 | 7.9 |
| SCAQMD DG Limit* | 0.07 | 0.2 | 3.3 | 15.7 |
| BACT Limit | N/A | N/A | 9.3 | 61 |

* With minimum allowable heat recovery credit

In addition, the CARB 07 0.07 lb/MW-hr NOx threshold is a state-wide fossil fuel DG eligibility requirement for the Self-Generation Incentive Program (SB 412) and for sell back of excess generation to the utilities (AB 1613).

### 1.1.3 Rich Burn Engine Technology State of the Art

In a conventional 3-way catalyst, NOx is minimized in a rich air/fuel (A/F) mixture (more fuel than stoichiometric). CO emissions are minimized in a lean A/F mixture (less fuel than stoichiometric). The A/F ratio range where both NOx and CO are in compliance with CARB 07 levels is very narrow. These levels have been temporarily achieved with a robust catalyst, post catalyst $O_2$ sensor feedback and precise air/fuel ratio control (AFRC), but maintaining these levels over time has proven to be very difficult.

## 1.2 Project Goals

The project goals were to develop and test ultra clean emission technology for small to medium (60 – 1,000 kW) engine CHP systems that 1) exceeds CARB 2007 emission guidelines; 2) provides control techniques for robust CARB 2007 emission compliance on a sustainable basis without the need for frequent hand held emission analyzer tests; and 3) has a cost premium less than 10 percent of existing CHP systems.

## 1.3 Report Structure

Section 2 outlines the project approach including task organization and description. Subsequent sections report the findings of the control software and component screening, laboratory performance testing and field testing. A technology transfer plan follows that describes target markets and commercial deployment strategies. The final section delineates key conclusions and recommendations from the research and development project.

# CHAPTER 2: Project Approach

The objective of this project was to increase acceptance of small (< 5 MW) CHP in California through the development of cost-effective ultra-clean and sustainable emission technology for rich burn reciprocating engines. The project was focused on Tecogen CHP products that prior to this project incorporated state-of-the-art packaging, utility interface features and emission technology. The starting point for this project was Tecogen's air/fuel ratio control (AFRC) system that emulates automotive practice with oxygen sensors upstream and downstream of the catalyst to enable self-correcting adjustments to the AFRC control setting as operating conditions change. The project was divided into three technical tasks leading to a robust emission control solution and development of a commercial deployment strategy to maximize the market impact.

## 2.1 Control Software and Component Screening

The goal of this task was to identify automotive emission control software platforms, and air/fuel ratio and exhaust after-treatment components that show the best potential for reaching CARB 2007 emission targets when adapted to operate on stationary, natural gas-powered engines. The activities included:

- A review of state-of-the-art emission control system components and methods. These components and methods were evaluated for suitability for small- to medium-sized natural gas engines. Components and methods that were screened include:
    - Three Way Catalysts (TWC);
    - Oxidation catalysts and methods for air injection;
    - Narrow- and wide-band $O_2$ sensors;
    - Air/fuel ratio controllers; and,
    - High energy ignition systems
- The performance of candidate components were profiled based on:
    - Manufacturer specifications and cost; and
    - Reconnaissance on performance, degradation, durability, drift, control, ease and frequency of maintenance, manufacturer's ability to support the project, and other non-emissions related attributes
- A screening was conducted for components and suppliers for components and methods that warranted detailed evaluation.
- The initial control software to operate the candidate components during laboratory testing was adopted

## 2.2 Laboratory Performance Testing

The goals of this task were to characterize component and emission system performance over a range of operating conditions; and to maximize the functionality of the emission system to achieve CARB 2007 emissions with minimal sacrifice to CHP system performance and cost.

The testing was performed on the Tecogen 7.4 liter engine. In preparation for the test series, a test plan was developed, instrumentation was procured and the test cell at Tecogen was up-fitted. The test cell was configured to allow easy retrofit of components. The test sequences were designed to find an optimal combination of electromechanical components, catalysts, and control algorithms. The final configuration was incorporated into the field test units.

The following activities were conducted:

- Characterized the aging effect of O2 sensors and catalysts
- Examined exhaust gas recirculation (EGR) to lower NOx production without severely impacting engine peak power.
- Compared the emissions performance capability of dithering and non-dithering air/fuel ratio control strategies
- Tested the impact of a downstream oxidation catalyst and the mechanisms for inducing air flow into the exhaust for downstream oxidation.
- Investigated NOx and CO emissions performance as a function of load

## 2.3 Field Verification Testing

The goal of this task was to verify performance of the developed emission systems under field conditions. Two operating CHP sites were selected field testing. Each of these sites was retrofitted with the enhanced emission control system, diagnostics, alarms and instrumentation per the Test Plan. Activities included:

- Testing at each of these sites was conducted over 6 month periods equipped with on-site semi-continuous emissions measuring systems capable of detecting and documenting deviations in CO and NOx emissions.
- Collected, reduced and assessed emission and relevant engine performance data
- Documented field test findings and verified attainment of performance targets in field verification reports.
- The nature of any observed deviations were documented and analyzed. Appropriate adjustments were made to the field test units to resolve any performance discrepancies.

## 2.4 Technology Transfer Plan

The goal of this task was to provide information on the ultra-low emission engine technology to key market participants to enable engine CHP to continue as a technology option in California. Activities included:

- Prepared a Technology Transfer Plan that explains how the knowledge gained in this project will be made available to the public. Information to be transferred includes, process flow and instrumentation diagrams, key component descriptions, test facility setup, and test results. The plan identified important CHP market participants active in California. Participants include:
    - State Government
    - Local air pollution control districts
    - Utilities

    - Energy service companies
    - Engine system packagers and manufacturers
    - Emission control equipment manufacturers (such as catalysts, air/fuel ratio controls, sensors, and so forth)
    - Professional Associations (such as ASME)
- Prepared a white paper on Internal Combustion Engine (ICE) CHP Environmental Regulations and State Energy Policy with linkage to advanced emission control technology developed through this project.
- Identified forums and methods to achieve the technology transfer objectives. This includes technical papers and power point presentations at key conferences and workshops and one-on-one meetings with select market participants. These activities are planned after the patent application is published in November 2011.

Conducted technology transfer activities in accordance with the Technology Transfer Plan. These activities were reported in the Monthly Progress Reports but were intentionally limited until the patent application is published, which is expected to be around November 2011.

# CHAPTER 3: Control Software and Component Screening

The screening process covered three-way catalysts, oxygen sensors, supplemental oxidation catalysts strategies, air/fuel ratio controllers and general control methodologies, and high-energy ignition systems. This chapter discusses the results of the screening process including a brief discussion on the control software features needed for operating the selected components.

## 3.1 Baseline Product Description

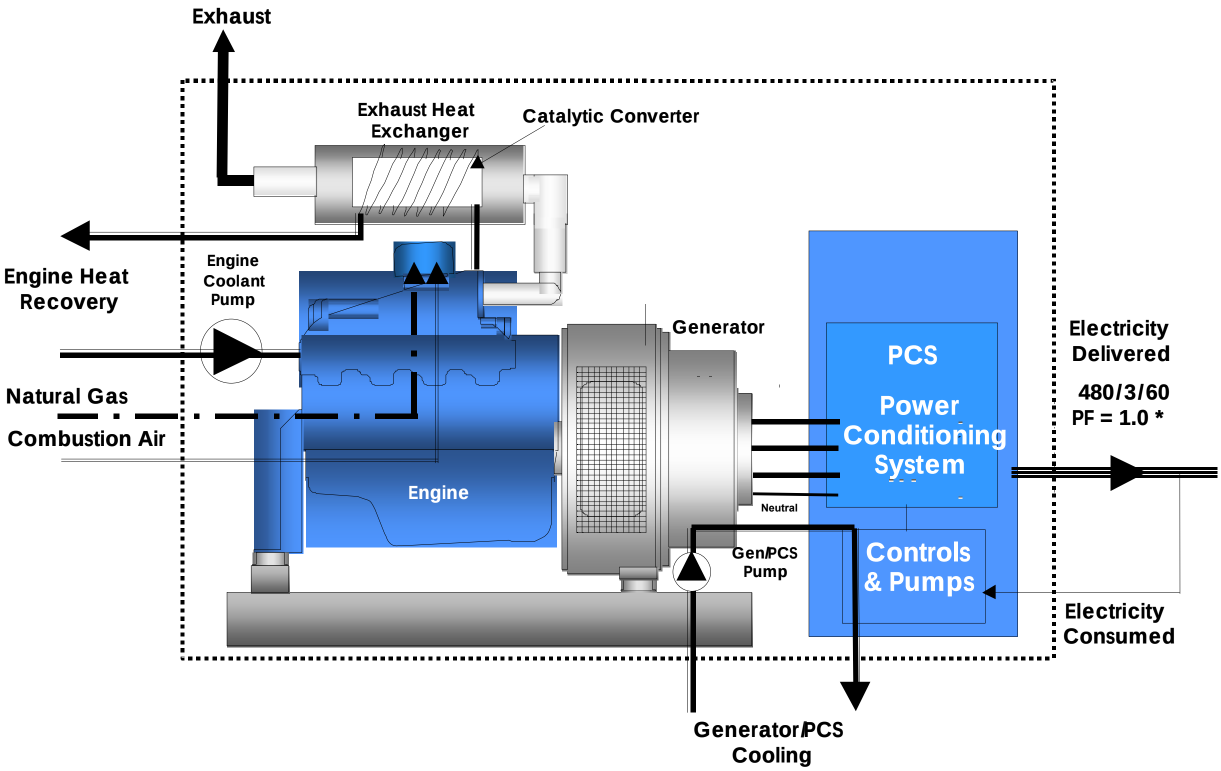
Tecogen has manufactured natural gas reciprocating engine driven products for more than two decades. The engine has been the cornerstone of all the product lines, with cogeneration modules ranging from 60 kW to 100 kW and chillers ranging from 50 tons to 400 tons. Tecogen's primary engine is a 454 cubic inch displacement, naturally aspirated, spark-ignited, V-8 gas engine, with a robust design for continuous duty operation. It is equipped with a customized factory emission control system that continues to evolve to meet very challenging and impending state and local regulations. This engine, along with Tecogen's prior emission control system, serves as the foundation for this project.

### 3.1.1 Premium Power CHP Unit

With the assistance of PIER funding (CEC Contract #500-03-009), Tecogen Inc. developed a 100 kW Premium Power CHP unit. It is a natural-gas, engine driven, inverter-based unit that can provide grid-tie operation, as well as standalone power in the event of a blackout. The engine drives a water-cooled permanent magnetic generator (PMG) at variable speed. The engine is operated over a wide speed range, depending on the load requirement, resulting in a variable frequency output from the PMG. The Power Conditioning System (PCS), which includes a rectifier and inverter, converts the PMG output to high quality 60-Hertz power. This variable speed operation maximizes fuel efficiency at part load, as well as allows for a "peaking" mode of 125 kW for several hundred hours per year. A Boundary Diagram of the unit is presented in Figure 3-1.

This Premium Power CHP system was considered to be the best choice of the Tecogen products for the consideration of the advanced emissions controls screening process. In some respects it required the least amount of modification since it already had Tecogen's most recent innovations in emission control technology, including AFR control using pre- and post-catalyst oxygen sensors. Lastly, the development of this Premium Power CHP module was funded by PIER because of the significant market potential in California, which makes it an ideal candidate for introducing the ultra-low emissions technology developed by this program.

**Figure 3-1: Boundary Diagram**




## 3.1.2 Unique Catalyst Housing Assembly

Tecogen's 100 kW Premium Power catalytic converter resides in a unique patented assembly that combines the functions of emissions reduction with exhaust heat recovery into a small envelope. The catalytic converter resides within a cylinder in the center of the heat exchanger. Finned heat recovery water tubing coils around the exterior of the cylindrical catalyst housing. This assembly is then mounted within a larger diameter cylindrical-shaped housing. This configuration safely manages the heat emitted by the catalyst in an unobtrusive way, which is a key design element in a compact, enclosed, piece of equipment.

Referring to Figure 3-2, the hot exhaust gas from the engine (~1220-1270 °F) first flows over the catalyst for treatment ($NO_x$ reduction and CO/VOC oxidation), where it picks up additional heat from the catalytic exothermic reaction. The flow then changes direction (180°) and flows over the water coil where it transfers heat to the engine coolant. Then, the cooled exhaust gas (~280 °F) discharges from the heat exchanger and catalyst housing via a stack. Figure 3-2 presents a schematic of the Exhaust Catalyst/Heat Exchanger assembly.

Whereas it is quite common for either the exhaust heat exchanger, the catalytic convertor, or both to reside outside the shell of an enclosed CHP module, Tecogen's patented TWC/EHRU design has allowed the combined functions to be positioned directly over the generator on the inside of a compact CHP enclosure (see Figure 3-3). However, this unique packaging also presents a challenge to Tecogen with respect to designing an enhanced emissions control system to meet the objectives of this program due to the finite space available for inserting additional TWC substrate volume. Lengthening the TWC/EHRU assembly would be a simple design change for the assembly itself, but there is effectively no extra length available within the interior of the Premium Power package. An increase in the diameter of the catalyst housing would represent a major design change to the entire TWC/EHRU assembly and is thus not desirable. Furthermore, the sharp reduction of exhaust gas temperature after the catalyst substrate portion of the assembly excludes the option of simply mounting an additional catalyst assembly downstream of the combined TWC/EHRU module because the exhaust gas temperature would be too low to promote further conversion reactions.

The description of the current catalyst assembly above is important because it provides important dimensional constraints presented to catalyst suppliers as part of the screening process. In order to prevent a major CHP package and core component redesign changes, the enhanced emissions reduction capabilities from a candidate TWC supplier were constrained to a 10.5″ x 13″ envelope with a practical backpressure limitation of 8 inches $H_2O$.

**Figure 3-2: Detailed Schematic of Exhaust Catalyst and Heat Exchanger Assembly**

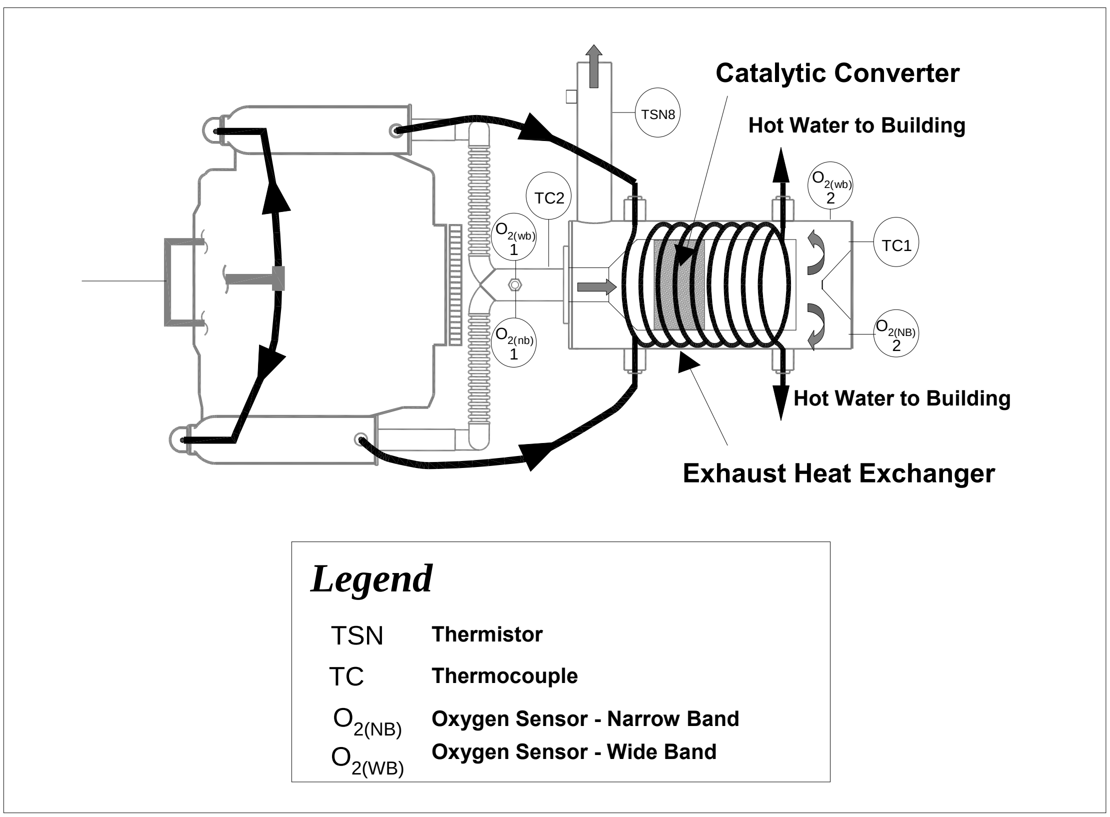
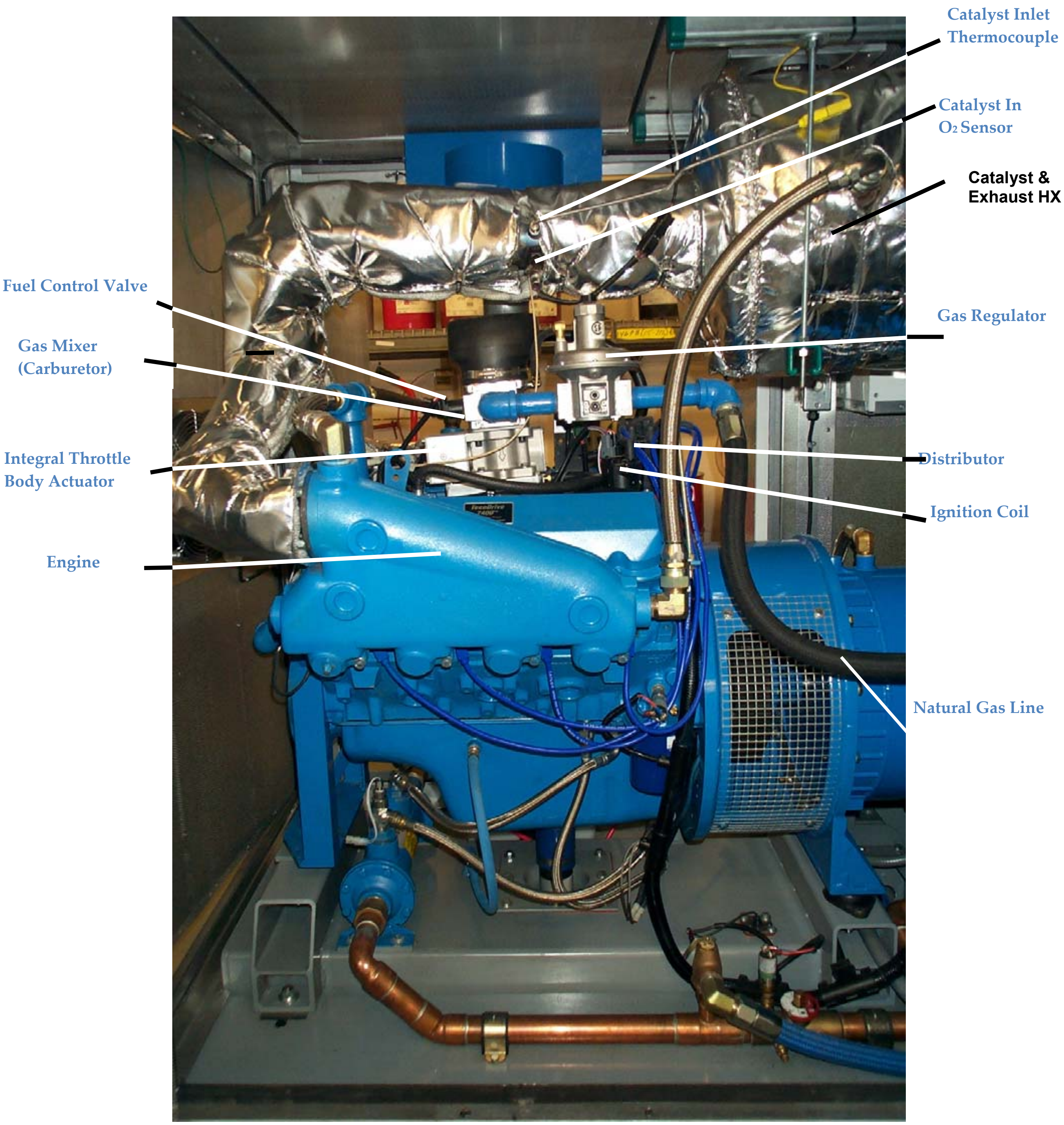


**Figure 3-3: Premium Power Unit Emissions Control System**



### 3.1.3 Fuel Delivery System

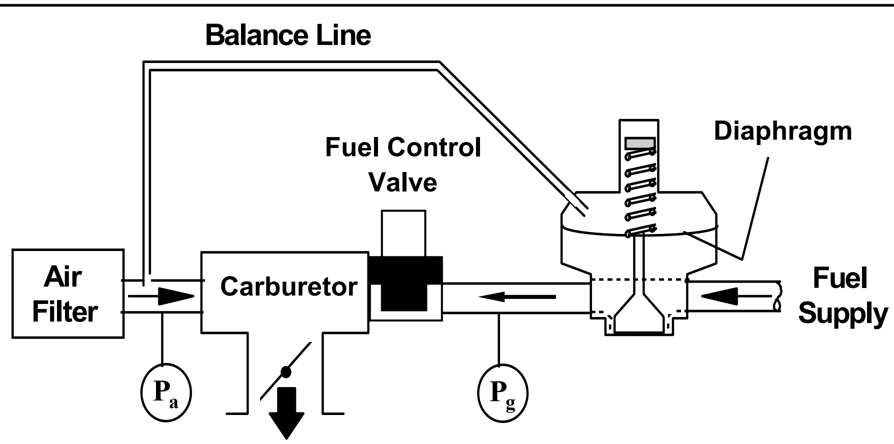
Tecogen's commercial natural gas fuel system for its current line of engine-driven products includes a gas regulator, a fuel control valve, a carburetor, and a throttle body. The system is depicted schematically in Figure 3-4. It is classified as a low pressure gas system, requiring less than 1 psig pressure into the unit.

The gas pressure regulator is a "Zero Governor" or "Zero Pressure" type, designed to reduce the gas pressure entering the carburetor to close to zero for safety reasons. The regulator is equipped with a balance line that compensates the fuel pressure, as the air filter becomes more restrictive over time. Figure 3-4 depicts the balance line connected to the gas regulator's vent connection and contains a brief explanation of its purpose. The regulator's adjustment is critical to the operation of the emission control system.

The fuel control valve is a stepper motor-driven valve, precisely controlled by the unit's microprocessor control system. It adjusts the fuel flow to maintain a stoichiometric air/fuel mixture based upon feedback of the two heated exhaust gas oxygen (HEGO) sensors in the exhaust system.

The carburetor-mixer is a venturi type, with no diaphragms or valves, which allows a more uniform fuel/air mixture to be delivered to the cylinders. Combustion air, drawn through the air filter by natural aspiration, mixes with the fuel in the carburetor-mixer before it is fed through the throttle to the intake manifold. The throttle is controlled by an electrical actuator as part of the governor speed control system.

**Figure 3-4: Fuel System Schematic**




As air filter restriction is increased, the corresponding pressure $P_a$ decreases. With the balance line, the gas regulator reduces $P_g$ relative to $P_a$ maintaining a constant air/fuel ratio.

### 3.1.4 Air/Fuel Ratio Control System

The air/fuel ratio (AFR) is controlled by precise manipulation of the stepper motor-driven fuel valve based on closed-loop control using feedback from the system's pre-catalyst and post-catalyst HEGO sensors. The HEGO sensors produce voltage outputs that are indicative of oxygen content or other related surrogate parameters such as AFR, equivalence, or lambda in a narrow region near the stoichiometric point where simultaneous high efficiency conversion of $NO_x$, CO, and VOCs occur in three-way catalysts.[5] The upstream $O_2$ sensor performs the primary (fast acting) AFR control function because it can respond to changing exhaust conditions much faster than the post-catalyst HEGO sensor which produces signals that are delayed by the chemical storage, release, and conversion reactions within the catalyst assembly. However, the post-catalyst location offers advantages for HEGO accuracy including: 1) reduced signal error due to much lower levels of CO and $H_2$ which have a cross-sensitivity to HEGO sensor's oxygen response; 2) reduced sensor fouling rates due to the catalyst's propensity to catch exhaust fouling agents and; 3) the its ability of the post-catalyst sensor to more accurate identify the net chemical status of the catalyst. Other monitored parameters that contribute to Tecogen's current fuel control algorithms are load (kW) and engine intake manifold pressure (MAP).

An important aspect of Tecogen's closed-loop AFR process is that the control algorithms have been executed by Tecogen's CHP system control microprocessor since about 2004, thus negating the need to purchase an external stand-alone controller. This has provided desirable cost savings while also providing Tecogen the flexibility to experiment with prototype control algorithms, as needed, without having to train personnel on multiple control platforms

## 3.2 Screening of Candidate Emissions Control Technologies and Methodologies

In order to achieve the goals of this program, Tecogen explored modifications to its existing emissions strategies regarding components and methodologies. To this end, a screening process was undertaken to consider upgraded three-way catalysts, alternative AFR controllers, or the general methodologies applied by the alternative controllers, wide-band oxygen sensors, the use of post-TWC air injection followed by supplemental oxidation catalyst, and ignition systems.

### 3.2.1 AFR Controllers and Product Features

Tecogen performed a basic review of stand-alone AFR controllers and their primary features to determine whether or not emissions reduction advancements sought in this program would be explored using Tecogen's existing hardware and software with modifications as needed, or

[5] Lambda is a common unitless engineering expression for the relative air-fuel ratio, or the actual air-fuel ratio in comparison to the stoichiometric air-fuel ratio for the given fuel. Equivalence is just the inverse of lambda. If an engine is operating at the stoichiometric air-fuel ratio, then lambda and equivalence equate to 1. Lean operation results in lambda > 1 and equivalence < 1, with the opposite relationships for rich operation.

with entirely independent AFR controller products. Several AFRC systems were reviewed through literature searches, team experience, and contacts with vendors. Highlighted features are described below.

#### *3.2.1.1 Load-Based AFR Control Targets*

All AFRC systems used for TWC after-treatment are programmed to adjust fuel flow to achieve post-combustion exhaust chemistry within a very tight window near the stoichiometric AFR. Depending on the brand of controller, the user enters a target for one of the following parameters; HEGO voltage, UEGO control analog output voltage, lambda, equivalence, AFR, or UEGO pumping current. It was once common for many brands of AFR controllers to have only one programmable target for the entire load regime. However, it is more common today for controllers to have a means of changing the AFR target based on another independent parameter, such as engine load. Figure 3-5 gives an example of the range of flexibility of one AFR controller screened, the Compliance Controls Model MEC-R. The MEC-R has mobile application heritage and can execute closed-loop AFR control using pre-catalyst and post-catalyst strategies. Figure 3-4 shows the MEC-R offers the emissions calibrating engineer the option to specify up to sixty-four individual equivalence ratio (Greek symbol phi, $\phi$) targets for both the pre-catalyst and post-catalyst HEGO sensors based on the operating load (manifold absolute pressure) and the engine speed with interpolation used for the areas between points.

Whether or not load-based AFR targets are necessary may be highly dependent on other aspects of the AFR control system or expected speed and load profile of the engine's end use. In one example, AFR controllers using a non-heated oxygen sensor would likely find the EGO target that results in the lowest TWC emissions change as a function of load because the EGO sensor's output voltage is affected by temperature which will change with engine load. In another example, engines that only operate at a fixed load do not justify significant research into emissions control at other loads. Tecogen currently uses load-based adjustments to pre-catalyst HEGO targets, thereby making it a relevant screening consideration for alternative AFR controllers.

**Figure 3-5: Example of Load-based AFR Targets**

Pre-Cat Phi Target (Base)

| Speed (rpm) \ MAP (psia) | 3.0 | 6.0 | 9.0 | 12.0 | 15.0 | 18.0 | 21.0 | 25.0 |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 200 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 400 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 |
| 600 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 |
| 800 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 |
| 1000 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 | 1.025 |
| 1200 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 |
| 1800 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 | 1.018 |

Phi

Post-Cat Phi Target Table

| Speed (rpm) \ MAP (psia) | 3.0 | 6.0 | 9.0 | 12.0 | 15.0 | 18.0 | 21.0 | 25.0 |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 200 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 600 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 |
| 800 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 |
| 1000 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 | 1.005 |
| 1200 | 1.013 | 1.012 | 1.011 | 1.010 | 1.010 | 1.010 | 1.010 | 1.010 |
| 1800 | 1.013 | 1.012 | 1.010 | 1.010 | 1.010 | 1.010 | 1.010 | 1.010 |

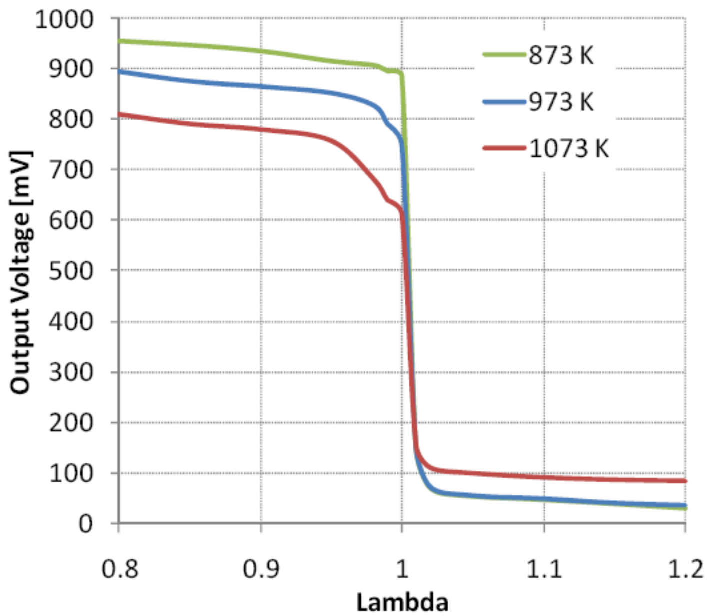
Phi-Target (phi)

(Courtesy: Compliance Controls MEC-R Controller Software Screen Capture)

### *3.2.1.2 Advanced Closed-Loop HEGO Heater Control*

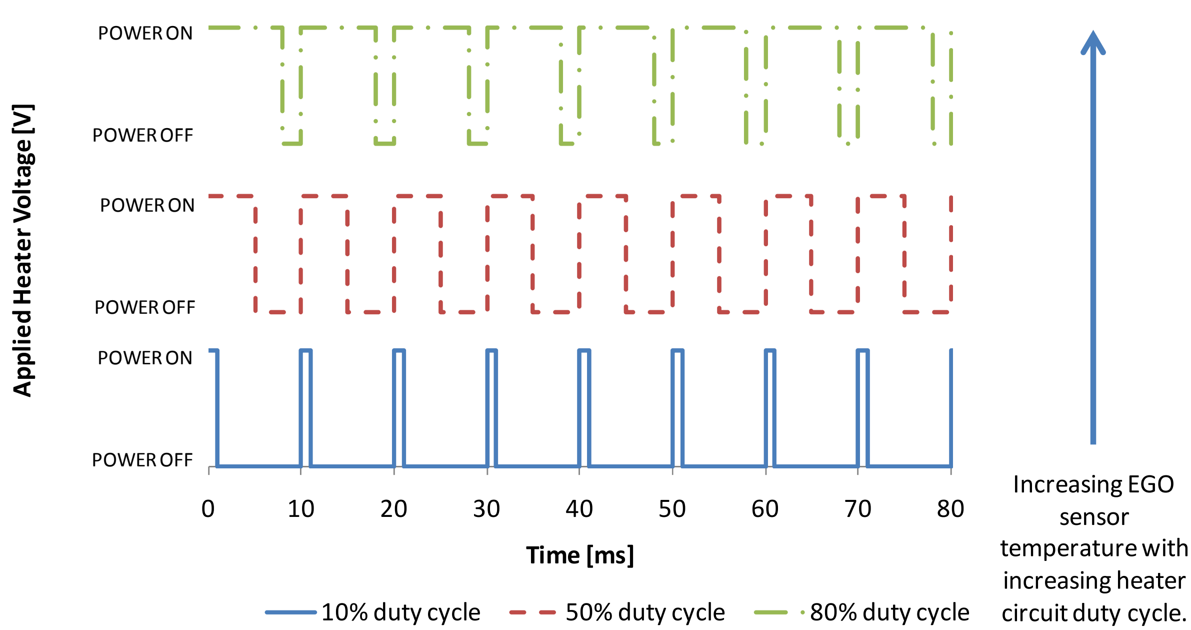
Figure 3-6 demonstrates typical voltage responses from narrow-band HEGO sensors as a function of lambda (Toema, M. 2010, p100). One can see the already non-linear output of a HEGO sensor is further affected by temperature of the sensing element. More consistent control of the HEGO sensing element temperature results in more consistent correlations between HEGO output and operating lambda. Some AFRC systems use the same methodology as modern automobiles to tightly control the HEGO heating process. This entails closed-loop control of the sensing element's impedance, which is a direct indicator of sensor temperature, to a specified target. The temperature the HEGO sensor is controlled by continuously adjusting the power applied to the heater circuit using pulse width modulated control. Figure 3-7 gives an example of such a process by showing the fixed frequency voltage waveform applied to the heater circuit. Higher sensor temperatures are achieved by increasing the duty-cycle, the ratio of *power on* time to *power off* time. Advanced closed-loop heater control is absolutely necessary for UEGO sensors, discussed below, but it is not standard within the stationary AFR controller market using HEGO sensors. Tecogen's current system does use heated EGO sensors, but does not apply closed-loop control of the sensor temperature.

**Figure 3-6: Typical HEGO Sensor Output Showing Influence of Sensor Temperature**




(Courtesy: Toema)

**Figure 3-7: HEGO Heater Control**



### *3.2.1.3 Dithering*

AFR dithering, or fuel dithering, is a standard fuel control process for stoichiometric spark ignition engines using TWC after-treatment in the automotive industry. Its widespread use in the automotive industry makes it a subject of interest with regards to this ultra-low emissions development program as an alternative to Tecogen's current steady-state fuel control process. With dithering, the amount of fuel fed to the intake air is increased and decreased on a 0.5 – 5 Hz cycle such that the resultant AFR cycles rich and lean of a nominal AFR target. This is in contrast to Tecogen's current steady-state fuel control algorithms that attempt to maintain the AFR as close as possible to a specified AFR, as represented by a target HEGO mV output. The AFR perturbations caused by dithering take distinct advantage of catalyst's ability to temporarily store and release exhaust constituents, such as oxygen. Oxygen storage capacity (OSC) is a critical design element of typical TWC catalyst for both steady-state and dithering fuel control strategies because it accommodates transient deviations from ideal chemical conditions before the catalyst.

It is generally reported that dithering can widen the instantaneous operating AFR window by up to 1 air/fuel ratio for high efficiency TWC conversion, but at the expense of some reduction in the absolute peak TWC conversion efficiency (Heywood, J. p656). Dithering is thought to favor automobile applications, in particular, because they operate under highly transient conditions and can take distinct advantage of the catalyst's ability to absorb significant excursions away from a nominal AFR condition. In addition, automobiles are tested for regulatory emissions compliance by EPA and CARB under transient drive cycles so better results are expected to be derived using the dithering fuel control strategy which is more forgiving of short term deviations in the target AFR. While Tecogen's inverter-based InVerde system is capable of running at variable engine speeds, InVerde installations are still expected to operate in base-load electrical production modes and thus operate mostly under steady-state conditions. With the CARB 2007 limits being aggressively low, it is unclear whether Tecogen's ultra-low emissions efforts would benefit from this automotive strategy, or be compromised by a potential sacrifice in peak catalyst efficiency.

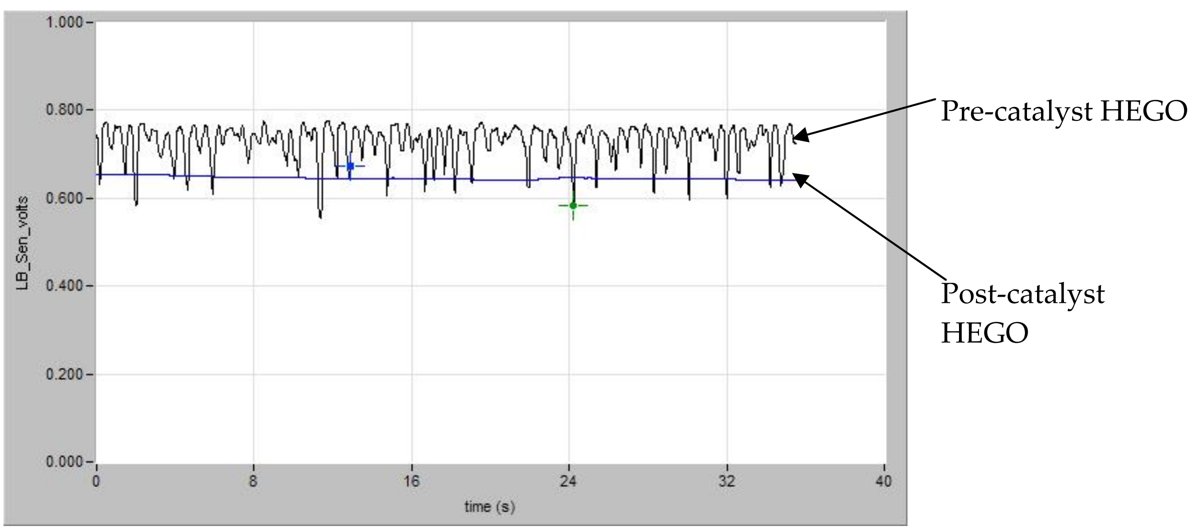
### *3.2.1.4 Post Catalyst HEGO Control*

Modern automobile AFRC processes employ pre-catalyst and post-catalyst oxygen sensors, whether HEGO or UEGO sensors. The output of the post-catalyst sensor is used to continuously update, or bias, the nominal target for the pre-catalyst sensor. One goal of using the post-catalyst sensor is to provide greater certainty that the oxygen level in the catalyst is neither depleted nor saturated to maintain the highest simultaneous conversion rates of $NO_x$, CO, and THCs possible. Figure 3-8 and Figure 3-9 provide insight into the chemical reaction buffering effects afforded by the oxygen storage capacity of the catalyst by recording the HEGO outputs before and after a catalyst. In Figure 3-8, the engine system was operating in a steady-state mode in which the AFR controller was attempting to adjust the fuel value to maintain the pre-catalyst HEGO output at a target condition. Even in a stable constant speed and load condition, normal engine variation resulted in somewhat random movement in the pre-catalyst HEGO signal (black line), but the post-catalyst HEGO signal was clearly more consistent in nature. This is largely due to the catalyst acting as a chemical storage buffer, absorbing increases and decreases in oxygen as needed to react with the criteria pollutants.

Figure 3-9 is an even more dramatic example of the OSC effect, and perhaps the potential usefulness of the post-catalyst HEGO sensor. In Figure 3-9 the engine system was operating in a dithering fuel control mode which intentionally oscillates the AFR rich and lean of the nominal AFR required for high catalyst conversion efficiency. This results in a HEGO sensor output that oscillates between the rich and lean output characteristics of the narrow-band sensor. Yet, while the pre-catalyst HEGO is clearly affected by the intentional fuel perturbations, the post-catalyst HEGO never produces a lean-side output. If, for instance, the post-catalyst sensor would produce an output less than 500 mV, it would be a clear indication of oxygen saturation (or breakthrough) and one could expect the NOx conversion efficiency to drop dramatically.

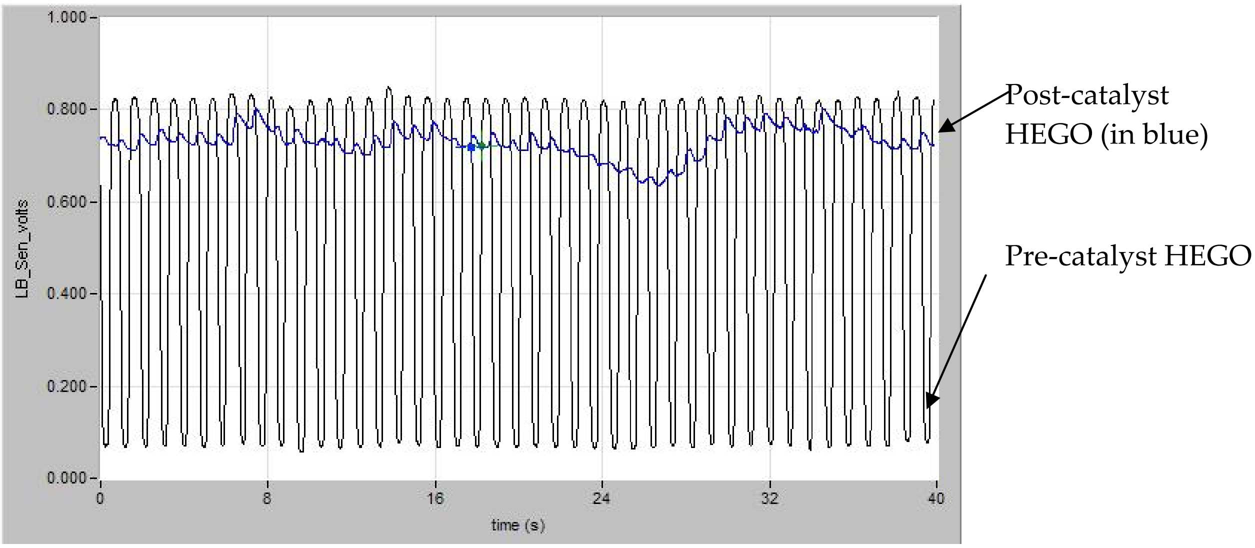
One aspect of dithering appears critical if used in stationary power applications, and that is the use of post-catalyst feedback control with an exhaust oxygen sensor to give the controller a continuous indication of whether the net effect of the dithering waveform is an exhaust chemistry that is still compatible with high catalyst conversion efficiency.

**Figure 3-8: Pre-Catalyst and Post-catalyst HEGO Voltage Outputs – Steady-state Control**




(Courtesy Ranson Roser)

**Figure 3-9: Pre-Catalyst and Post-Catalyst HEGO Sensor Outputs – Dithering Control**




(Courtesy Ranson Roser)

Another goal of the post-catalyst sensor when used with a dithering strategy is to measure the oxygen storage capacity of the catalyst in more quantitative terms that manufacturers correlate to anticipated emissions. Such methodologies are a component of the U.S. vehicle industry's requirement to provide On-Board Diagnostics that illuminate a malfunction lamp when the emissions control system is believed to be operating under conditions that are compromising emissions. These on-board OSC computations are quite complex. Oxygen storage calculations are not employed by any industrial AFRC systems because they require extensive modeling of the catalyst system backed up by large statistical data sets as well as the use of a dithering AFR strategy which is already a rarity in the stationary power market. Despite this, the first purpose of using the post-catalyst HEGO is still valid, and of interest, to this emissions program and to the AFR controller screening process. This is especially since Tecogen's embedded controls have derived benefits from adopting post-catalyst feedback since 2005.

#### *3.2.1.5 UEGO Closed-Loop Control*

It is believed using UEGO sensors may offer advantages over HEGO sensors with regards to maximizing the consistency of emissions compliance in stationary power engine applications when using steady-state, non-dithering, AFR control and that they may facilitate easier adaptation to stationary systems wishing to employ dithering fuel control. Therefore, it is of interest in the screening process to know whether or not particular AFRC systems include an integrated UEGO controller.

#### *3.2.1.6 Electronic Fuel Control, Full-Authority Versus Partial-Authority Strategy*

Electronic fuel control for low pressure gaseous fuel engines can be divided into two categories, those that exhibit full-authority over the gas flow and those that electro-mechanically control only a small fraction of the possible fuel flow, sometimes through a bypass path around primary mechanical fuel metering device. While full-authority and bypass systems each have their own generic advantages, neither have inherent characteristics that preclude them from being able to achieve ultra-low emissions under steady-state conditions with the correct catalyst system. Tecogen's fuel control valve has partial-authority over the fuel flow.

#### *3.2.1.7 AFR Controller Screening Results*

Table 3-1 shows the results of screening several AFR control system with regards to the technological features discussed above. Many of the AFRC systems had at least some of the capabilities of interest to Tecogen, but none of the controllers could do everything of potential interest. None of the AFRC systems could be used to drive Tecogen's current very low cost stepper motor driven Fuel Control Valve, simply meaning that Tecogen would not only have to add the cost of an external AFR controller, but also have to accommodate changes in fuel control hardware, and yet still accept limitations to the breadth of control options. Such issues are not absolute disqualifiers, but in comparison to the open architecture capabilities of the Tecogen system, Tecogen found no compelling reasons to abandon using its embedded controls as the candidate platform for advanced AFR investigations.

**Table 3-1: Comparison of Air/Fuel Ratio Control System Features**

| AFRC Manufacturer: | Tecogen | Compliance Controls | Compliance Controls | Gill | Continental Controls | Woodward | Woodward | Altronic |
|---|---|---|---|---|---|---|---|---|
| Feature/Model: | RMCS | MECR | MECL | AF120 | EGC2 | L Series | GECO | EPC-100E |
| Load-Based AFR Target Mapping? | Yes | Yes | Yes | Yes | Yes | No | No | Yes |
| HEGO-Based Control? | Yes | Yes | Yes | n/a | No | Yes | Yes | Unheated EGO |
| Integrated UEGO-Based Control? | No | n/a | Yes | Yes | Yes | No | No | No |
| Closed-Loop HEGO Heater Control? | No | Yes | Yes | n/a | n/a | ? | Post cat only | Unheated EGO |
| Post-Cat Control Loop Feedback? | Yes | Yes | HEGO only | n/a | No | No | Yes | |
| Full-Authority Fuel Valve Control? | No | Yes | Yes | No | Yes | Yes | Yes | Yes |
| By-Pass Fuel Valve Control? | No | Yes | Yes | Yes | No | Yes | Yes | Yes |
| Dithering Fuel Control Option? | No | Yes | HEGO only | n/a | No | Yes | Yes | No |
| UEGO Sensor Used? | No | n/a | NTK | Bosch LSU4.2 | Bosch LSU4.2 | n/a | n/a | n/a |

### *3.2.1.8 AFR Controller Selection*

Tecogen's current embedded AFR control system already has some of the features of interest, although not all, and is flexible enough to conceptually adapt others. Tecogen already employs load-based pre-catalyst HEGO AFR target mapping to some degree, although this map is ultimately overridden by the post-catalyst HEGO control loop using Tecogen's proprietary algorithms. Furthermore, the current HEGO sensor outputs currently land on 0-10V analog input channels that are capable of accepting the analog output of any UEGO controller on the market regardless of the polarity of the AFR versus Voltage response. Thus Tecogen's control system is presumably already capable of adapting UEGO controllers to the AFR control process, which if found successful over HEGO sensors, would inherently remove interest in developing closed-loop HEGO heater control. Tecogen could adapt its AFR control process to that of a bypass controller, but no evidence in the screening process has unveiled that the bypass methodology would produce an advantage over its current full electronic authority over the fuel control process. Finally, although Tecogen does not have experience with dithering AFR strategies, its absolute control over the AFR algorithms offers it the freedom to experiment as necessary. Based on the AFR controller screening process, inclusive of consideration of Tecogen's current system, Tecogen decided to continue the project with its own system which has its own successful history of evolving with increasingly more stringent exhaust emissions standards.

One final important consideration that led to the decision to continue to use Tecogen's embedded AFR controls for the program concerns the field demonstration and commercial implementation aspect of the program. Tecogen's RMCS remote monitoring and control system, which also includes the AFR control code, allows Tecogen factory and field personnel to remotely connect to CHP units using modem connections and to retrieve engine operating data integrated with AFR control data as well as to download new experimental control code as needed. This level of system integration would be much more difficult to implement, albeit not impossible, with independent controllers.

### 3.2.2 Exhaust Oxygen Sensors Screening

#### *3.2.2.1 Narrow-Band HEGO Sensors*

Tecogen's standard closed-loop AFR control process for all emissions control regions in the U.S. relies upon the outputs of pre-catalyst and post-catalyst Delphi label HEGO sensors (PN: GM25312178). Like all narrow-band oxygen sensors, the Delphi HEGO sensor relies upon a Nerst cell that produces an output voltage in response to changes in the oxygen level in the exhaust in comparison to a reference cell filled with ambient air. In the combustion region near the stoichiometric air/fuel mixture, there is an abrupt change in the oxygen content in the exhaust which causes an abrupt change in the output voltage of the sensor (3- 6). Narrow-band HEGO sensors are often described as switching sensors because their use in the pre-catalyst location of dithering AFR systems makes them appear to simply switch from one voltage regime to another with very small changes in AFR. Although different sensors produce slightly different relationships between output voltage and exhaust conditions, and users should expect to choose and commit to one sensor, Tecogen is unaware of any differentiating features that exist between HEGO sensors that justify any form of technical screening for consideration of this low-emissions program. However, such is not the case when considering the adoption of wide-band sensing.

#### *3.2.2.2 Universal Exhaust Gas Oxygen (Wideband) Sensors*

Growing interest in wide-band oxygen sensors, also known as universal exhaust gas oxygen (UEGO) sensors, has been developing within the stationary power industry due to informal reports of lower sensor calibration drift as a function of sensor age as well as simplified PID control loops due to reduced (or eliminated) non-linearity of the control variable response to changing exhaust conditions. Within the automotive gasoline industry, UEGO sensors exist but pre- and post-catalyst HEGO sensors are still the norm. The widest commercial application of UEGO sensors is found in engines employing closed-loop lean-burn gasoline, diesel, and heavy-duty mobile natural gas strategies, where the desired exhaust gas oxygen content is far from the measurement range of HEGO sensors. UEGO sensors are also very popular in the automotive racing industry for tuning engines to achieve best power without emissions constraints, which occurs under conditions that are significantly rich of stoichiometric. UEGO sensors require additional circuitry to operate in comparison to a HEGO sensor resulting in either additional control circuitry embedded in the base engine controller or an additional external control module.  This circuitry manages the UEGO's oxygen pumping cell, heater control, signal conditioning, and production of either an analog or digital output.

#### *3.2.2.3 UEGO Sensor Manufacturers*

The three primary UEGO sensor manufacturers are NTK, Bosch, and new-comer Delphi.  NTK developed the first UEGO in "laboratory" and commercial grades.  There is no such thing as a laboratory grade UEGO specification, but original NTK UEGO contained high levels of expensive platinum for added accuracy and durability, and found enthusiastic customers in engine laboratories and performance tuning centers.  However, it was generally too expensive for commercial applications.  NTK's more commercial variant is still more expensive than Bosch and Delphi brands.  Tecogen has not been able to obtain specifications for any of the NTK UEGO sensors, but the added expense of the NTK and its laboratory market heritage have led many suppliers to convey the opinion that even the commercial sensor has some benefits in either accuracy or durability.  This appears to be an assumed rather than quantified opinion.

However, the NTK has been known to exhibit greater durability than the Bosch sensor based on the anecdotal observations of a confidential laboratory that performs catalyst durability studies for major automotive manufacturing clients.  Catalyst are typically tested under engine conditions that produce exhaust streams that are quite abusive to catalysts, such as operating at high loads and high temperatures, in an effort to accelerate degradation mechanisms such that longer-term performance projections for different designs can be generated in reasonable time frames.   Regardless of whether the OEM's engine controller in such tests uses HEGO or UEGO sensors for closed-loop control during the process, UEGO sensors are definitively used by such testing laboratories to record the exhaust chemistry during the cycles of catalyst abuse.  This aforesaid anonymous laboratory had found that the Bosch LSU4.2 sensors had a notable rate of failure in these abusive high temperature applications whereas the NTK sensors did not.  Therefore, the laboratory switched to NTK sensors for durability considerations alone.  Such anecdotal evidence may be a moot point for many mass produced commercial applications.  NTK UEGO sensors are found on industrial engine applications for Caterpillar, John Deere, and Detroit Diesel.

Bosch LSU4.2 sensors are found on a number of light-duty automotive applications such as models of Cadillac, Volkswagen, Porsche and others.  Thus the Bosch UEGO is present in the market in quantities expressed in millions.  Unlike the NTK UEGOs, technical specifications for the Bosch LSU4.2 sensor are readily available.  These specifications document the fact that sensor-to-sensor variation does exist and quantifies the expected extent of variation from new and aged sensors.  Although such documents could not be found for NTK or Delphi sensors in the public domain, they surely exist for high volume OEM customers.  The Bosch UEGO sensors are available at neighborhood automotive stores for as little as $50 depending on the make and model of car they were applied to.  Although it is clear the Bosch LSU4.2 comes with many different connectors dependent on the final vehicle application, it is not known if Bosch varies the platinum content from one OEM to another  to achieve discrete performance versus price point differences than are not conveyed through the general LSU4.2 specifications.

#### 3.2.2.4 UEGO Controllers

UEGO sensors must be used in conjunction with UEGO controllers matched to the particular model of sensor. The controller manages sensor heating functions for precise temperature control, pumping current to the pump cell, free-air calibrations if equipped, and transfer of pumping currents to analog or digital forms of other engineering units such as AFR. The UEGO sensor is useless without the UEGO controller, which is sometimes adapted into an OEM's powertrain control module or is integrated into a system as a stand-alone module that transmits data via analog or digital signals. Fortunately the usefulness and popularity of UEGO sensors in the automotive performance aftermarket has led to a wide availability of aftermarket UEGO controller products that make use of UEGO sensors. These aftermarket UEGO controllers have a range of features, some which may or may not be useful to an industrial engine end-user wanting to integrate the system into an AFR controller for emissions control. For Tecogen, the most important considerations are lambda accuracy, industrial robustness, and cost. Other factors of non-critical interest are signal latency (response time) and whether or not the controller has the ability to perform field recalibration of the UEGO sensor in ambient air. Some of the product differential comes in the form of the ability to use manufacturer software to log UEGO data, or include additional analog inputs for more powerful data logging.

Fortunately for Tecogen, *FordMuscle* magazine sponsored a technical comparison of eight popular UEGO systems using the inexpensive Bosch LSU4.2 sensor in 2007 (Kojima, M.). The effort attempted to rank the systems based on a combination of quantitative assessments of accuracy and signal latency, as wells as subjective reviews of module display quality, ease of use, and software functionality. Rather than ranking cost, the authors simply limited their comparison to systems with similar costs and left out alternative systems that were significantly more expensive. Table 3-2 shows the eight systems in the order of best-to-worst resultant ranking from *FordMuscle*. For Tecogen, the most important feature was system accuracy, which in the *FordMuscle* comparison, was determined with the use of an expensive AFR meter using NTK's high-dollar UEGO sensor and a certified calibration gas representing a specific rich AFR. Incidentally, the AFR meter using the expensive NTK sensor exactly agreed with the stated composition of the calibration gas. The Innovate and AEM brand UEGO systems received top scores for AFR accuracy falling within a range of +/- 0.1 AFR on the calibration gases whereas the next best UEGO system did not score better than +/- 0.5 AFR reading accuracy. This alone was enough for Tecogen to select Innovate and AEM UEGO systems from the performance aftermarket industry as candidate systems for select laboratory investigations.

While it was fortuitous that the aftermarket performance industry sponsored a comparative evaluation between several UEGO controllers that Tecogen could use in its UEGO screening process, it was also understood that the screening was focused through the eyes of a market that focuses on winning short duration races through more accurate AFR adjustments to rich engine tuning targets, rather than trying to maintain AFR within a very tight window for optimum three-way catalyst emissions conversion for thousands of hours. Areas of concern between racing versus OEM industrial or automotive use include the controller's physical packaging robustness with regards to environmental conditions, vibration, and noise immunity, consistency of long-term supply, and manufacturing quality control. It is a reasonable assumption that a UEGO controller that has been accepted as an OEM component on a mass-produced product in a regulated industry, such as on-highway emissions controls, is likely to have passed a number of qualifying tests with more depth than an automotive racing magazine comparison.

**Table 3-2: Automotive Performance Aftermarket Review of UEGO Systems**

| Vendor | Model # | MSRP | Accuracy | Latency | Software |
|---|---|---|---|---|---|
| Innovate | XD-16 Kit | $399 | +/- 0.1 AFR | <100 ms | Yes |
| AEM | All-in-one UEGO Gauge | $350 | +/- 0.1 AFR | <400 ms | No |
| FAST | Air/Fuel Meter | $467 | +/- 0.5 AFR | <400 ms | No |
| FJO | Controller, Sensor,Display | $640 | +/- 0.5 AFR | <100 ms | Yes |
| PLX | M300 Air/Fuel Gauge | $315 | +/- 1.0AFR | <200 ms | No |
| Dynoject | Wideband Commander | $530 | +/- 0.75 AFR | <500 ms | Yes |
| Zeitronix | ZT-2 | $279 | +/- 0.75AFR | <300 ms | Yes |
| NGK | AFX Meter | $295 | +/- 1.0 AFR | <300 ms | No |
| Test's sponsored by *FordMuscle* magazine | | | | | |

(Courtesy: FordMuscle)

With such interests in mind, Tecogen was also able to identify a pair of UEGO controllers from E-Controls, Inc. based in Texas. The E-Controls UEGO controllers are packaged into robust no-frills modules (Figure 3-10) for heavy-duty mobile applications requiring closed-loop lean-burn AFR control. The modules are said to have passed the noise immunity tests of their original heavy-duty engine manufacturer client, as well as Ford Motor Company noise immunity specifications for such products. The end-user can select one of several pre-defined linear analog output correlations to equivalence ratio from the factory when ordering, but otherwise the calibration is fixed as it is with the AEM UEGO controller. These controllers have none of the software interface frills found on some of the automotive performance options as there is no need for such in the OEM market. The E-Controls modules use only the NTK UEGO sensor. The fact that the NTK sensor is often thought to have additional benefits in accuracy and robustness over the Bosch sensor, although not commercially quantified or proven, promoted even more interest in adding the E-Controls UEGO controller to the systems to be evaluated in the laboratory in addition to the Innovate and AEM systems. The cost of the E-Controls controllers can be compared to yet other UEGO controllers in Table 3-3.

A unique UEGO controller option identified in the screening is sold by Powertrain Electronics and was developed for OEM's who wanted a UEGO controller that could be integrated into their engine control modules at the circuit level. It exists in a small circuit board configuration and is meant for OEMs to solder directly into their own powertrain control module circuit boards. This facilitates the lowest high-volume cost to the OEM as well as control over the final packaging robustness. This controller can transmit AFR data via an analog output or a digital communications protocol known as serial peripheral interface (SPI). The digital protocol would eliminate issues pertaining to AFR accuracy lost from the analog transmission and interpretation process. However, while the digital communications option is of particular interest to Tecogen, the adaptation of Tecogen's generator control system to accommodate SPI communications is outside the scope of the program, especially until UEGO technology in general can demonstrate advantages over Tecogen's long-standing use of pre- and post-catalyst HEGO sensors.

**Figure 3-10: Commercially Available UEGO Controller**

**Table 3-3: Additional UEGO Systems**

| Manufacturer | Model | Cost | Typical Market |
|---|---|---|---|
| E-Controls | E10600B | $550 | Regulated On-Highway OEM |
| ECM | AFR1000 | $1495 | Performance Engine Tuning Shop, Individual Performance Enthusiast |
| Motec | PLM | $2208 | |
| ECM | Lambda Pro | $3495 | |

### 3.2.3 Three-Way Catalyst Screening

Sales contacts for four different catalyst manufacturers, which serve the stationary power market, were sent the three-way catalyst sizing inputs shown in Table 3-4. The vendors were further instructed that the request was for 10.5 inch O.D. substrate alone, with a maximum length, or cumulative length for multiple substrates, of 13 inches to fit within Tecogen's combined catalyst-exhaust gas heat recovery assembly. Maximum back pressure was defined as 8 inches of water column. In practice, Tecogen has some discretion to increase that limit at the expense of reducing the amount of additional backpressure that could be incurred by site-specific CHP installation issues such as long piping runs and sound attenuation. Lastly, the vendors were given a 1275 degree F catalyst operating temperature, that already included normal exothermic reaction temperature increases, based on expectations for the 100 kW InVerde system.

**Table 3-4: Catalyst Sizing Inputs**

| Parameter | | Units | Value |
|---|---|---|---|
| Engine Brake Power | | hp | 152 |
| Equivalence Ratio | | | 1.00 |
| Exhaust Mass Rate | | lb/hr | 1118 |
| Exhaust Temperature | | °F | 1275 |
| Actual Exhaust Flow Rate | | $m^3$/hr | 1328 |
| Actual Exhaust Flow Rate | | acfm | 782 |
| Standard Exhaust Flow Rate | | scfm | 250 |
| Assumed Untreated Pre-Catalyst Emissions (Volumetric Concentrations Referenced to 0% $O_2$, or Raw Values) | CO | ppm | 4690 |
| | $NO_x$ | ppm | 2380 |
| | VOC | ppm | 40 |
| | CO | g/bhp-hr | 13.0 |
| | $NO_x$ | g/bhp | 10.9 |
| | VOC | g/bhp | 0.6 |
| Compliance Limits (Volumetric Concentrations Referenced to 0% $O_2$, or Raw Values) | CO | ppm | 27.8 |
| | $NO_x$ | ppm | 11.8 |
| | VOC | ppm | 9.7 |
| | CO | g/bhp-hr | 0.079 |
| | $NO_x$ | g/bhp | 0.055 |
| | VOC | g/bhp | 0.016 |
| Three-Way Catalyst Efficiency Required | CO | % | 99.4 |
| | $NO_x$ | % | 99.5 |
| | VOC | % | 75.8 |

Table 3-5 compares various aspects of the commercial offerings from the catalyst manufacturers polled as they relate to Tecogen's interests. It is important to recognize there are no manufacturers with significant experience providing any segment of the stationary power ICE with catalysts proven to meet CARB 2007 or current SCAQMD Rule 1110.2 distributed generation limits on a durable, commercially viable, basis. In addition, the vendors do not disclose technical details, such as precious metal loading used, which can add to the complexity of making comparisons between the products. Based on the responses from the catalyst manufacturers described in the following section, Tecogen decided to acquire product from DCL and Süd-Chemie. Pricing, provided in confidence, was not a deciding factor since none of the candidates stated they had an outright solution that did not have at least one serious detracting issue.

**Table 3-5: Selected Characteristics of Catalyst Manufacturer Products for Tecogen's Application**

| Questions | DCL | Johnson Matthey | Miratech | Süd-Chemie |
|---|---|---|---|---|
| Did the manufacturer's TWC sizing efforts identify a specific TWC configuration meeting the constraints? | Yes | Yes | Yes | No |
| What cell density (cells per square inch) is recommended by the sizing analysis? | 400 | 400 | 200 | 500/300 |
| Is the operating temperature compliant with the manufacturer's commercial limits for warranty? | No | No | No | Yes |
| What is a typical warranty for a commercially accepted application? | 1 year | 1 year | 2 years | 1 year |
| Was a warranty offered for this CARB 2007 effort? | No | No | No | No |
| Are the substrates brazed for added mechanical integrity? | Yes | No | No | No |

### *3.2.3.1 DCL, Inc.*

DCL's sizing analysis predicted two 3.94" length elements could achieve the program limits at 400 cpsi although the vendor demonstrated a healthy respect for the CARB 2007 emissions constraints by noting that three elements might prove more successful. Even with three elements at 400 cpsi, the pressure drop was estimated to be 7.4" WC which was below the specified constraints. DCL's 300 cpsi product was stated to not meet the requirements even with three substrate elements. A deciding factor in choosing DCL's product over other viable options was their substrate brazing process. This offered a perceived advantage that the increased structural integrity could reduce loss of washcoat from the rubbing of adjacent substrate foil layers during the vibration from normal operation, or from the direct handling that occurs during service. Tecogen's desired application requires packaging a TWC substrate into Tecogen's combined catalyst and exhaust heat exchanger assembly. The catalysts are more difficult to install and remove in Tecogen's product than in typical catalyst housings provided by the catalyst manufacturers. The catalyst assembly is also mounted inside the CHP module package over the generator housing and is subject to some system vibration. The brazing process was considered a positive mitigating factor for these aspects of the application. Another attraction to the DCL product is DCL's public availability of a technical paper describing in great detail the technical foundations of their catalyst sizing program (Aleixo, J.). Such a document generates added confidence in the science behind the product. Unfortunately, DCL's maximum operating temperature for commercial warranties is 1250 °F, which Tecogen 100 kW InVerde system can exceed on a continuous basis.

#### *3.2.3.2 Süd-Chemie*

Süd-Chemie's sizing analyses did not identify a product configuration that could achieve the emissions reduction requested within the space and back pressure limits given. However, Süd-Chemie is Tecogen's current catalyst supplier for all its commercially available products so it behooved Tecogen to evaluate Süd-Chemie product in the context of this program's emissions limits. Besides the existing commercial relationship, Süd-Chemie is literally a close neighbor with offices and some catalyst evaluation analytical services within ten miles of Tecogen. Süd-Chemie's rated maximum continuous operating temperature is 1350 °F, making it the only manufacturer in which Tecogen's 100 kW operating temperature will not violate its commercial temperature limit. Whether or not Süd-Chemie catalysts actually have greater resistance to thermal degradation than competitors is not known.

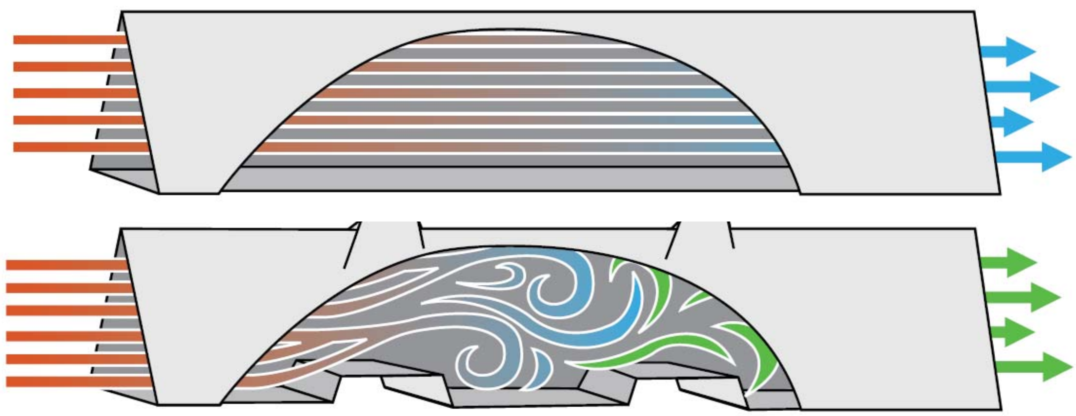
#### *3.2.3.3 Miratech*

Miratech provided a very interesting product solution in the form of three 3.54" length 200 cpsi elements that use a novel substrate channel design that re-induces turbulent exhaust flow at periodic intervals along the channel length. Turbulent flow in individual channels of the monolith increases the rate of pollutant conversion reactions (Cornelius, S.). Typically, the flow through the straight channels of standard design catalyst substrates is turbulent in just the initial portion of the channel length before turning laminar for the remaining length. Miratech's "NEXT" technology creates periodic disruptions in the flow channels which induce cascading sections of turbulent flow (Figure 3-11). These flow disruptions induce increased backpressure compared to an equivalent cell density straight-through configuration, but it appears the increase in performance for a given pressure drop increase is more effective when induced by the flow disruptions than by increasing cell density. The total pressure drop for three 200 cpsi NEXT substrates is only 4.2" WC, which is impressive.

The process for manufacturing the NEXT technology results in a variable diameter along the substrate's outer cylindrical surface. There are concerns that this may pose an additional challenge to proper sealing of the elements into Tecogen's custom catalyst housing. Miratech does not braze the substrate like DCL does, but does make the reasonable claim that the channel protrusions that induce turbulent zones also act as interlocking indexing keys that increase mechanical integrity and prevent catalyst telescoping. Overall, the Miratech offering was quite intriguing.

Miratech specified the maximum exhaust gas "inlet" temperature to the first catalyst as 1250 F which the Tecogen InVerde system often exceeds on a continuous basis.

**Figure 3-11: Turbulent Flow Induced By Miratec's NEXT Technology**



Laminar flow exists through most of the length of standard straight through catalyst substrate channels (top). Intentional flow field disruptions induce repetitive sequences of turbulent flow (bottom).

(Credit: Miratec NEXT technology sales literature)

### *3.2.3.4 Johnson Matthey*

Johnson Matthey's maximum commercial "operating temperature" is 1250 F, again suggesting Tecogen would have difficulty obtaining sustained success for the 100 kW InVerde system. This issue aside, JM predicted 0.33 cubic feet of 400 cpsi catalyzed substrate would achieve the emissions goals. Two elements would just barely provide this volume in consideration of JM's standard 3.5" substrate length, and the effective diameter of catalyzed material when accounting for the circumferential banding JM applies to the substrate. One should not be surprised, therefore, if three elements were required to achieve the program targets. The pressure drop for two and three elements was predicted as 5.4" WC and 8.1" WC, respectively. Technically, the pressure drop for three elements is over the specified limit, but as noted earlier, that limit is not so rigid as to disqualify JM as a candidate supplier in and of itself.

Johnson Matthey's methodology to increase structural integrity of the individual elements is to drill long rods into the substrate from the outside circumference towards the center. It is not known whether or not JM accounts for these stability rods when calculating the pressure drop.

### 3.2.4 Alternative Ignition System

The ignition system on a spark ignited engine can play an important role in both short-term and long-term emissions compliance. The role of the ignition system is to provide enough thermal energy, provided by a localized electrical spark, to excite a very small quantity of pre-mixed air and fuel to the point that chemical combustion occurs. Furthermore, the spark needs to be of such a magnitude, frequency, or duration to create a kernel of combustion around the spark plug that is sufficiently large to self-propagate throughout the remaining air-fuel mixture in the subsequent absence of the spark. An analogous comment would be; the lighting of a match stick does not guarantee the lighting of a fire.

Spark ignition engines experience occasional misfires without detrimental operational or emissions consequences. However, when the frequency of complete misfire or partial misfire events increases, engine operation and post-catalyst emissions can be impacted.

- Misfires result in increased hydrocarbon and oxygen emissions to the catalyst. These will ignite in the catalyst and induce increased exothermic reactions that can moderately or severely damage the catalyst. In the case of CARB 2007 emissions limits, even slight thermal damage can result in the inability to achieve the regulatory thresholds.
- The oxygen pulses from misfires can induce erratic signals from the oxygen sensor, thus compromising the stability of the feedback control loop for the AFR control process, which can also result in increased emissions out of the catalyst.
- Increase hydrocarbon emissions into the catalyst generally result in increased hydrocarbon emissions out of the catalyst.

The tendency for an ignition system to misfire can be increased by:

- Very high loads associated with forced induction
- Very low speed and light load, such as at idle
- Poor oil control in the cylinders from high blow-by or leaking seals as an engine ages
- Ignition system degradation due to inadequate service intervals and/or component service life
- Operating with an ignition system that provides borderline performance with regards to the challenges stated above

Ignition systems can be grouped into inductive and capacitive discharge groups. Both are found in automotive and stationary power applications. Inductive systems provide a spark characterized by lower voltage and longer duration than capacitive discharge systems. Capacitive discharge system store and release energy so quickly that they can provide multiple spark events to compensate for much shorter individual spark durations. Capacitive discharge emissions systems are often classified as high-energy ignition systems, yet they do not automatically provide more spark energy than an inductive ignition system.

Tecogen's stock ignition system uses 1980's vintage GM inductive coils and a distributor. The system does not have any outstanding flaws in a typical regulatory environment, yet there is recognition that the ability to achieve or maintain CARB 2007 emissions limits may require added performance from the ignition system. To this end, Tecogen identified a capacitive discharge ignition system that is compatible with the GM 5.7 L test platform. This system will provide multiple spark discharges per combustion event at substantially higher voltage than Tecogen's stock components. Testing this alternative ignition system will allow Tecogen to determine if there are any discernible emissions benefits with regards to achieving low emissions in the laboratory while also comparing the effective energy output in comparison to the stock ignition system.

The capacitive discharge system chosen is a MSD Ignition Model 6A. MSD generally serves the high performance automotive industry, of which the 5.7L GM block is a frequent application. The most important operational specifications for this model are shown in **Table 3-6**. Laboratory testing will show how many sparks actually occur per combustion event at typical Tecogen operating conditions and whether the emissions can be improved.

**Table 3-6: MSD Model 6A Capacitive Discharge Ignition Specifications**

| | |
|---|---|
| Spark Energy | 105-115 milljoule Per Spark |
| Primary Voltage | 540-480 Volts |
| Secondary Voltage | 45,000 Volts |
| Spark Series Duration | 20 Degrees Crankshaft Rotation |

## 3.3 Emission Control Software

Based on the conclusions of the screenings described above, Tecogen's investigations were expected to span enhanced catalyst assemblies, use of UEGO sensors, AFR dithering, supplemental oxidation catalysts, exhaust gas recirculation, and enhanced ignition systems. Of these, only UEGO sensors and AFR dithering were expected to require modifications to the emissions control software. Although some EGR-equipped engine systems employ electronic control over the EGR, it was not Tecogen's intent to pursue such a course.

UEGO sensors require sophisticated management of the sensor's heater control and oxygen pumping cell circuits. Developing such a controller was not practical for Tecogen, so it screened the market for available stand-alone UEGO controllers with analog outputs that Tecogen could easily input into its control system. For many existing AFR controllers on engine systems currently using HEGO sensors, the selection of which UEGO controller to purchase would require consideration of the nature of the analog output currently used for the HEGO input. HEGO sensors produce a voltage that increases from lean-to-rich and is never greater than 1 volt. Many AFR controllers optimized for these HEGO signals would not be able to accept a UEGO controller analog output. Many UEGO controllers produce outputs greater than 1 volt at stoichiometric using reverse AFR response logic, meaning the voltage decreases with lean-to-rich changes. Fortunately, Tecogen's embedded AFR control system can accommodate 0-10 volt signals and the base code can be programmed to accept either rising or falling voltages for a given change in AFR. Therefore, no "special" developments were necessary for the Tecogen controller to accept the integration of UEGO sensors into the AFR control loop.

The concept of air/fuel ratio dithering is simple, toggle the AFR rich and lean of stoichiometric at a certain magnitude and frequency. However, Tecogen envisioned challenges with regards to implementing this control strategy within its existing controller. The challenges come from limits posed by the current hardware and by the potential complexities of developing dithering-based control. Regarding the hardware, Tecogen's generator control system, including the AFR component, has a memory limit that is near its capacity limit regarding the ability to accept new control code. It is believed that the code necessary to perform AFR dithering would be extensive enough to exceed the remaining memory of the system. Unfortunately, adding memory to the current electronics is not possible. However, Tecogen's screening process identified a controller that is already reported to have dithering capability. This would allow Tecogen to determine if it could realize tangible benefits from a dithering AFR strategy without having to first invent the capability within its existing controls architecture. If dithering were successful, then Tecogen could opt to either use the successful product or attempt to integrate a dithering option within its existing control system.

## 3.4 Conclusions

Through a screening process, Tecogen reviewed various AFR control strategies and hardware control systems, wide-band oxygen sensors and their controllers, and catalysts. The screening process obtained information through literature searches and inquiries to manufacturers and their vendors, which was then considered in light of Tecogen product characteristics and the experience of the Tecogen program team. Based on the review of hardware and strategies, Tecogen conclusions on the technical direction for this project are summarized below:

1. Attempt to achieve program goals with the existing Tecogen fuel system and embedded capabilities of its generator control system and associated software, altering code as necessary.
2. Obtain a MEC-R AFR controller, and compatible fuel train hardware, solely for the purpose of observing the dithering combustion technique and its results, as this controller said to have such capability.
3. Obtain UEGO controllers using the Bosch LSU4.2 wide-band oxygen sensor from the aftermarket automotive performance industry (AEM and Innovate), and one UEGO controller using the NTK wide-band sensor from an OEM supplier (E-Controls). Obtain such sensors and controllers for pre-catalyst and post-catalyst observations.
4. Procure candidate TWCs sized for the goals of this program from DCL and Süd-Chemie.
5. Test the raw capability of candidate catalysts to achieve the program goals in steady-state or dithering AFR control modes.
6. Test UEGO sensors as a replacement to HEGO sensors in the AFR control loop to observe any benefit to be derived in the areas of short or long-term control consistency.

7. Test the efficacy of widening the AFR control window and increase net emissions reduction by injecting air into the exhaust after a standard TWC assembly and before a final catalyst that will perform further oxidation reactions.

# CHAPTER 4: Laboratory Performance Testing

The goals of this task were to 1) Characterize component and emission system performance for the Tecogen 7.4 liter engine over a range of operating conditions; and 2) Maximize functionality of emission system to achieve CARB 2007 emissions with minimal sacrifice to CHP system performance and cost.

The laboratory test program, test cell layout and test cell instrumentation were detailed in a Test Plan that was generally followed but adjusted as warranted by interim test results. The laboratory investigations were intended to identify areas where current exhaust after treatment approaches could be enhanced to achieve compliance with CARB 2007 DG limits. The areas investigated involved testing of candidate three-way catalysts, universal exhaust gas oxygen sensors, exhaust air injection with supplemental oxidation catalysts, dithering air/fuel ratio control, capacitive discharge ignition, and exhaust gas recirculation. The following sections provide background information on each of these, or related topics, to provide context for the laboratory work performed and the results generated.

## 4.1 Background of Laboratory Test Program Elements

Tecogen performed a series of laboratory investigations intended to identify areas where Tecogen's current exhaust after treatment approaches could be enhanced to achieve compliance with CARB 2007 DG limits. The areas investigated involved testing of candidate three-way catalysts, universal exhaust gas oxygen sensors, exhaust air injection with supplemental oxidation catalysts, dithering air/fuel ratio control, capacitive discharge ignition, and exhaust gas recirculation. The following sections provide background information on each of these, or related topics, to provide context for the laboratory work performed and the results generated.

### 4.1.1 Evaluating TWC Performance

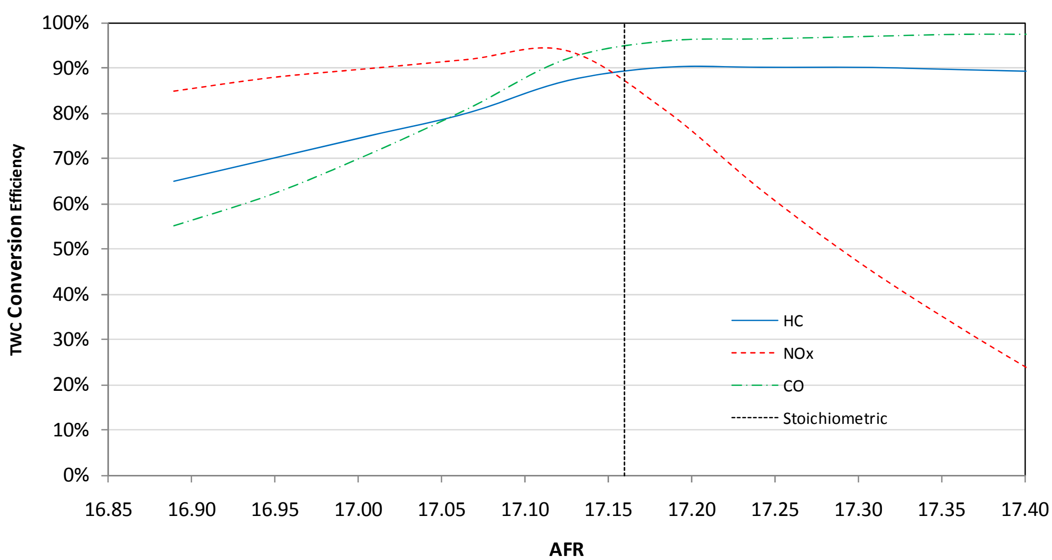
The catalytic converter is the device on a stoichiometric engine system that provides the primary contribution towards compliance with air emission regulations. Other aspects of stoichiometric engine design and control may influence the magnitude of criteria pollutants entering the catalytic converter, the short-term and long-term performance and effective lifetime of the catalyst, or the finer capabilities of the catalyst itself, but it is ultimately the catalyst that can reduce engine-out $NO_x$ and CO emissions by over 99 percent. Therefore, one of the initial efforts of the laboratory phase of the program was to assess whether candidate three-way catalyst substrates, procured for this program, could achieve the CARB 2007 limits using Tecogen's basic fuel control methods.

Simultaneous high-efficiency catalytic conversion of engine-out $NO_x$, CO, and HC pollutants to more desirable products, such as $N_2$, $H_2O$, and $CO_2$, requires precise control of the engine's combustion AFR such that the oxygen content in the TWC does not approach either oxygen saturation or depletion. The AFR for such operation is nominally stoichiometric with just enough air to burn all the fuel. Engines designed to operate with TWC after treatment are often classified as stoichiometric AFR, rich-burn, lambda 1, or equivalence 1 engines, depending on the audience, so these terms will be used synonymously in this report to describe the nominal air/fuel mixture composition. More precisely, highest TWC performance occurs slightly rich of stoichiometric in spark ignited engines as measured by a pre-catalyst lambda sensor. Figure 4-1 shows a generic example of the conversion performance of a TWC, as a function of AFR, for natural gas with a stoichiometric AFR = 17.16. One can see that lean (AFR > stoichiometric) environments take advantage of excess oxygen in the exhaust to enhance oxidation reactions at the expense of significantly less $NO_x$ conversion. Rich operation favors $NO_x$ conversion, but then starves the catalyst of the oxygen required to support CO and HC oxidation reactions.

The AFR control window for > 80 percent conversion of all three criteria pollutants is very narrow, only about 0.1 AFR units or 0.007 lambda (Heywood) using steady-state (non-dithering) fuel control. The width of the window decreases with reduced emissions limits, so excellent AFR control will be imperative to achieve the best possible outcome with any catalyst arrangement with regards to the CARB DG limits. Tecogen's control system does not receive AFR (or related engineering parameter) data directly, but rather receives AFR surrogate data by means of the pre-catalyst HEGO sensor output.

**Figure 4-1: Typical NOx, CO, And THC Conversion Efficiency Trends**

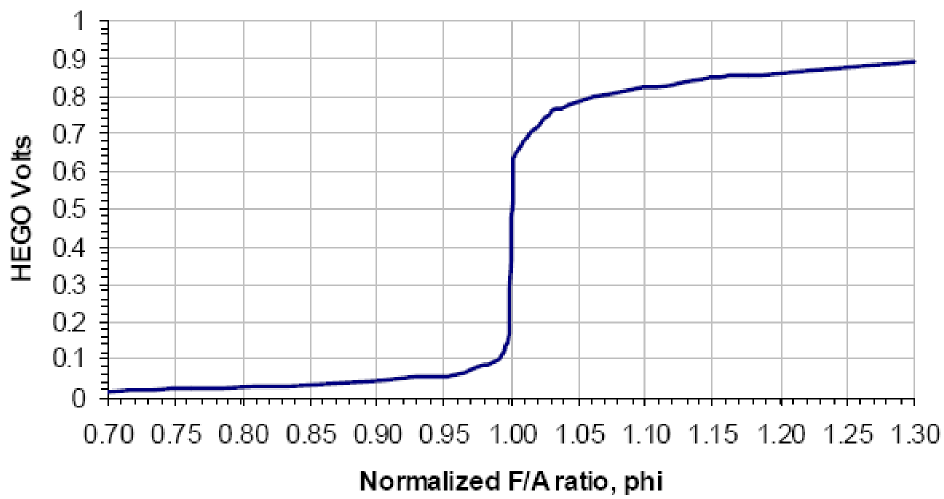
In A TWC As A Function Of AFR




HEGO sensors produce a voltage response to exhaust oxygen using Nernst cell technology. The Nernst cell produces a voltage based on the rate of diffusion of oxygen ions across an impermeable solid state electrolyte fixed between catalyzed porous electrodes. One electrode is exposed to exhaust gas, while the other is exposed to air as a reference gas. At temperatures above 350 C, the electrode exposed to the exhaust gas brings the exhaust gases at its surface into chemical equilibrium. Then, the electrolyte promotes oxygen ion transfer between the reference gas and the exhaust gas, resulting in a voltage difference between the electrodes in proportion to the difference in oxygen partial pressures between the two gases. There is an abrupt change in the partial pressure of the oxygen in the exhaust gas at stoichiometry, which leads to the abrupt "switching" voltage characteristic found in all narrow-band sensors as depicted in Figure 4-2. The voltage in the middle of the switch point is about 450 mV and correlates to stoichiometry.

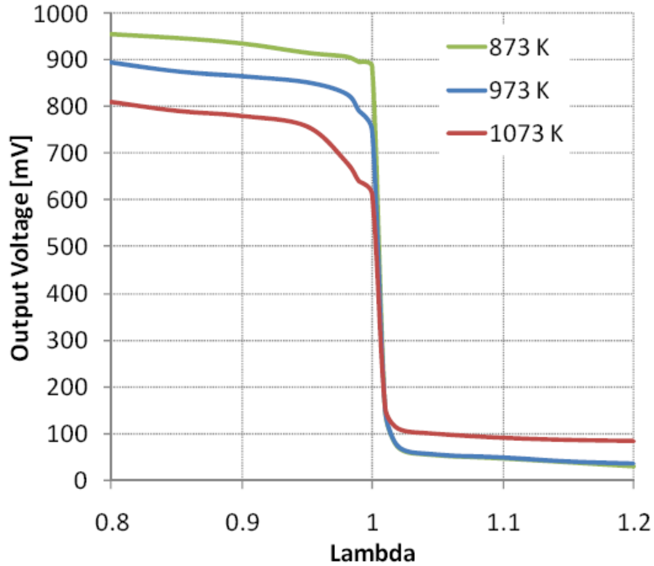
Figure 4-3 shows HEGO sensors are affected not only by changes in exhaust chemistry as represented by lambda, but also by Nernst cell temperature (Toema), which is why all automotive systems and some stationary power controllers employ closed-loop control of the HEGO's sensors heater circuit to maintain a constant sensing element temperature. Tecogen's AFR controller does power the sensor's heater circuit, but does not precisely control the Nernst cell temperature, and thus does not attempt to translate HEGO output into specific engineering units such as AFR, lambda, or equivalence ratio as in. However, for any stabilized engine operating condition and resultant HEGO output, the Tecogen controls operate with the valid logic that reductions in the HEGO mV output represent a shift in the lean direction, while increases represent shifts in the rich direction. Plotting post-catalyst emissions against HEGO output in the region of lowest simultaneous $NO_x$ and CO, therefore, provides a representative look at the window of peak performance of a TWC as a function of changing AFR as shown in Figure 4-4.

**Figure 4-2: Characteristic HEGO Sensor Response.**




(Courtesy Woodward L Series Controller compatible HEGO calibration)

**Figure 4-3: HEGO Output vs. Sensing Element Temperature**



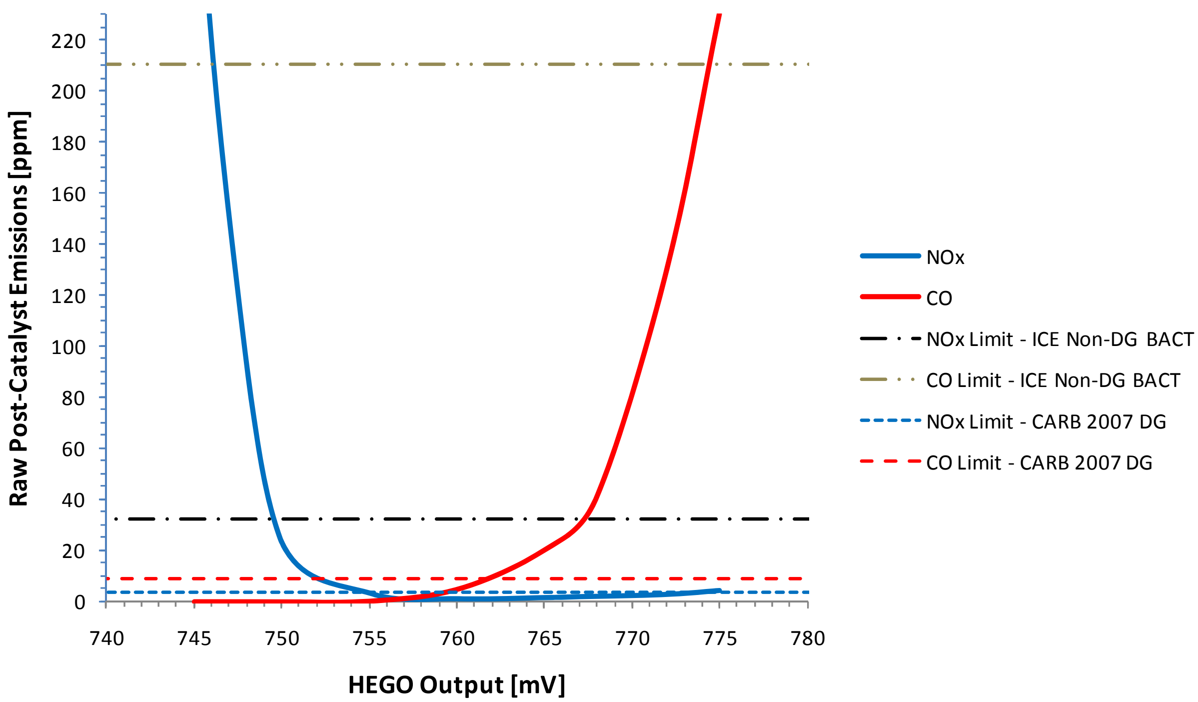

(Courtesy Toema)

Figure 4-4 provides a preview of how Tecogen's catalyst evaluations will be presented later in this report with the following considerations to be kept in the reader's mind.

- The pre-catalyst HEGO mV location of lowest simultaneous $NO_x$ and CO emissions can change as a function of HEGO sensor age, engine operating conditions, and when switching from one sensor to another. Therefore, the apparent mV location of the peak TWC performance that will be shown in various graphs in this report is immaterial. What is important is whether or not the catalyst being testing is sufficient to allow $NO_x$ and CO to simultaneously comply with the CARB 2007 DG limits and, if yes, what the size of the compliance window is.
- Tecogen's commercial AFR control uses a proprietary post-catalyst HEGO sensor algorithm that continuously adjusts the pre-catalyst HEGO target as necessary to account for the pre-catalyst HEGO characteristics mentioned above. The post-catalyst algorithm does not rely upon a specific post-catalyst HEGO output target and it is designed to adjust the active pre-catalyst HEGO mV target very slowly. The very slow response of the post-catalyst algorithm is suitable for making pre-catalyst target adjustments on an as-needed basis during commercial operation, but is not conducive for demonstrating catalyst performance cause-and-effect in the laboratory. Therefore, pre-catalyst target AFR control was the typical fuel control mode used for defining catalyst performance during laboratory testing as a means of achieving reasonable testing efficiency and data clarity.

- When field operators observe emissions results from a rich-burn stationary power engine that are non-compliant with expectations or regulations, the operator must first ask, "Is the source of the problem simply that the fuel control is producing an AFR that no longer correlates to the region of optimum catalyst performance?" A sweep of emissions versus HEGO mV targets (or whatever AFR-related parameter the given controller uses) is one of the best ways to determine if the operator is facing a catalyst issue or a basic control issue, because one can see the full $NO_x$ versus CO trends. This added clarity is why much of Tecogen's laboratory work involved emissions sweeps.
- The shape of the curves in Figure 4-4 accurately conveys that the AFR control window for CARB 2007 compliance, using a TWC system, can be expected to be much smaller than the control window for less restrictive limits, making such compliance a matter of catalyst sizing and excellent AFR control.
- Although the generic Figure 4-4 depicts a TWC system capable of achieving the CARB 2007 limits, such results should not be taken for granted. Not all TWC arrangements tested by Tecogen were capable of achieving such limits even in the laboratory.

**Figure 4-4: Representative Post Three-Way Catalyst Trends vs. HEGO mV**




## 4.1.2 Universal Exhaust Oxygen Sensors

Tecogen's standard AFR control process relies upon the signals from pre-catalyst and post-catalyst HEGO sensors that have exhaust response characteristics already described in Figure4-2 and Figure 4-3. These sensors are also known as narrow-band, switching, or binary output sensors; the former due to a very narrow region, just rich of stoichiometry, in which there is a degree of output proportionality to changes in AFR, and the latter two due to the abrupt shift in output voltage between high and low voltage states at the stoichiometric point.

Growing interest in universal exhaust gas oxygen (UEGO) sensors, also known as wide-band sensors, has been developing within the stationary power industry with some AFR controller manufacturers having modified their products to use UEGO sensors exclusively. UEGO sensors use Nernst cell technology just as HEGO sensors do, but they also include a second Nernst cell that works in a reverse manner and is referred to as an oxygen pump cell. When an externally induced current is applied to the Nernst cell, it actively pumps oxygen ions in a direction and magnitude corresponding to that of the current applied. In a UEGO sensor, exhaust gas enters a monitoring chamber where it diffuses across a standard Nernst cell and is compared to a reference air cell to produce the characteristic voltage response of HEGO sensors. Additional circuitry in the sensor, in combination with an external controller, monitors this voltage and responds with a current that either pumps oxygen out of the gas in the monitoring chamber (if lean), or pumps oxygen from the surrounding exhaust gas into the chamber (if rich). The UEGO controller controls the pumping current magnitude and direction such that additional oxygen ion supply, or removal, results in a modified exhaust gas in the monitoring chamber that produces a continuous stoichiometric response (~450 mV) from the standard Nernst cell. Thus the pumping current provides a proportional response to changing exhaust conditions. This technology allows UEGO sensors to provide meaningful AFR data from lambda values between 0.7 – 4 (Bosch brochure).

UEGO sensors must be used in conjunction with external UEGO controllers designed to be compatible with the particular model of sensor. The controller manages sensor heating functions for precise Nernst cell temperature control, pumping current to the pump cell, free-air calibrations if equipped, and transfer of pumping current to analog or digital formats that can be calibrated to engineering units such as percent oxygen, AFR, lambda, or equivalence. The UEGO sensor is useless without the UEGO controller, which is sometimes adapted into an OEM's powertrain control module or is integrated into a system as a stand-alone module. A discussion of various controller options was discussed in Tecogen's Task 2 – Component Screening Report.

Why would stoichiometric engines with TWC after treatment benefit from a UEGO (wideband) sensor when AFR control is desired to be kept in an extremely narrow band of control near stoichiometry? First, within the industry there are informal or non-public reports, of a critical reduction in oxygen sensor calibration drift as a function of sensor age[6]. This statement pertains only to steady-state, pre-catalyst, fixed-target fuel strategies (such as non-dithering) as they relate to the correlation of the oxygen sensor output to best TWC performance. In other words, the UEGO mV output range that correlates to best TWC performance is thought to not change dramatically with sensor age and can even remain valid throughout the life of the sensor[8]. Although the pre-catalyst set point may need to be redefined each time the sensor is replaced,

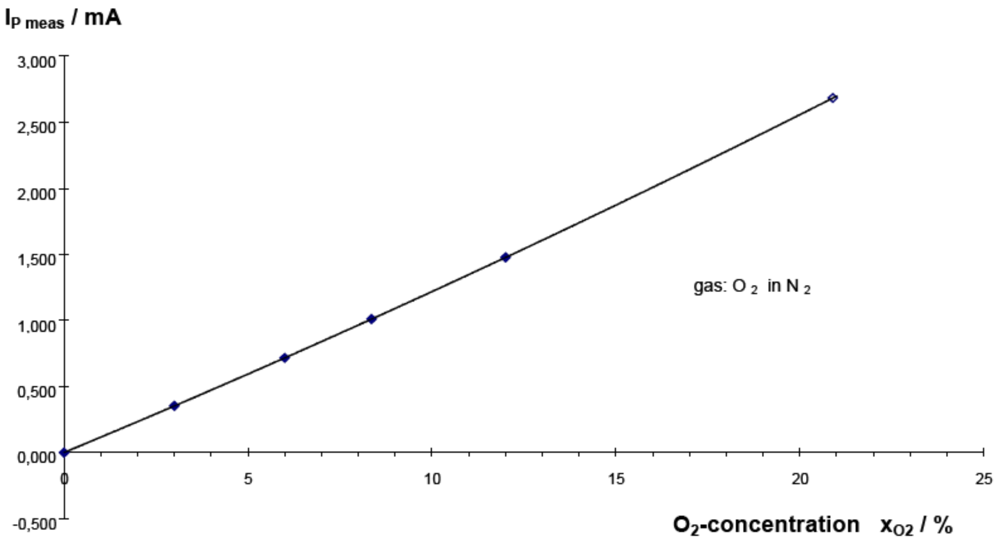
[6] No public information sources were found.

this is a favorable prospect in lieu of other more complicated strategies, such as AFR control based on post-catalyst feedback algorithms or AFR dithering.

Other advantages can be derived from the linear, near-linear, or at least non-discontinuous nature of the UEGO controller output as a function of exhaust composition. The discontinuous switching nature of a HEGO sensor output can represent a challenge for AFR control algorithms. The control points that result in lowest emissions during steady-state fuel control are typically in the rich knee of the output curve as shown in Figure 4-2. Process controllers typically determine the magnitude of the incremental changes to be made to control devices (in this case fuel valves) to achieve a particular process variable target (in this case the output of an oxygen sensor) based on the error between the actual process variable and the target process variable. One can see from 4-2 that rich deviations from typical targets will produce small voltage target errors, while the same AFR deviation in the lean direction will induce a much larger voltage error. Such non-linear and highly disproportionate behavior can complicate steady-state AFR control algorithms. Also, although modest lean deviations from stoichiometric create an abrupt drop in HEGO voltage, any further deviations in the lean direction produce almost no further voltage change. This often results in steady-state control algorithms that produce less concise control than they might otherwise result if using a sensor that provides more proportional correlation to the process variable being controlled.

Figure 4-5 shows the linear pumping current response of the Bosch LSU4.2 UEGO to oxygen content in a mixture with nitrogen (LSU4.2 spec). Note that the UEGO provides linear output for oxygen concentrations between zero and to that of ambient air (20.9 percent), yet another justification for the "wideband" moniker. Indeed, all UEGO sensors are expected to have linear relationships between pumping current and oxygen content, thus supporting yet another nickname of UEGO sensors as "linear $O_2$ sensors."

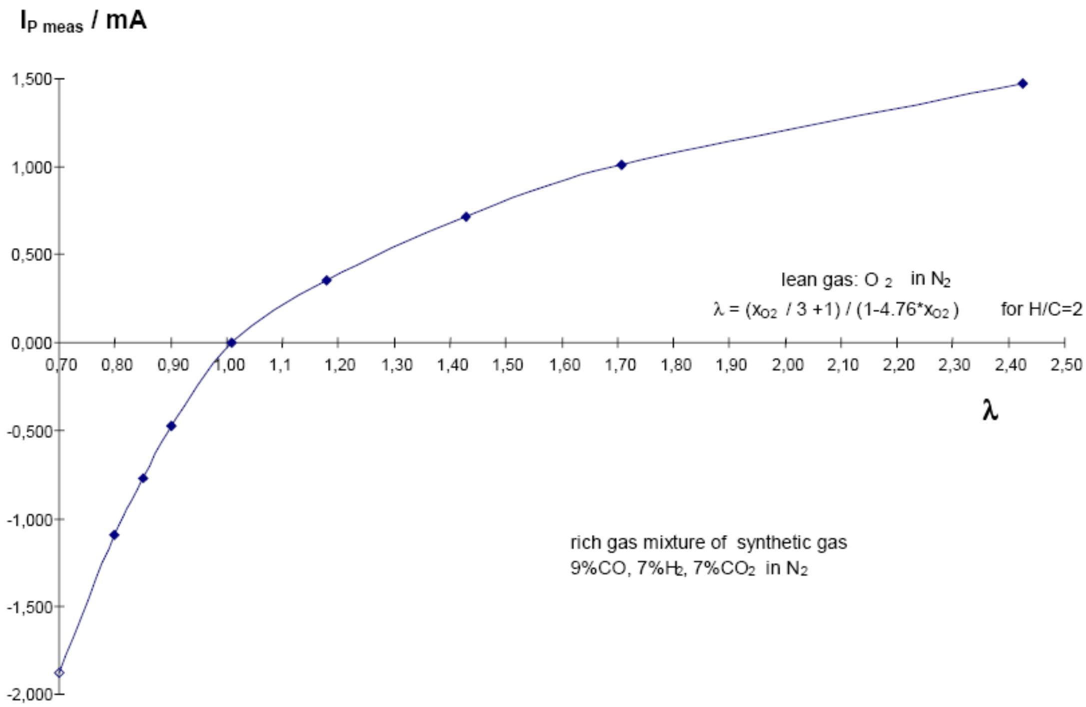
**Figure 4-5: Bosch LSU4.2 UEGO Sensor Pumping Current vs. O2**




(Courtesy Bosch LSU4.2 specifications)

Figure 4-5 shows the response of the pumping current from the Bosch UEGO to oxygen content, but of course there is no such thing as negative oxygen percent to represent rich operation, so a process variable, other than $O_2$ percent, is required to demonstrate the negative portion of the base UEGO pumping current transfer function. If the same Bosch LSU4.2 sensor pumping current, $I_{p\ meas}$, is characterized as a function of lambda, as in Figure 4-6, then one sees the basic pumping current response from the sensor itself is no longer linear in either the lean or rich regions. However, it is still a relationship that does not exhibit any aspects of the discontinuous nature of a HEGO's output near lambda = 1, and in the very narrow region of operation expected for TWC operation, the pumping current-to-lambda transfer function is nearly linear.

**Figure 4-6: Bosch LSU4.2 UEGO Sensor Pumping Current vs. Lambda**

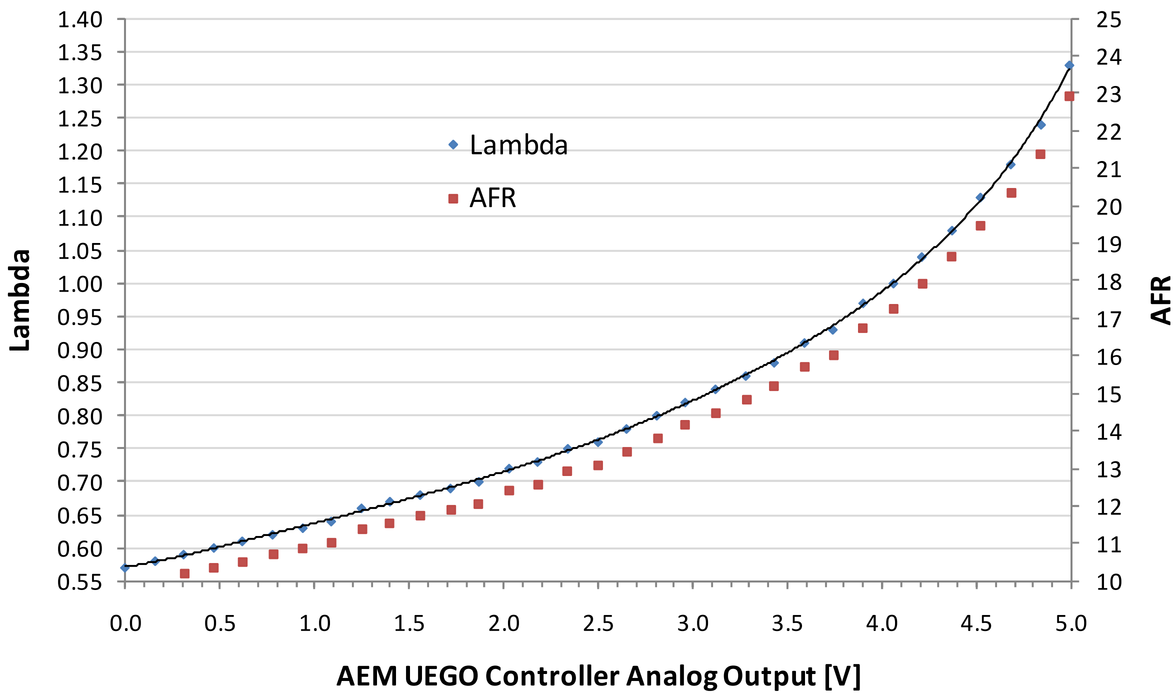



(Courtesy Bosch LSU4.2 specifications.)

Some engine or air/fuel ratio control systems with highly integrated UEGO controllers may use the pumping current to lambda translation directly in their control algorithms. Other UEGO controllers, like the external stand-alone devices evaluated by Tecogen, use other analog or digital translations that may or may not be truly linear to the given process variable used by the AFR controller. However, in all cases UEGO control provides the benefits of a continuous transfer function and near linearity over the small operating window of TWC equipped engines.

Figure 4-7 gives an example of the 0-5 Volt analog output translation AEM's UEGO controller provides for AFR or lambda. This example shows the AEM controller can be expected to output around 4 Volts when operating in the stoichiometric region that produces excellent TWC conversion performance. It also suggests the AFR controller must be able to accept a 0-5 Volt input for the oxygen sensor input, a potential complication for controllers with analog channels optimized for the 0-1 V range of HEGO sensors. Tecogen's controller accepts 0-10 V inputs so the AEM signal is compatible.

**Figure 4-7: AEM UEGO 0-5V Analog Output Calibration**




(Courtesy AEM UEGO specifications)

### 4.1.3 Air Injection and Supplemental Oxidation After Treatment

It has been stated that three-way catalysts reduce $NO_x$, CO, and VOC emissions simultaneously at very high efficiencies, just rich of stoichiometric, in a band of operation that is no more than 0.004 lambda units wide, and presumably smaller for the CARB 2007 limits. Unfortunately, NOx has a mutually opposing conversion trend with CO and VOCs. Near zero $NO_x$ can be achieved and readily maintained with a rich bias away from the optimum simultaneous conversion of all three criteria pollutants. Likewise, near zero CO and very low VOCs can be achieved with a lean bias. Enhanced reduction of one pollutant generally comes at the expense of another. As a result of the magnitude of the reductions required for CARB 2007 limits, much larger catalyst volume and tighter AFR control is needed. This, coupled with the unavoidable presence of catalyst degradation, challenge the viability of maintaining CARB 2007 compliance over commercially viable time frames using traditional rich-burn after treatment strategies that rely on one nominal chemical atmosphere for catalyst reactions to take place.

Tecogen arranged to explore a two-stage catalyst process in which each stage would operate under a significantly different chemical atmosphere. The first stage would simply be a standard set of TWC substrates receiving typical oxygen deficient exhaust constituents from a stoichiometric AFR controller. After the first stage, air would be introduced to the exhaust stream to produce an oxidizing environment as if the combustion AFR had been biased significantly lean. After some mixing, the exhaust constituents and externally added air would enter the second stage catalyst system. With a slightly rich bias from the AFR, the first stage TWC would be expected to reduce the bulk of engine-out $NO_x$, CO, and VOC emissions, but possibly not enough CO and VOCs to achieve CARB 2007 limits. However, the goal of the air injection and the second stage would be to take advantage of the oxidizing atmosphere and significantly reduce these emissions below what could have been achieved with an identical volume of additional first stage catalyst.

The two stage catalyst approach has been used in the US automotive industry before but without temperature conditioning prior to the second stage. There was a narrow period of time in which some vehicles were equipped with air pumps and two-stage catalyst systems. In these systems, air was injected in between an upstream TWC bed and a downstream oxidation bed to achieve a better combination of $NO_x$, CO, and THC reduction than could not otherwise be achieved given the limited state of gasoline-based cylinder-to-cylinder AFR distribution control, combustion quality, EGO-based feedback control, and catalyst technology. Of course, the success at that time was measured against the automotive emissions regulations in effect during that era. The two-stage catalyst strategy did not last long. First, advances in electronic AFR control, feedback control strategies, and catalyst technology, increased in sophistication such that more could be achieved with stoichiometric AFR control and TWCs. Second, as the allowable emissions limits were decreased, the two-stage catalyst strategy encountered a problem, namely the oxidation of exhaust ammonia into new $NO_x$.

Ammonia is a byproduct of conversion reactions in a TWC when the AFR is rich of stoichiometric. The amount of $NH_3$ produced increases with increasingly rich AFR. As vehicle $NO_x$ emission requirements became more stringent, it was found that the dual-stage catalyst strategy could not comply because $NO_x$ reductions achieved in the forward TWC were partially undone by the creation of new $NO_x$ from $NH_3$ oxidation within the artificially induced oxidizing atmosphere of the downstream oxidation catalyst (Heywood). TWC-only systems began to outperform dual-stage catalyst strategies and would continue to benefit from advances in engine control technology without the added burden of an engine driven air pump.
Why would an exhaust after treatment strategy abandoned by the automotive market decades ago be of interest to Tecogen? The answer is that the CARB 2007 limits may be ratcheting $NO_x$ and CO levels below the practical limits of commercially viability given the mutually opposing $NO_x$ versus CO/VOC TWC conversion reactions as a function of AFR. It was in Tecogen's interest to identify whether or not there was an approach that could mitigate the post-TWC reformation of $NH_3$ into $NO_x$ in a downstream oxidation catalyst assisted by air injection. One variable that Tecogen can employ on its engine, essentially a light-duty automotive derivative that does not exist on its automotive counterparts, is a significant amount of exhaust temperature control via exhaust gas heat recovery. Thus, the goal of Tecogen's laboratory dual-stage catalyst testing was to determine whether or not Tecogen could achieve enhanced net CO reductions in the oxidation catalyst, without the creation of counterproductive new $NO_x$ from $NH_3$ using reduced exhaust temperature into the supplemental oxidation catalyst as a control variable. Such experiments were explored and compared to traditional single-stage TWC approaches.

### 4.1.4 Air/Fuel Ratio Dithering

AFR dithering, or fuel dithering, is a standard fuel control process for stoichiometric spark ignition engines using TWC after-treatment in the automotive industry. Its widespread use in the automotive industry makes it a subject of interest with regards to this ultra-low emissions development program as an alternative to Tecogen's current steady-state fuel control process. With dithering, the amount of fuel fed to the intake air is increased and decreased on a 0.5 – 5 Hz cycle, such that the resultant AFR cycles rich and lean of a nominal AFR target. This is in contrast to Tecogen's current steady-state fuel control algorithms that attempt to maintain the AFR as close as possible to a specified AFR, as represented by a target HEGO mV output. The AFR perturbations, caused by dithering, take distinct advantage of catalyst's ability to temporarily store and release oxygen, a feature gained by adding components such as ceria (rare earth metal). Oxygen storage capacity (OSC) is a critical design factor in typical TWC catalysts for both steady-state and dithering fuel control strategies, because it buffers the effects from transient AFR deviations away from ideal chemical conditions.

It is generally reported that dithering can widen the instantaneous operating AFR window by up to 1 air/fuel ratio for high efficiency TWC conversion, but at the expense of some reduction in the absolute peak TWC conversion efficiency[7] (Heywood, J. p656). Dithering is thought to favor automobile applications, in particular, because their real world operation and regulatory compliance testing are both highly transient and can take distinct advantage of the catalyst's ability to absorb significant excursions away from a nominal AFR condition. While Tecogen's inverter-based InVerde system is capable of running at variable engine speeds, InVerde installations are still expected to operate in base-load electrical production modes and thus operate mostly under steady-state conditions. With the CARB 2007 limits being aggressively low, it is unclear whether Tecogen's ultra-low emissions efforts would benefit from this automotive strategy, or be compromised by a potential sacrifice in peak catalyst efficiency. However, the overwhelming use of this strategy in the automotive market justifies exploration by Tecogen.

### 4.1.5 Post Catalyst HEGO Control and Oxygen Storage Capacity

Modern automobile AFR control processes employ pre-catalyst and post-catalyst oxygen sensors, whether HEGO or UEGO sensors. The output of the post-catalyst sensor can provide a an indication of the catalyst's net oxygen storage capacity when used with a dithering fuel control strategy, and it is used in automobiles to continuously update, or bias, the AFR target for the pre-catalyst sensor. Automakers use significant test data and modeling to correlate oxygen storage capacity to anticipated catalytic conversion performance, making oxygen storage capacity a catalyst diagnostic function in OBD II regulations. Tecogen also uses the post-catalyst sensor to modify the pre-catalyst HEGO target over time, but it does not have the resources to attempt oxygen storage capacity calculations and does not currently employ prerequisite dithering fuel control mode.

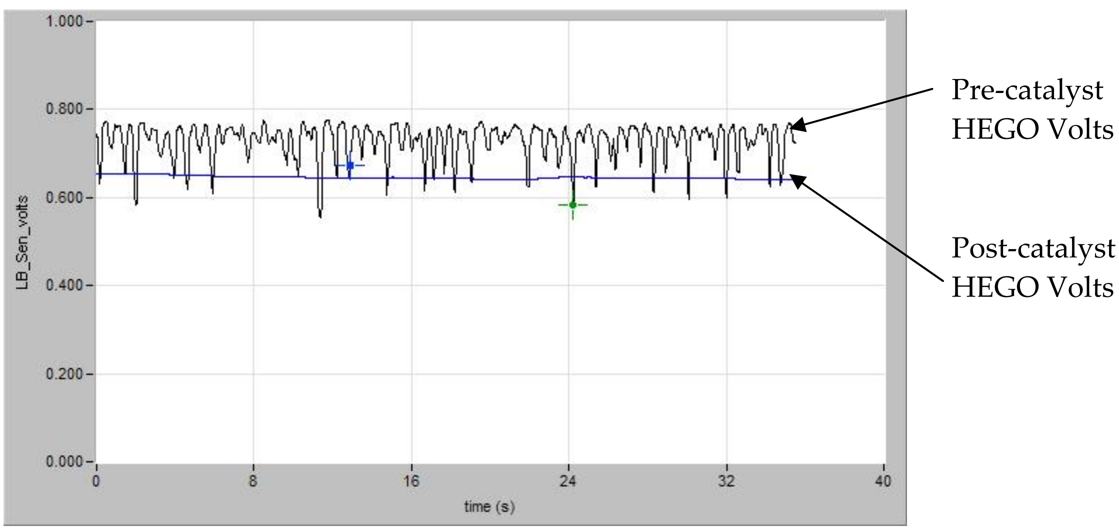
---

[7] For example, the stoichiometric air/fuel ratio for gasoline is approximately 14.7:1. With dithering, the short term deviations in nominal air/fuel ratio, while dithering, could range from 14.2:1 to 15.2:1, and still achieve very high TW conversion of pollutants.

Figure 4-8 and Figure 4-9 provide insight into the chemical reaction buffering effects afforded by the oxygen storage capacity of the catalyst by recording the HEGO outputs before and after a catalyst. Figure 4-8 shows an engine that was operating in a steady-state fuel control at constant engine speed and load. Even under steady-state conditions, normal cycle-cycle combustion variation resulted in somewhat random movement in the pre-catalyst HEGO signal (black line), but the post-catalyst HEGO signal was clearly more consistent in nature. This is due to the catalyst acting as a chemical storage buffer, storing and releasing oxygen as needed to react with the criteria pollutants.

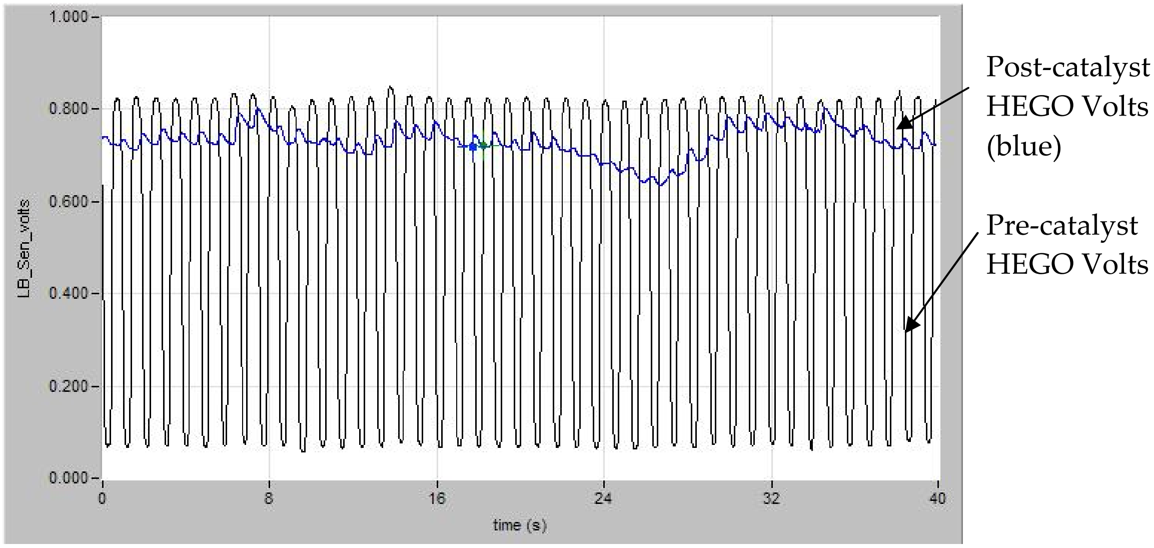
Figure 4-9 is an even more dramatic example of the OSC effect, and should demonstrate the usefulness of the post-catalyst HEGO sensor output. In Figure 4-9, the engine system was operating in a dithering fuel control mode. This resulted in a HEGO sensor output that oscillated between the rich and lean output characteristics of the narrow-band sensor. Yet, while the pre-catalyst HEGO was clearly affected by the intentional fuel perturbations, the post-catalyst HEGO never produced a lean-side output. If, for instance, the post-catalyst sensor would produce an output less than 400 mV, it would be a clear indication of oxygen saturation (or breakthrough) and one could expect the $NO_x$ conversion efficiency to drop dramatically.

**Figure 4-8: Pre-Catalyst and Post-Catalyst HEGO Voltage Outputs With Steady-State Control**




(Courtesy Ranson Roser)

**Figure 4-9: Pre-Catalyst and Post-Catalyst HEGO Sensor Outputs With Dithering Control**




(Courtesy Ranson Roser)

### 4.1.6 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a commonly employed automotive technique applied to produce benefits in the form of lower fuel consumption and lower $NO_x$ emissions. EGR is the process of mixing products of combustion with the fresh intake of air and fuel. Its implementation and benefits are normally limited to part-load conditions where it can promote the greatest improvements in fuel efficiency without impacting drivability or maximum engine performance. Under part load conditions, hot exhaust gas is induced into the intake manifold, which displaces fresh charge air. This results in the throttle being opened more to allow the original amount of air into the engine to maintain power, thus decreasing pumping losses and increasing fuel efficiency. As with other forms of charge dilution, EGR also lowers the peak combustion temperature, which lowers engine out $NO_x$ formation. Lower $NO_x$ into the TWC typically means less $NO_x$ coming out. High enough charge dilution could also reduce the exhaust temperature, something Tecogen would benefit from because its pre-catalyst exhaust temperature is considered to be too high for some TWC manufacturers.

### 4.1.7 Alternative Ignition System

The ignition system on a spark ignited engine can play an important role in both short-term and long-term emissions compliance. The role of the ignition system is to provide enough thermal energy, provided by a localized electrical spark, to excite a very small quantity of pre-mixed air and fuel to the point that chemical combustion occurs. Furthermore, the spark needs to be of such a magnitude, frequency, or duration as to create a kernel of combustion around the spark plug gap that is sufficiently large to self-propagate throughout the remaining air-fuel mixture in the subsequent absence of the spark. An analogous comment would be; the lighting of a match stick does not guarantee the lighting of a fire.

Spark ignition engines experience occasional misfires without detrimental operational or emissions consequences. However, when the frequency of complete misfire or partial misfire events increases, engine operation and post-catalyst emissions can be impacted.

- Misfires result in increased hydrocarbon and oxygen emissions to the catalyst. These will ignite in the catalyst and induce increased exothermic reactions that can moderately or severely damage the catalyst. In the case of CARB 2007 emissions limits, even slight thermal damage can result in the inability to achieve the regulatory thresholds.
- The oxygen pulses from misfires can induce erratic signals from the oxygen sensor, thus compromising the stability of the feedback control loop for the AFR control process, which can also result in increased emissions out of the catalyst.

Increased hydrocarbon emissions into the catalyst generally result in increased hydrocarbon emissions out of the catalyst.

The tendency for an ignition system to misfire can be increased by:

- Very high loads associated with forced induction
- Very low speed and light load, such as at idle
- Poor oil control in the cylinders from high blow-by or leaking seals as an engine ages
- Ignition system degradation due to inadequate service intervals and/or component service life
- Operating with an ignition system that provides borderline performance with regards to the challenges stated above

Ignition systems can be grouped into inductive and capacitive discharge groups. Both are found in automotive and stationary power applications. Inductive systems provide a spark characterized by lower voltage and longer duration than capacitive discharge systems. Capacitive discharge system store and release energy so quickly that they can provide multiple spark events to compensate for much shorter individual spark durations. Capacitive discharge emissions systems are often classified as high-energy ignition systems, yet they do not automatically provide more spark energy than an inductive ignition system.

Tecogen's stock ignition system uses 1980's vintage GM inductive coils and a distributor. The system does not have any outstanding flaws in a typical regulatory environment, yet there was a concern that the ability to achieve, or maintain, CARB 2007 DG emissions limits may require added performance from the ignition system. To this end, Tecogen identified the MSD Model 6A capacitive discharge ignition (CDI) system to evaluate against its stock GM inductive components. The MSD system will provide multiple spark discharges per combustion event at higher secondary voltage than Tecogen's stock components. Testing this alternative ignition system will allow Tecogen to determine if there are any discernible $NO_x$ and CO emissions benefits with regards to achieving low emissions in the laboratory

MSD generally serves the high performance automotive industry, of which the 7.4L GM block is a frequent application. The most important operational specifications for this CDI system are shown in Table 4-1. Laboratory testing will show how many sparks actually occur per combustion event at typical Tecogen operating conditions and whether the emissions can be improved.

**Table 4-1: MSD Model 6A Capacitive Discharge Ignition Specifications**

| | |
|---|---|
| Spark Energy | 105-115 milljoule Per Spark |
| Primary Voltage | 540-480 Volts |
| Secondary Voltage | 45,000 Volts |
| Spark Series Duration | 20 Degrees Crankshaft Rotation |

## 4.2 Data Collection and Reporting

Most of the data collected during the laboratory phase of the program were collected via two software links, one using Tecogen's RMCS (Remote Monitoring and Control System) link to the Premium Power unit's microprocessor, and the other one using Testo's software link to the 350XL portable emissions analyzer. Gas flow, when necessary, was recorded using an external meter with no electrical interface capabilities. Before any data were collected, the unit was operated at a specific power output until stabilization had been established, typically no less than 45 minutes to one hour after an engine start.

The instrument used to measure exhaust gas emissions was a Testo 350 XL (see Figure 4-10). The Testo is one of the few portable instruments that can be configured to provide continuous monitoring, as well as remote access of the data. The features that enable it to operate as a continuous monitoring device are an advanced sample conditioning system for moisture drop-out, a dilution system for sensor protection, and an automatic air purge cycle to periodically cleanse the unit as required. The Testo was calibrated before and after test series using 24.2 ppm NO and 100.2 ppm CO span gases in nitrogen.

Southern California Gas Company sponsored a "Field Comparison of Portable Electrochemical Analyzers to a Continuous Emissions Monitoring System (CEMS) for Measurement of NOx and CO Emissions from a Rich Burn Engine". The portable analyzer used in the test was a Testo 350 XL configured for continuous monitoring. The Testo NO analyzers exhibited excellent performance with good to very good correlation, low variability and slightly high bias (5-10 percent) compared with the CEMS. The Testo CO analyzers measured significantly lower values than the CEMS CO analyzer. However, it was concluded that the CEMS CO analyzer, not the Testo analyzer, suffers positive cross interference from nitrous oxide ($NO_2$) which NSCR-fitted engines can generate. The Testo CO measurements were deemed to be reasonable.

Figure 4-11 presents a view of the RMCS data monitored and captured during emission measurements with the Testo.

**Figure 4-10: Testo 350XL Portable Emissions Analyzer**

**Figure 4-11: Tecogen's Microprocessor Based RMCS Data Collection**

**Operating Status: Monday, March 16, 2009**

| | | | | |
|---|---|---|---|---|
| Site | | | | |
| Record | | | | 135 / 165 |
| Date | | | | 02/25/09 |
| Time | | | | 11:13:00.20 |
| RPM | | | | 2362 |
| MAP ("Hg) | | | | 27.1 |
| Hourmeter | | | | 25.4 |
| Starts | | | | 53 |
| KWH | | | | 1802 |
| MBTU | | | | 85050 |
| Power Setpoint (kW) | | | | 102.0 |
| Temp Setpoint (F) | | | | 200.0 |
| kW1 / kW2 / kW3 / kW | 35.9 | 33.6 | 35.3 | 101.3 |
| kVA1 / kVA2 / kVA3 / kVA | 37.9 | 36.4 | 37.1 | 101.6 |
| kVAR1 / kVAR2 / kVAR3 / kVAI | 11.4 | 13.2 | 11.1 | 11.3 |
| PF1 / PF2 / PF3 / PF (%) | 94.7 | 92.3 | 95.1 | 99.7 |
| V1 / V2 / V3 / Vavg | 284 | 286 | 282 | 286 |
| I1 / I2 / I3 / Iavg | 121 | 122 | 121 | 118 |
| Frequency | | | | 60.0 |
| Generator In / Out Temp (F) | | | 86.1 | 92.6 |
| Water In / Out Temp (F) | | | 185.6 | 231.0 |
| Coolant / Oil Temp (F) | | | 203.6 | 193.7 |
| Enclosure / Exhaust Temp (F) | | | 123.2 | 295.9 |
| SKiiP Temp (F) | | | | 82 |
| Customer 1 / 2 Temp (F) | | | 13.7 | 13.7 |
| Customer 3 / 4 Temp (F) | | | 13.9 | 14.1 |
| Customer 5 / 6 Temp (F) | | | 14.2 | 14.2 |
| Customer 7 Temp (F) | | | | 14.1 |
| Catalyst In / Out Temp (F) | | | 1235 | 1309 |
| Vlogic / Vanalog / Vbat | | 5.085 | 11.869 | 12.844 |
| Oxygen Sensor In / Out (mV) | | | 634 | 420 |
| Oxygen Bounce In / Out (mV) | | | 13 | 18 |
| LT / ST Block Learn | | | 100 | 128 |
| Fuel Valve (%) | | | | 454 |
| MAP / Barometric ("Hga) | | | 27.1 | 30.0 |
| Customer Analog 1 / 2 (V) | | | 0.000 | 0.000 |
| Customer Analog 3 / 4 (V) | | | 0.000 | 0.000 |
| Customer Analog 5 / 6 (V) | | | 0.000 | 0.000 |
| Counter 1 / 2 | | | 33369 | 6 |
| Counter 3 / 4 | | | 5 | 8 |
| Plant / Building Power (kW) | | | 0 | 0 |
| Units Running / Ready to Run | | | 0 | 0 |
| Inverter State / Status / Faults | | 0x0003 | 0x12C0 | 0x0000 |

| | |
|---|---|
| Operating Mode | Run |
| Alarm | None |
| Prealarm | None |
| Runback | None |
| Start Flag | ON |
| Cycling Flag | OFF |
| Master Start Flag | ON |
| Network Start Flag | OFF |
| Network Slave Flag | OFF |
| Temperature Control Flag | OFF |
| Closed Loop Flag | ON |
| Standby Run Flag | OFF |
| Standby Start Flag | OFF |
| Fuel Step | OFF |
| Fuel Open | OFF |
| Inlet O2 Heater | ON |
| Outlet O2 Heater | OFF |
| Gas & Ignition | ON |
| Starter | OFF |
| Pump | ON |
| Contactor | ON |
| Alarm Output | OFF |
| Radiator Fan | OFF |
| Inverter Wakeup | ON |
| Hourmeter | OFF |
| EFLH Meter | OFF |
| Unit Started | ON |
| Load Shed | OFF |
| Status LED | ON |
| Hi Water Press | ON |
| Lo Water Press | ON |
| Lo Oil Press | ON |
| Oil Level | ON |
| Ignition Power | ON |
| Emergency Stop | ON |
| Protective Relay | ON |
| Remote Runswitch | OFF |
| Standby Run | OFF |
| Temperature Control | OFF |
| Customer Alarm 1 | OFF |
| Customer Alarm 2 | OFF |
| Counter 1 | OFF |
| Counter 2 | OFF |
| Counter 3 | OFF |
| Counter 4 | OFF |
| TCP Information | |
| Master Start Output | OFF |

## 4.3 Laboratory Test Program Elements

### 4.3.1 Evaluation of Three-Way Catalysts

#### *4.3.1.1 Catalyst Product Descriptions*

Three-way catalysts from DCL International and Süd-Chemie were procured for performance evaluations against the CARB 2007 DG limits, with emphasis on the DCL product (see Task 2 – Component Screening Report). Table 4-2 describes the attributes of the TWC products. Catalyst housings were not provided by the manufacturers as the TWC substrates were simply required to fit within the constraints of Tecogen's patented combined exhaust gas heat recovery unit and three-way catalyst housing assembly, while inducing no more than 8 inches wc pressure drop. DCL's sizing program predicted two of its 400 cpsi Mine X Series substrates could achieve the CARB 2007 limits, but they noted their practical experience with such ultra-low limits suggested three substrates might be more appropriate. Süd-Chemie's sizing program indicated one 5.91" length element, at 300 cpsi, would achieve the limits, but Tecogen's commercial experience with one element left no doubt that one such substrate could not succeed. Experience with two substrates also suggested CARB 2007 DG limit compliance would not be likely, but Tecogen decided to use two Süd-Chemie 300 cpsi elements as its baseline for comparison against the DCL product, since it was already a product with strong vendor ties.

Table 4-2 shows that the maximum catalyst volume evaluated from each manufacturer was the same (1023 $in^3$), and as a result, so was the space velocity at full load (25,000 $hr^{-1}$). The precious metal loadings were not disclosed by the manufacturers. If the loadings were equal, then one would expect greater emissions conversion from the DCL substrates due to the increased surface area that would come from higher cell density.

**Table 4-2: Three-Way Catalyst Features**

| Catalyst Information | DCL | Süd-Chemie |
|---|---|---|
| Cell density [cpsi, cells per square inch]: | 400 | 300 |
| Single substrate dimensions, OD x L : | 10.5″ x 3.94″ | 10.5″ x 5.91″ |
| Maximum # elements tested in series: | 3 | 2 |
| Maximum Combined length of substrates [in]: | 11.82 | 11.82 |
| Maximum combined TWC volume tested [$in^3$]: | 1023 | 1023 |
| Space velocity of max substrate configuration [$hr^{-1}$]: | 25,000 | 25,000 |
| Precious metal contributors: | Rh, Pt, Pd | Rh, Pt |
| PGM loading: | Unspecified | Unspecified |
| Did the manufacturer's TWC sizing efforts identify a specific TWC configuration meeting the constraints? | Yes | No |
| Is the operating temperature compliant with the manufacturer's commercial limits for warranty? | No | Yes |
| What is a typical warranty for a commercially accepted application? | 1 year | 1 year |
| Was a warranty offered for this CARB 2007 effort? | No | No |
| Are the substrates brazed for added mechanical integrity? | Yes | No |

#### *4.3.1.2 Three-Way Catalyst Experimental Setup and Methodology*

The 7.4L liter InVerde engine in the test cell was alternately fitted with three different configurations of TWC. The catalyst combinations tested were 1023 $in^3$ of Süd-Chemie TWC and both 682 $in^3$ and 1023 $in^3$ of DCL TWC. In each case, the catalysts were de-greened for at least 20 run hours with the InVerde system at 100 kW. Catalyst performance was evaluated using the pre-catalyst HEGO mV sweep technique described in Section 4.1. Data from a post-catalyst emissions sweep was also collected at the full rated power of 100 kW. Incremental pre-catalyst HEGO mV targets were set in the RMCS AFR control, generally in a direction that progressed from non-compliant rich (high CO) to non-compliant lean (high $NO_x$) conditions. Tecogen's RMCS control system recorded all engine and generator control parameters while the Testo 350XL recorded exhaust $NO_x$, CO, $H_2$, and $O_2$. The typical emissions sweep procedure was to:

- change the HEGO mV target
- wait three minutes for engine conditions to stabilize
- start Testo sampling, but not data recording, to condition the Testo for the exhaust stream and preview the general emissions trends
- record five minutes of RMCS and Testo data at 1-2 Hz
- save RMCS and Testo data to a common file and average data
- start three minutes Testo air rinse and set a new HEGO mV target an increment in the lean (lower mV) direction.

At best, one data point every fifteen minutes was obtained in this manner. With the Testo sampling at 1 Hz, each average emissions data point was comprised of at least 300 sample readings.

#### *4.3.1.3 Süd-Chemie Three-Way Catalyst Evaluation Results*

Figure 4-12 shows the average $NO_x$ and CO emissions from 1023 $in^3$ of Süd-Chemie TWC substrates as a function of average HEGO output during steady-state control. Figure 4-12 shows the Süd-Chemie assembly was able to produce only one average data point that was CARB 2007 compliant at the 656 mV. Although a small compliance window is suggested by the trends, it was too small and left no margin for catalyst degradation or normal AFR control deviation. This data suggests this engine and after treatment configuration could demonstrate CARB 2007 compliance under an optimized condition, but would most likely fall out of compliance at an unacceptable operating time in the field.

Later in the program, Tecogen again had the opportunity to test a second new pair of Süd-Chemie TWC. Figure 4-13 shows the results of an emissions sweep performed with the replacement set of Süd-Chemie elements. The replacement set did not perform nearly as well as the original pair. Although $NO_x$ could be reduced to zero with the second catalyst set and not the first, second set still could not reduce simultaneous $NO_x$ and CO averages to CARB 2007 compliant levels. The test team could not identify any non-catalyst source for the emissions deviation between the two identical catalyst data series. Comparing reasonable $NO_x$/CO points between the two Figures, one could reasonably quantify the difference between the two series as the first catalyst pair reducing CO by 99.2 percent and the second pair reducing CO by 98.7

percent. In other words, what appears to be a gross inequality in performance is actually a demonstration of just how aggressive the emissions limits are. It is possible that the performance deviations are simply a sign of TWC-to-TWC deviation in manufacturing, but this question will remain unanswered.

#### *4.3.1.4 Süd-Chemie Discussion*

The Süd-Chemie 300 cpsi three-way substrate configuration could not reliably achieve program goals at 25000 $hr^{-1}$ space velocity, or within the space constraints dictated by the Tecogen catalyst housing. The laboratory work compliments less rigorous emissions samples gathered among the commercial fleet in California, as well as from pre-shipment tests at Tecogen on products destined for California. These random factory and field results sometimes show CARB 2007 compliant results and sometimes do not. The emissions sweep results produced in this program suggests that the Süd-Chemie product, as configured, does not offer a sufficiently wide AFR operating window, or any room for catalyst degradation. Süd-Chemie was desirous of Tecogen to try combinations of 500 cpsi and 300 cpsi product with the intent to provide better results while perhaps staying under the backpressure limits, but such configurations were not tested.

**Figure 4-12: Süd-Chemie Catalyst Performance With 1023 $in^3$ Volume**

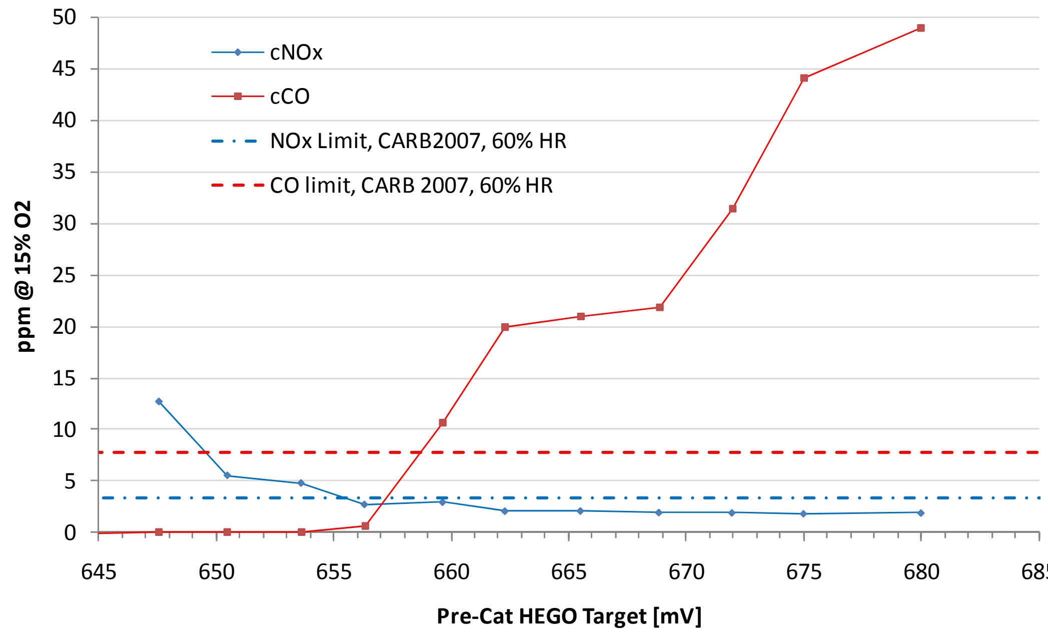
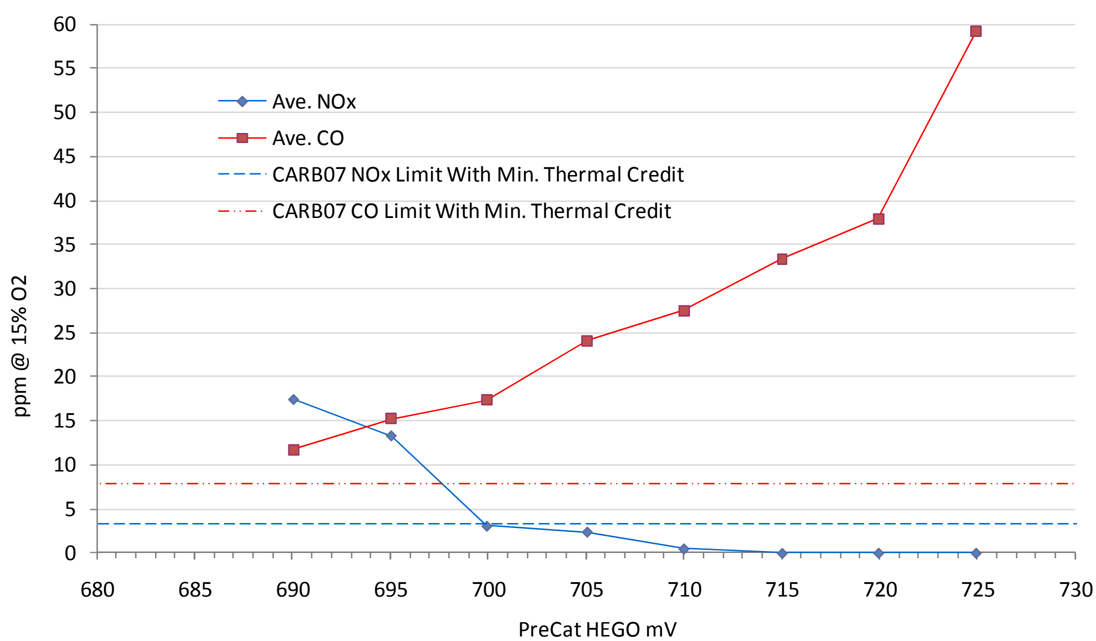



**Figure 4-13: Performance Evaluation With Second Set of Süd-Chemie TWC**



#### *4.3.1.5 DCL Three-Way Catalyst Evaluation – Initial Results*

DCL's TWC sizing analysis predicted two 3.94" substrate segments (682 $in^3$) would achieve the program goals, but suggested three such substrates (1023 $in^3$) might be more appropriate. DCL provided these catalysts with the first two 3.94" elements in a single 7.88" length body of 682 $in^3$ volume, but the third 3.94" element was kept as a separate substrate. This first set of DCL TWC product was available before Tecogen's dedicated R&D test cell was complete and fitted with an InVerde system dedicated for R&D use. As a result, initial DCL testing was performed on a production 100 kW InVerde CHP system that was to be delivered to the end-user, the Rancho San Antonio Boys Home in Chatsworth, California, on a schedule that left insufficient time for formal emissions sweep investigations. The Rancho San Antonio InVerde was fitted with the 682 $in^3$ DCL TWC for emissions validation. The efforts to tune the AFR control system to achieve CARB 2007 limits with the 682 $in^3$ DCL TWC were not successful, so the RSA commercial system was shipped to the end-user with a TWC housing fitted with standard Süd-Chemie TWC, while the DCL assembly was kept at the factory to be reconfigured with the additional DCL substrate length to bring the total TWC volume to 1023 $in^3$.

The maximum DCL volume configuration was subsequently tested on another factory InVerde system, as this production unit was completed and became available for limited testing before shipment to its customer. Data showed the 1023 $in^3$ DCL TWC volume was cable of being tuned to CARB 2007 compliant conditions, so an expanded series of tests was performed to characterize the DCL performance within the time allotted.

The backpressure measurement, with the full DCL catalyst, was 18 in wc at the outlet of the engine at 100 kW. After the catalyst/heat exchanger, the pressure measurement was 5 in wc, resulting in a 13 in wc exhaust pressure loss across the catalyst/heat exchanger assembly. Even with these losses, there was still 5" of remaining pressure for the rest of the exhaust system (piping and silencer). At the design exhaust flow rate of 215 scfm, the pressure loss of the piping is approximately 2 in wc for every 100 feet of piping. Typical INV-100 installations usually do not exceed 50 feet of exhaust piping, so the 5 in wc available at the outlet of the unit was more than adequate. Therefore, the pressure loss across the catalyst was deemed within an acceptable range so as not to exceed the engine backpressure limit or reduce installation flexibility below an acceptable level.

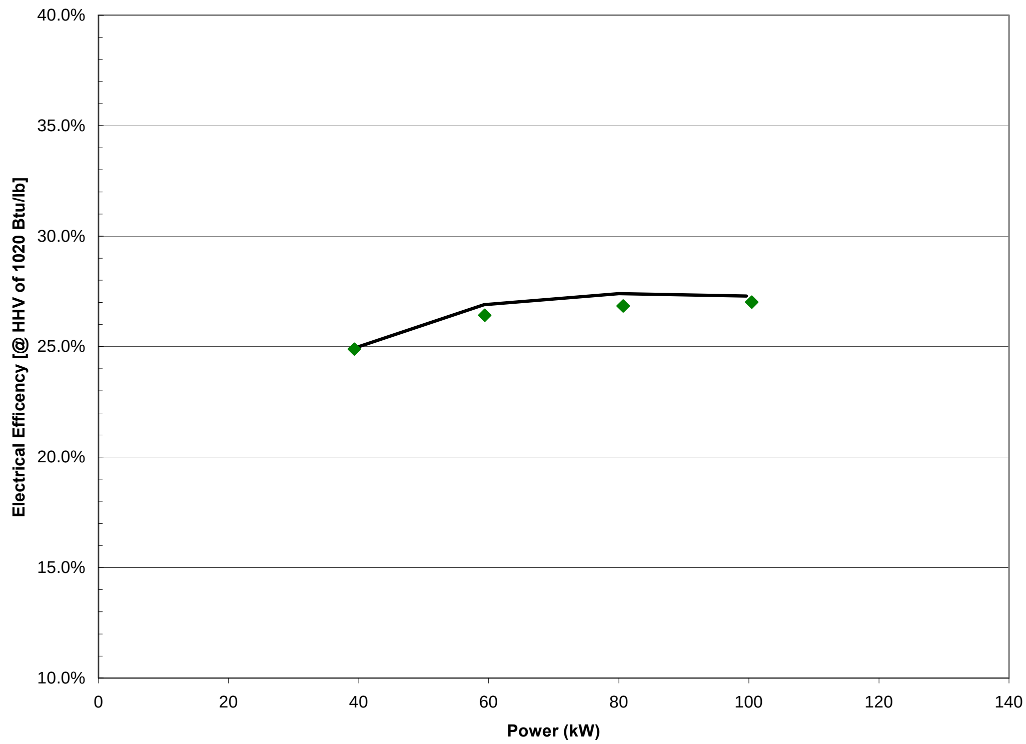
The test results demonstrated that the emission measurements met the CARB requirements at all four load points (40, 60, 80 and 100 kW). However, these results were obtained using a pre-catalyst only AFR control strategy and different HEGO mV targets were required to achieve best emissions for each load point. Only the pre-catalyst control loop was used because it achieves cause-and-effect results much faster than Tecogen's commercial post-catalyst algorithm s. It is not known whether or not one set of tuned commercial parameters using the post-catalyst strategy would have produced CARB 2007 compliant emissions at 40, 60, 80, and 100 kW.

Figure 4-14 presents the Electrical Efficiency versus Load. The data was within 2 percent of the typical INV-100, so tuning for ultra-low emissions did not impact the performance. The emissions data collected by the TESTO emissions analyzer was captured every 15 seconds, for 15 minutes, as per the SCAQMD Rule 110.2. The analyzer also calculated an arithmetic mean for each data set.

Figure 4-15 and Figure 4-16 present the mean average for $NO_x$ and CO emissions, respectively, at each load point. Also shown on the graphs is a line representing the CARB 2007 limit with 100 percent heat recovery, which seemed the appropriate bar at the beginning of the program. As presented, all the data falls below these limits. Table 4-3 presents a summary of the data and provides a comparison to CARB 2007 in lb/MW-hr. Later, when testing was expanded into the test cell, it was decided to compare all results to the CARB 2007 DG limits with the heat recovery credit for a 60 percent total efficiency system to account for the fact that not all customers of CHP equipment take 100 percent of the heat available from the CHP product 100 percent of the time.

Figures 4-17 through 4-24 presents the emissions data taken directly from the Testo. For each load point, these Figures show the $NO_x$ and CO are not fixed values, but rather they vary with time. Some of the emissions spikes vary by several hundred percent more than the calculated average. Unsteady emissions values, especially CO values, are normal for post-catalyst emissions sampling so it is important to take averages over time rather than instantaneous samples. Fifteen minute timed runs were used for this early DCL catalyst testing at the best-tuned condition to provide early results consistent with SCAQMD protocols that show the TWC platform was capable of achieving program goals. However, most subsequent laboratory-derived trends were produced with conditions that were averaged over five minutes to facilitate sweep characterizations of TWC performance, with intentionally compliant and non-compliant data, within reasonable time constraints.

## Figure 4-14: InVerde Electric Efficiency vs. Load




## Figure 4-15: $NO_x$ Emissions vs. Load

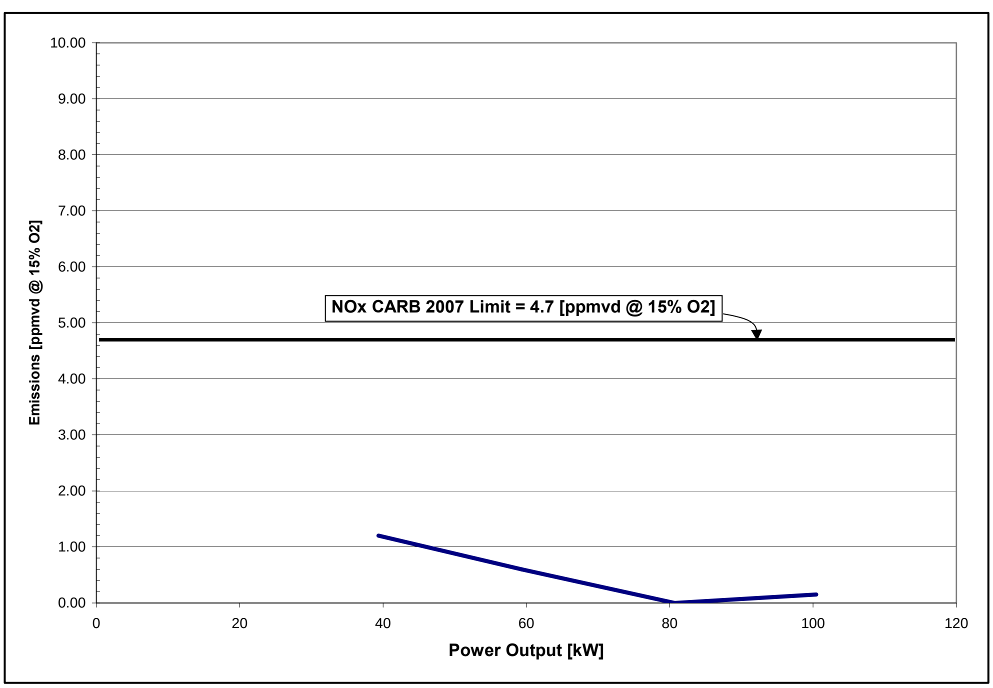


**Figure 4-16: CO Emissions vs. Load**

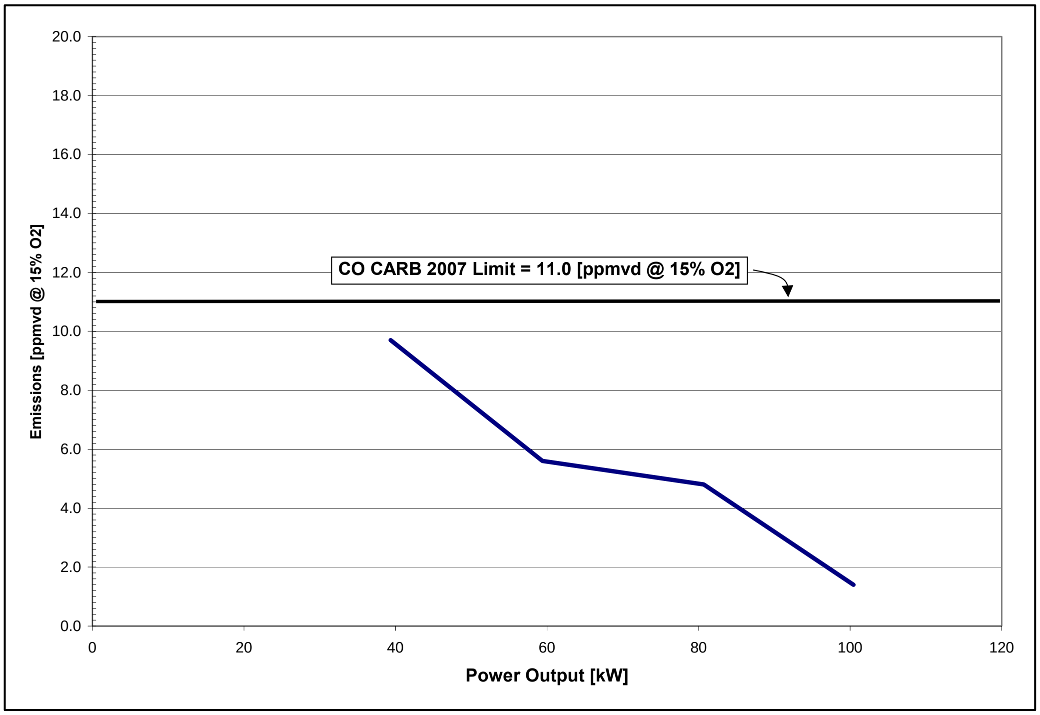



**Table 4-3: Emissions Comparison To CARB 2007 DG Limits**

| | | | | |
|---|---|---|---|---|
| kW | **100** | **81** | **59** | **39** |
| Fuel [scfh] | 1244 | 1006 | 752 | 529 |
| Heat Recovery [Btu/hr] | 652,459 | 519,345 | 393,046 | 289,998 |
| **NOx** | | | | |
| Measured (ppmvd) | 0.600 | 0.200 | 0.6 | 4.4 |
| ppmvd @ 15% | 0.15 | 0.000 | 0.10 | 1.20 |
| lb/hr | 0.001 | 0.000 | 0.000 | 0.002 |
| lb/MW-hr | 0.008 | 0.003 | 0.008 | 0.060 |
| **Measured** lb/MW-hr (100% HR) | **0.003** | **0.001** | **0.003** | **0.019** |
| **CARB Standard** (lb/mW-hr) (100 % HR) | **0.07** | **0.07** | **0.07** | **0.07** |
| **CO** | | | | |
| Measured (ppmvd) | 4.800 | 16.800 | 19.6 | 33.8 |
| ppmvd @ 15% | 1.40 | 4.80 | 5.60 | 9.70 |
| lb/hr | 0.00 | 0.01 | 0.01 | 0.01 |
| lb/MW-hr | 0.04 | 0.13 | 0.15 | 0.28 |
| **Measured** lb/MW-hr (100% HR) | **0.01** | **0.04** | **0.05** | **0.09** |
| **CARB Standard** (lb/mW-hr) (100 % HR) | **0.1** | **0.1** | **0.1** | **0.1** |

**Figure 4-17: NOx Emissions vs. Time - 100 kW**

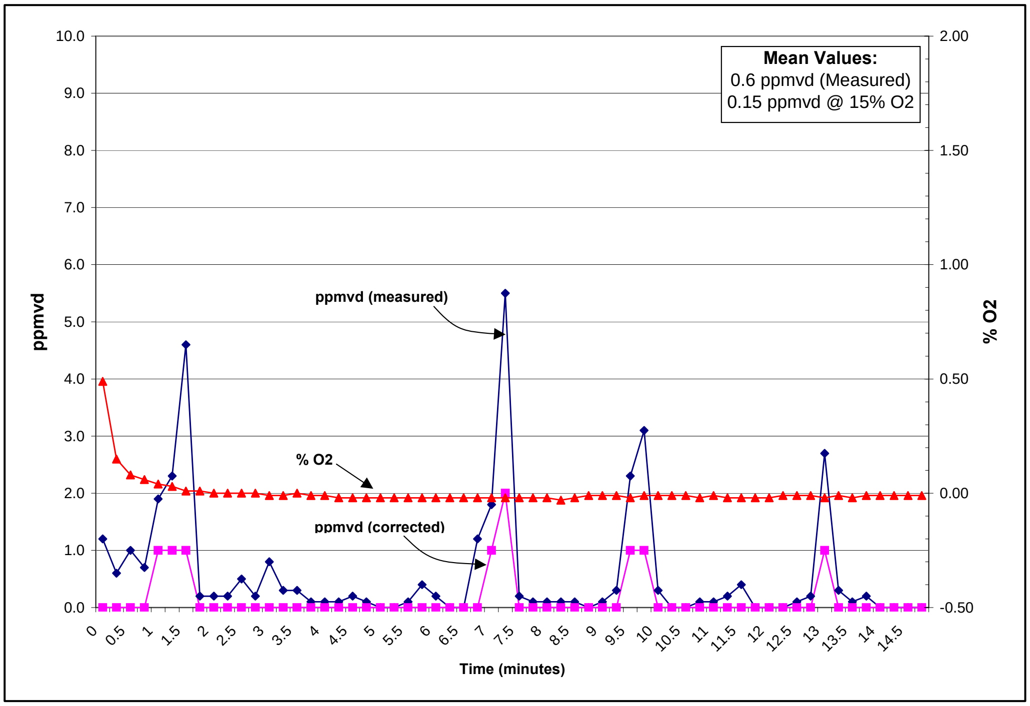


**Figure 4-18: CO Emissions vs. Time - 100 kW**

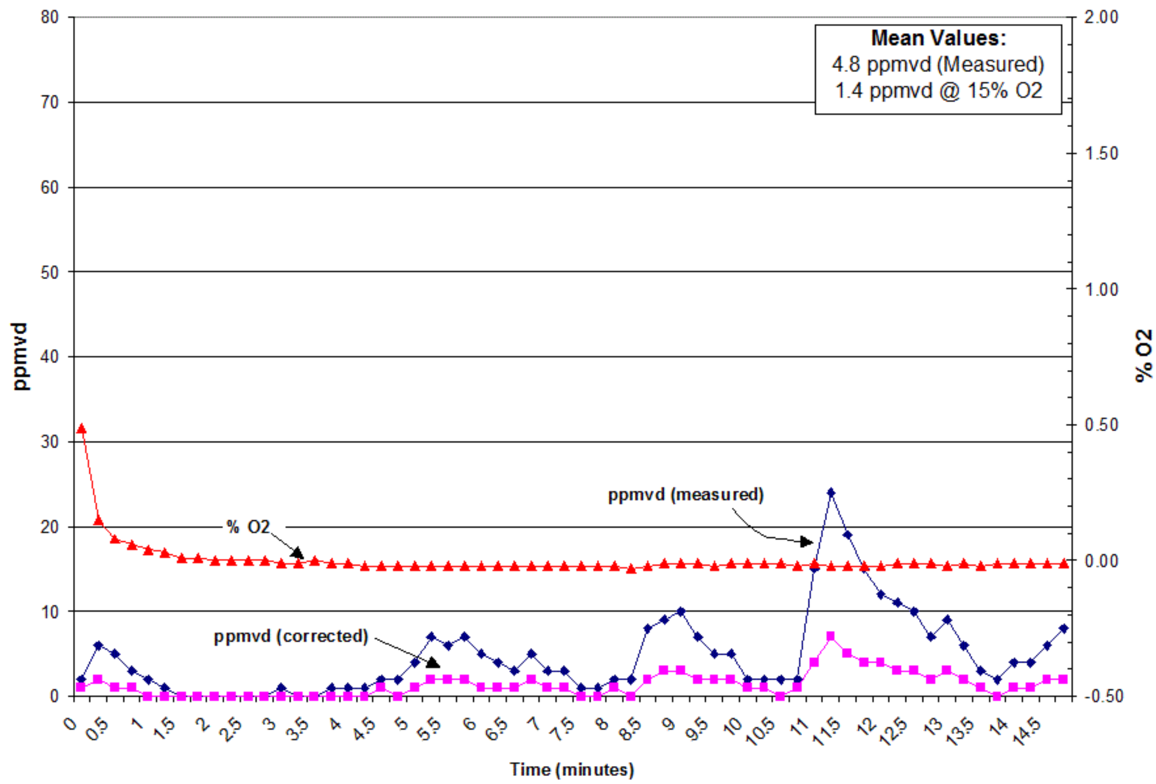
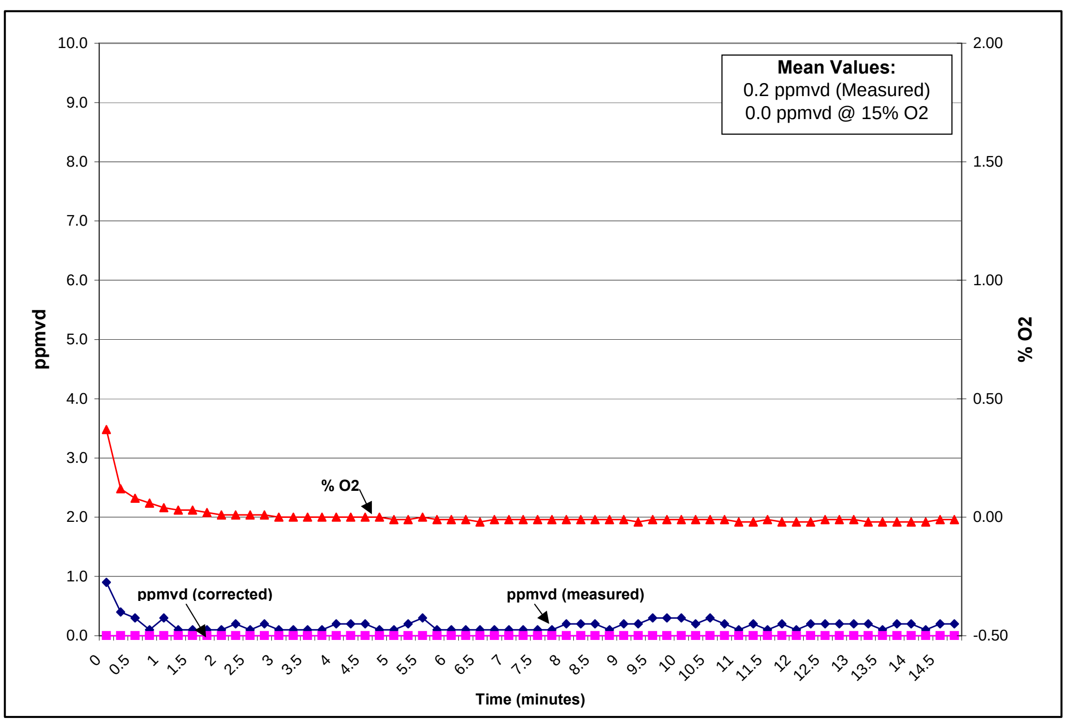
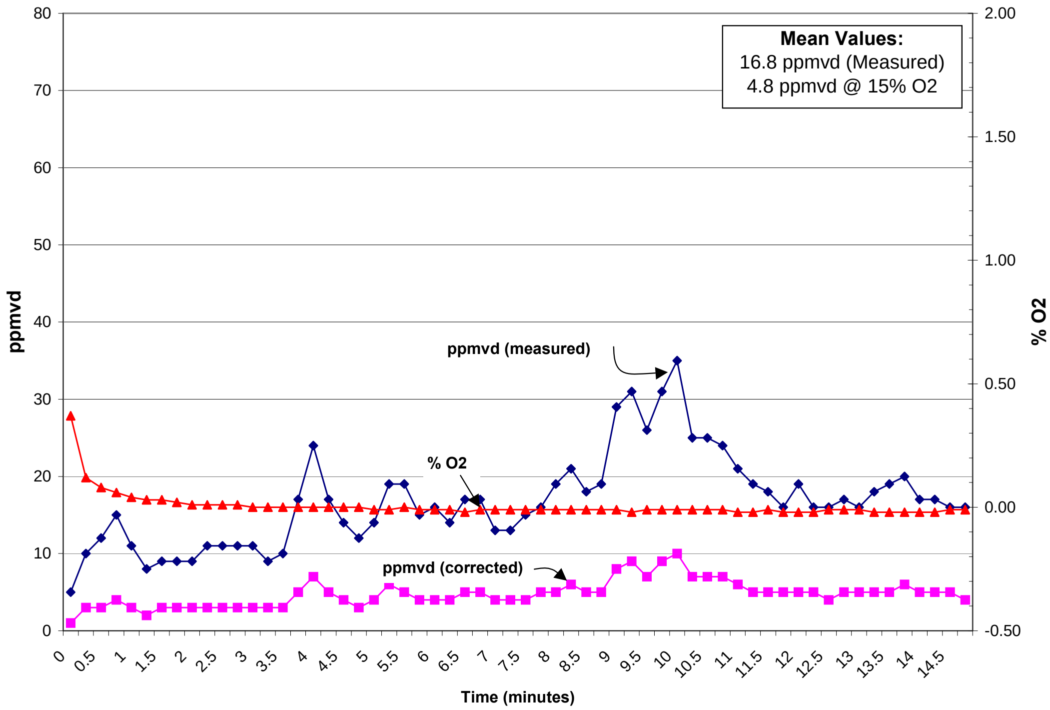


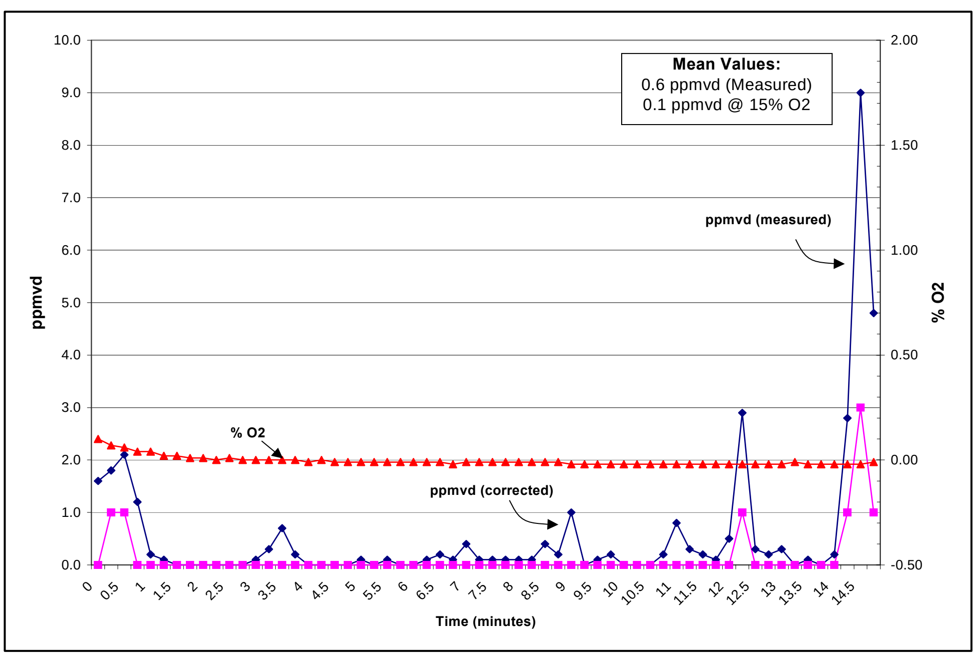

**Figure 4-19: NOx Emissions vs. Time - 80 kW**



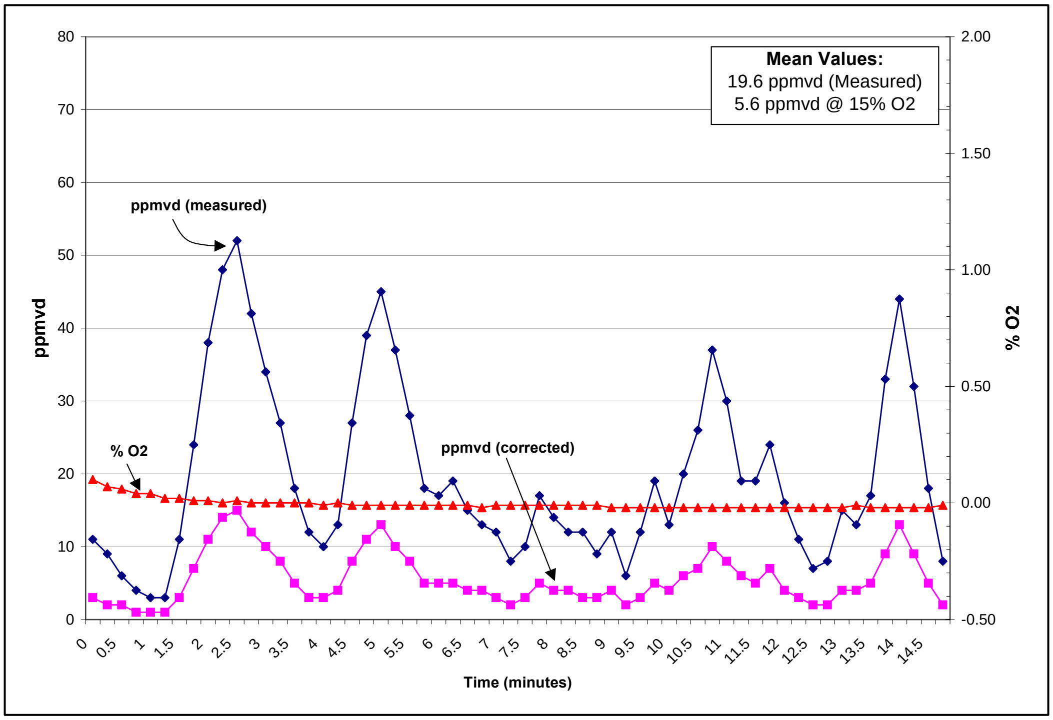
## Figure 4-20: CO Emissions vs. Time - 80 kW




## Figure 4-21: NOx Emissions vs. Time - 60 kW



## Figure 4-22: CO Emissions vs. Time - 60 kW




## Figure 4-23: NOx Emissions vs. Time - 40 kW

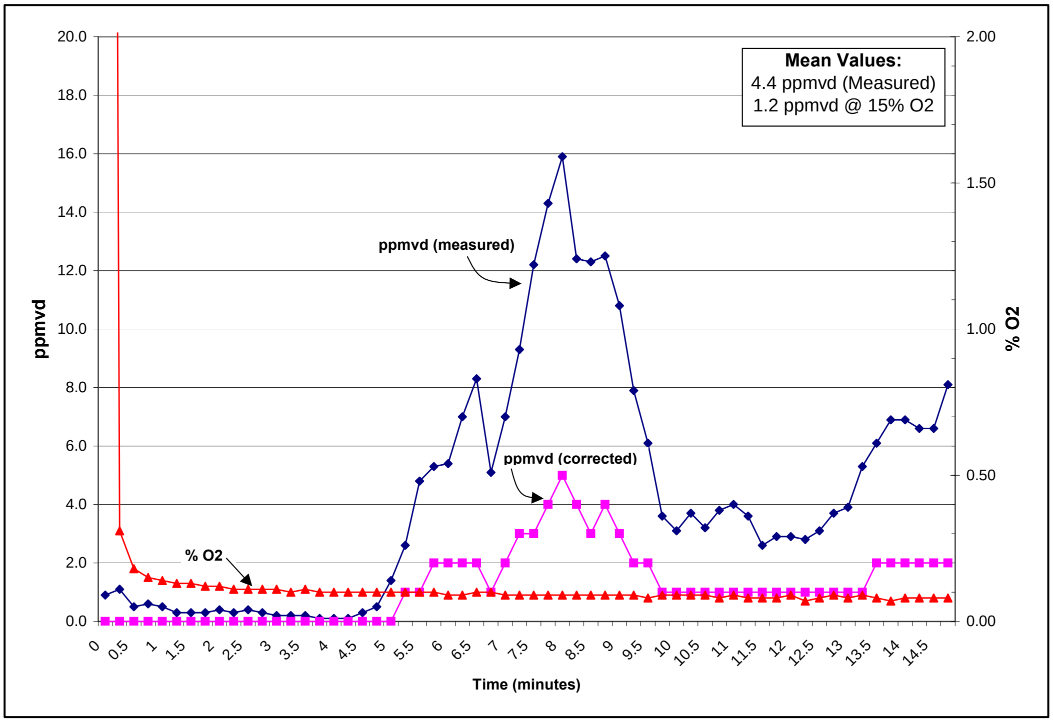
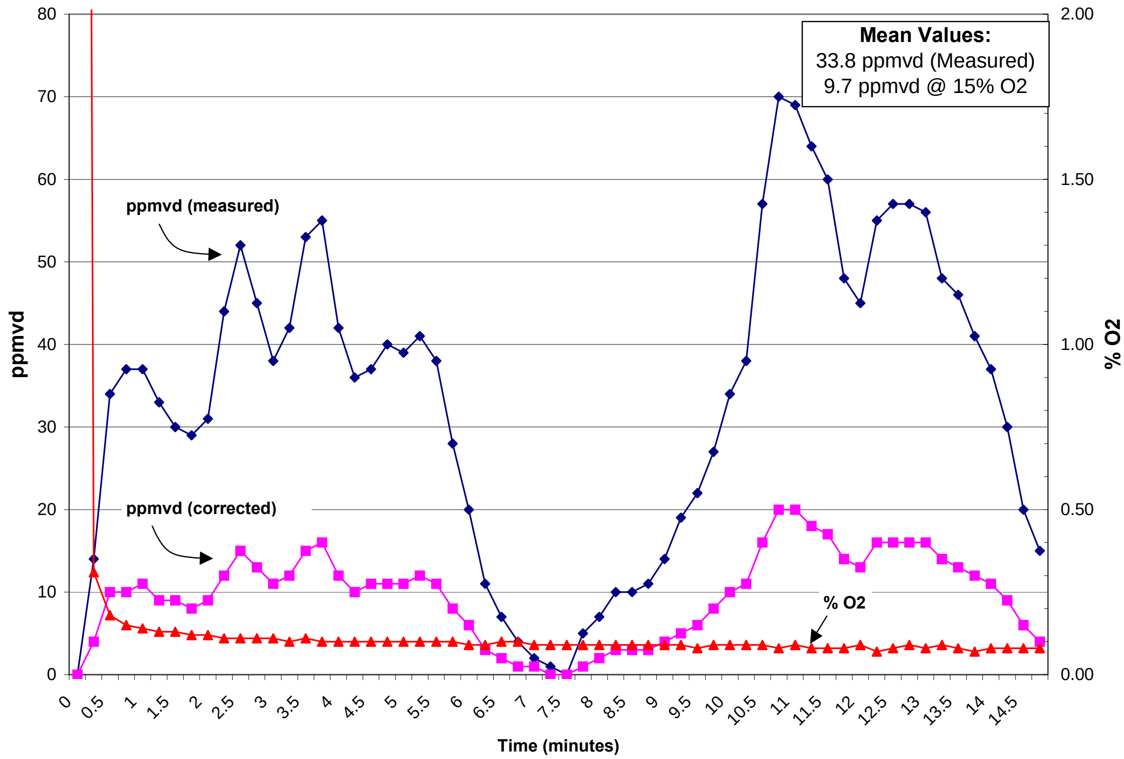
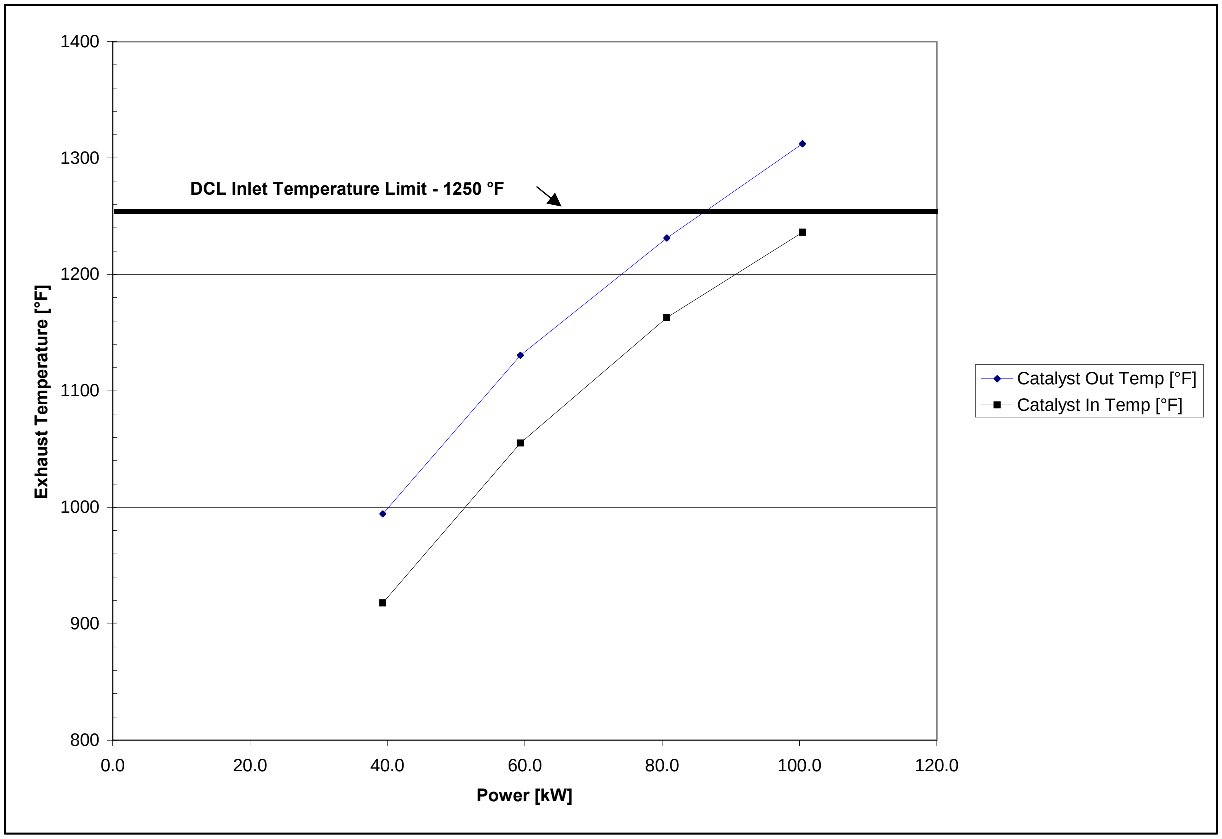


**Figure 4-24: CO Emissions vs. Time - 40 kW**




Finally, Figure 4-25 shows the exhaust temperatures entering and exiting the catalyst as a function of load. Since an exothermic reaction occurs within the catalyst, the outlet temperature ran consistently about 70 °F higher than the inlet temperature. DCL established an inlet temperature limit of 1250 °F. As a result, Tecogen did not test at the peaking load of 125 kW.

**Figure 4-25: Catalyst Inlet and Outlet Temperatures vs. Load**




The test results achieved by testing the full volume of DCL catalysts, on borrowed production units, were favorable and justified further DCL testing as the test cell InVerde system came on line.

#### *4.3.1.6 DCL Three-Way Catalyst Evaluation – Test Cell Program*

DCL TWC investigations were initiated again when Tecogen's test cell and InVerde test platform were completed. New DCL TWCs were purchased and aged for 20 hours to de-green the catalysts. Tests were conducted in the sweep format to define best possible operating emissions, as wells as the sensitivity of the emissions to the operating AFR based on the surrogate, HEGO mV output. Figure 4-26 and Figure 4-27 show the results of the emissions sweep evaluations performed on the DCL for the two volumes tested. In Figure 4-26, the HEGO mV output data was shifted to normalize the location of the lean edge of $NO_x$ compliance to identical points and thus provide visual clarity. Also, the emissions scale (y-axis) of Figure 4-26 is intentionally large to facilitate crude observations such as: 1) there is not a strong distinction between the performance of 682 $in^3$ volume and 1023 $in^3$ volume and; 2) the slope of the CO benefit, achieved as a result of tighter AFR control, changes dramatically between the realm of ICE BACT limits and CARB 2007 limits. Thus, incremental improvements in the long-term consistency of AFR control cannot produce dramatic emissions reductions during short-term tests, but can mitigate sharp NOx or CO emissions increases, as a result of the AFR drifting towards the lean or rich boundaries, respectively, in the field. The sweep for the 682 $in^3$ configuration was extended far enough in the rich direction to show that the compliance window for SCAQMD ICE BACT standards for non-DG applications is approximately 30 mV of the HEGO output.

Figure 4-27 shows the same data, but on an emissions scale more appropriate for observing results in the context of CARB 2007 limits. Also, the plots are presented with the as-tested HEGO mV correlations, rather than the normalized shift, and show that peak performance occurred at different pre-catalyst HEGO mV control settings for the 682 $in^3$ versus the 1023 $in^3$ volume series. In the context of this discussion, it is the width of the apparent compliance window that is important, not the location. Figure 4-27 shows that both DCL volumes could operate under conditions that would comply with CARB2007 limits. However, the 682 $in^3$ volume produced CO data that was more erratic and, as a result, produced a smaller region of AFR compliance. The data suggests the compliance windows, as a function of HEGO output for the two configurations, were 7 mV for the 682 $in^3$ TWC volume and 12 HEGO mV for 1023 $in^3$.

The shape of the 1023 $in^3$ trend suggests that just a minor amount of normal age and poisoning based degradation would lead to a control window as small as the 682 $in^3$ version. Therefore, although these two DCL TWC volume configurations can achieve CARB 2007 limits, it must be recognized that to do so in the field would require a very narrow AFR control. In other words, the system would have to operate within 25 percent of the AFR control deviation that would work for non-DG SCAQMD ICE BACT if using 682 $in^3$ TWC, or 40 percent if using1023 $in^3$. Although there is clearly a severe decline in value when increasing the catalyst volume and cost by another 50 percent to 1023 $in^3$, the small $NO_x$ advantage and marginal benefit in the size of the compliance window still appear critical for the goal of CARB 2007 compliance. The expanded laboratory testing with the DCL TWC showed the 1023 $in^3$ variation to be a CARB 2007 capable arrangement, but the field data will be important to observe in the context of the ability of the AFR control system to maintain operation within the highest TWC conversion zone and in the context of overall catalyst degradation.

**Figure 4-26: Broad View of 682 in³ vs. 1023 in³ DCL Catalyst Volumes**

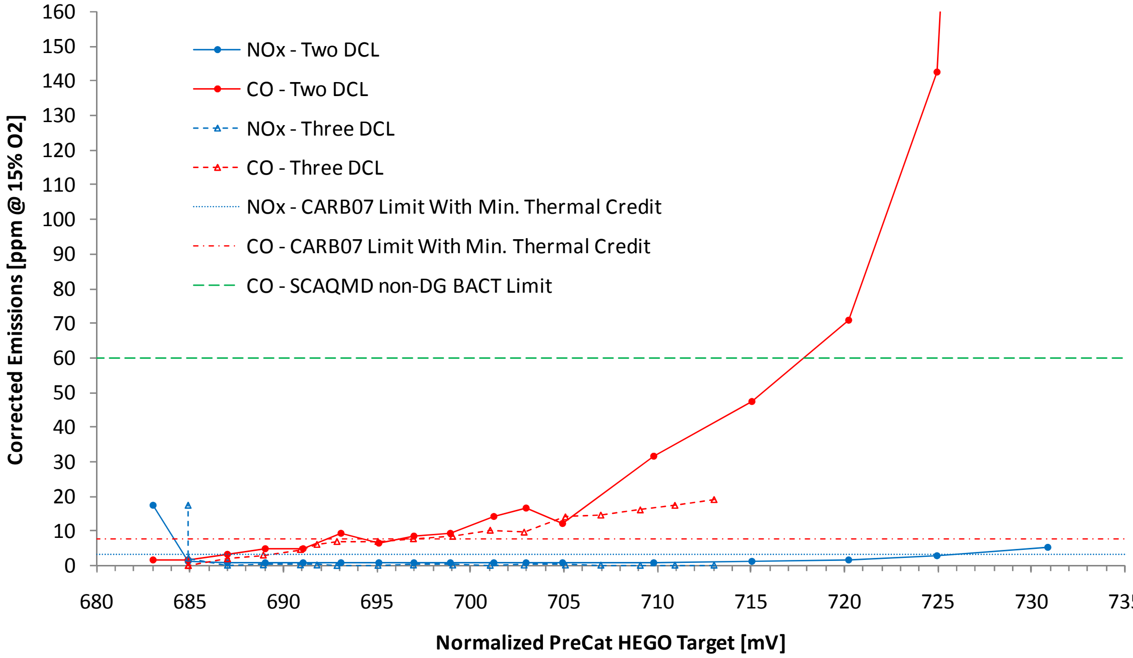
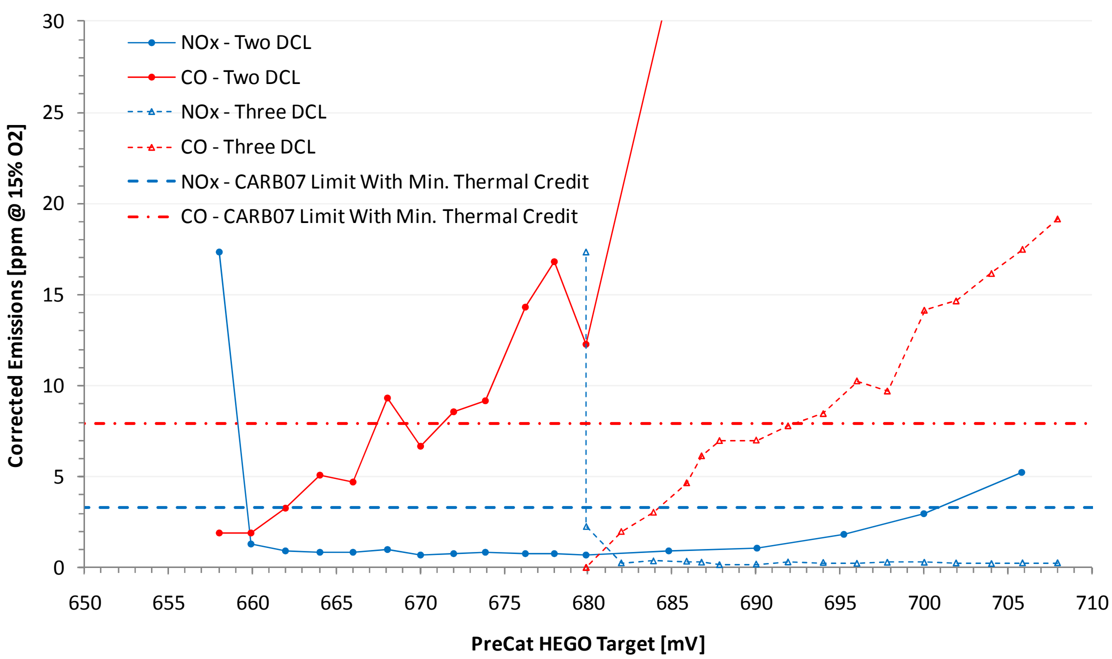



**Figure 4-27: Closer Inspection of DCL Three-Way Catalyst Performance**



## 4.4 HEGO Sensor Aging

### 4.4.1 Experimental Setup and Methodology

Pre-catalyst HEGO characteristics were evaluated as a contextual baseline for subsequent UEGO sensor testing. Four new HEGO sensors were installed for simultaneous measurement of the pre-catalyst exhaust stream. These were identified as HEGO-010, HEGO-011, HEGO-012, and HEGO 013. The HEGO sensors were Tecogen's standard Delphi model HEGOs (PN: GM25312178) and were supplied with fixed power supply to the heater circuits. The outputs of the HEGO sensors were provided to Tecogen's RMCS control system's 0-10V input channels. Data from all four sensors were recorded during engine operation, but only HEGO-010 output was an input to AFR feedback control loop.

At the time of this effort to document the effects of HEGO aging, the InVerde's exhaust after treatment was configured for oxidation catalyst testing using all Süd-Chemie's 300 cpsi TWC product, with 1023 $in^3$ substrate in the $1^{st}$ stage and 511 $in^3$ in the second. The $2^{nd}$ stage temperature was controlled to approximately 550 °F. The engine was operated at 100 kW. Brief emissions observations were made to determine the approximate HEGO-010 mV locations where very high $NO_x$ and CO would occur to pre-define the range of the emissions sweep. The RMCS AFR controller was then programmed to perform defined auto-sweeps, an automated function by which the AFR control automatically starts at one pre-catalyst HEGO mV target and then continuously adjusts the target to a defined end-point over a 15 minute period. Such 15 minute auto-sweeps were performed in both rich-to-lean and lean-to-rich directions while all HEGO data and exhaust emissions were recorded at 1 Hz. In this way, the Testo recorded $NO_x$ and CO as a function of slow, but continuous changes in exhaust chemistry as, defined by the HEGO-010 mV output. In addition, the same emissions could then be correlated to the other three HEGO outputs, thus allowing the procedure to characterize four HEGO sensors at a time.

Continuous emissions measurements with the new sensors were recorded with one rich-to-lean sweep and one lean-to-rich sweep. Then the sensors were aged for 50 hours at full load and the tests repeated. The aged series were slightly expanded to include three 15 minute auto-sweeps in each direction.

### 4.4.2 HEGO Sweep Results

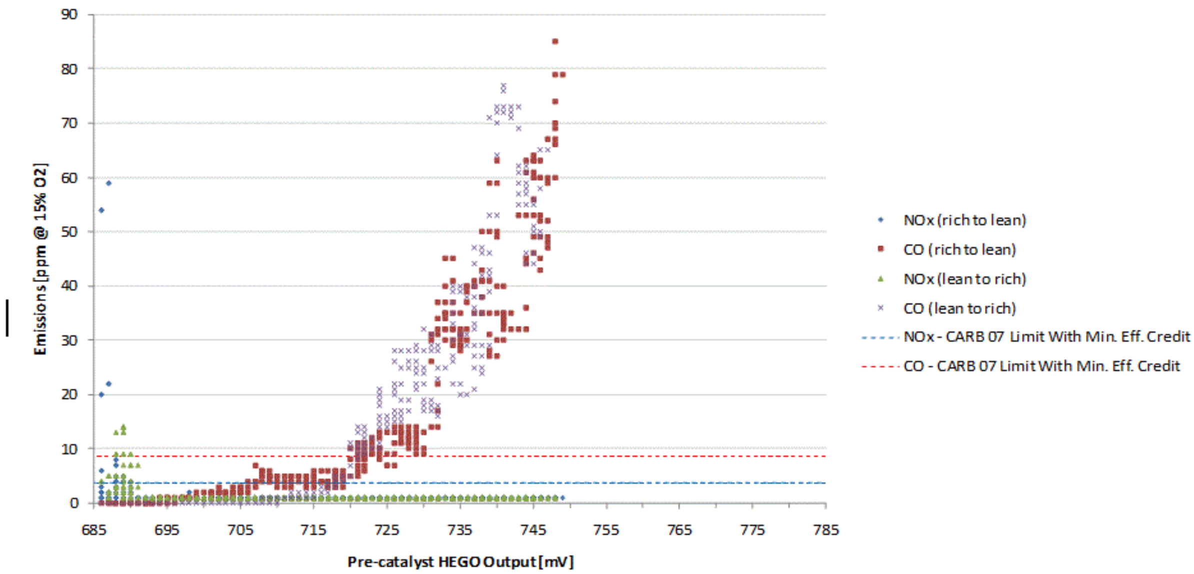
Figure 4-27 and Figure 4-28 show the new and aged results for HEGO-010, respectively. First note that the data is presented in a "point-cloud" format. Sweep data in other sections of this report are presented with average $NO_x$/CO data points for a fixed AFR control condition, a format that is most appropriate for showing the anticipated size of the compliance window. In these experiments, though, the AFR is continuously moving. Although the AFR movement is not fast, it did not stay at any one AFR long enough to make it appropriate to define average emissions for any particular HEGO output mV. By showing all data points, one can still clearly see the traditional trade-offs between $NO_x$ and CO emissions as a function of HEGO mV as an AFR surrogate.

Comparing Figures 4-28 and Figure 4-32 gives an excellent example of a likely shortcoming to any AFR controller using steady-state (non-dithering) closed-loop AFR control, based on the pre-catalyst HEGO input and no post-catalyst feedback. With HEGO-010 in new condition, best emissions were achieved at 700 mV, but at 50 hours the optimum set point was 755 mV. It should be evident that such drift in the correlation between pre-catalyst HEGO output and the best TWC performance with such minor aging represents a distinct liability for a controller relying on such a strategy. Although Tecogen does not use an AFR strategy that relies upon just a fixed pre-catalyst HEGO target, this HEGO characteristic with steady-state fuel control is the basis for Tecogen's interest in trying to integrate UEGO sensors into the AFR control loop, for which these HEGO auto-sweep tests are to represent the baseline.

Figure 4-29 and Figure 4-33 show the new and aged auto-sweep results for HEGO-011. In this case the approximate location of the best TWC performance did not change, showing that HEGO drift characteristics are not absolute, at least not at 50 hours. However, comparing new and aged profiles for both HEGO-010 and HEGO-011 show an apparent narrowing of the size of the compliance range. The comparison between Figure 4-27 and Figure 4-28 also shows the potential for the sensor aging to significantly narrow the size of the HEGO mV compliance window by about two thirds. Tecogen's experiments did not rule out the potential that some form of catalyst degradation was responsible for the narrowing of the compliance window, but it is felt that the culprit is the aged-altered characteristics of the HEGO sensor. This means the size of the compliance window is suspected to have not changed in terms of true AFR, or lambda, and so forth, but that the HEGO mV surrogate to these parameters, itself, changes with time and makes the control window smaller.

Figure 4-30 and Figure 4-31 show the 15 minute auto-sweep results for new sensors HEGO-012 and HEGO-013. The sweeps suggest 700 mV would have been an excellent pre-catalyst HEGO target for both sensors, as it was for new HEGO-010. However, comparing the point-cloud data from HEGOs -012 and -013 with the first two sensors shows a broader array of data scatter, most noticeable with the CO data. The scatter for the aged data for HEGOs -012 and -013 was so prevalent that $NO_x$ and CO trends appeared to merge and make the resultant data non-discernible, and thus their aged plots are not shown. It was later speculated that the RMCS data channels responsible for HEGOs -012 and -013 were not programmed for identical signal filtering as HEGOs -010 and -011 for the new sensor experiments, and that the level of averaging or filtering that did exist on those two channels changed between the new and aged auto-sweeps.

## Figure 4-28: New HEGO-010 Emissions Auto-Sweep




## Figure 4-29: New HEGO-011 Emissions Auto-Sweep

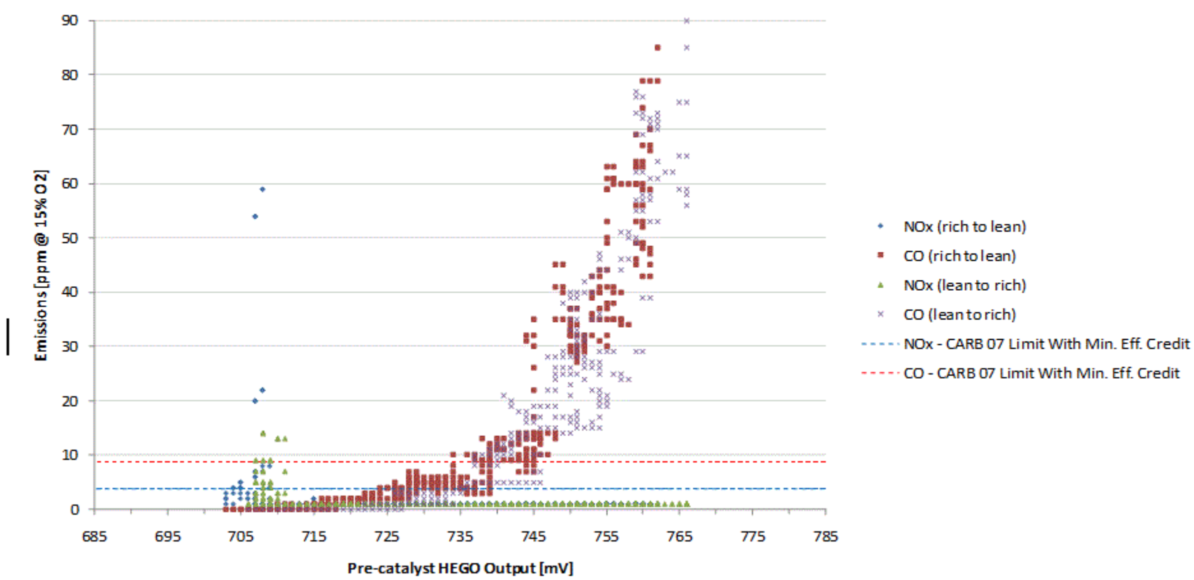


Figure 4-30:  New HEGO-012 Auto-Sweep

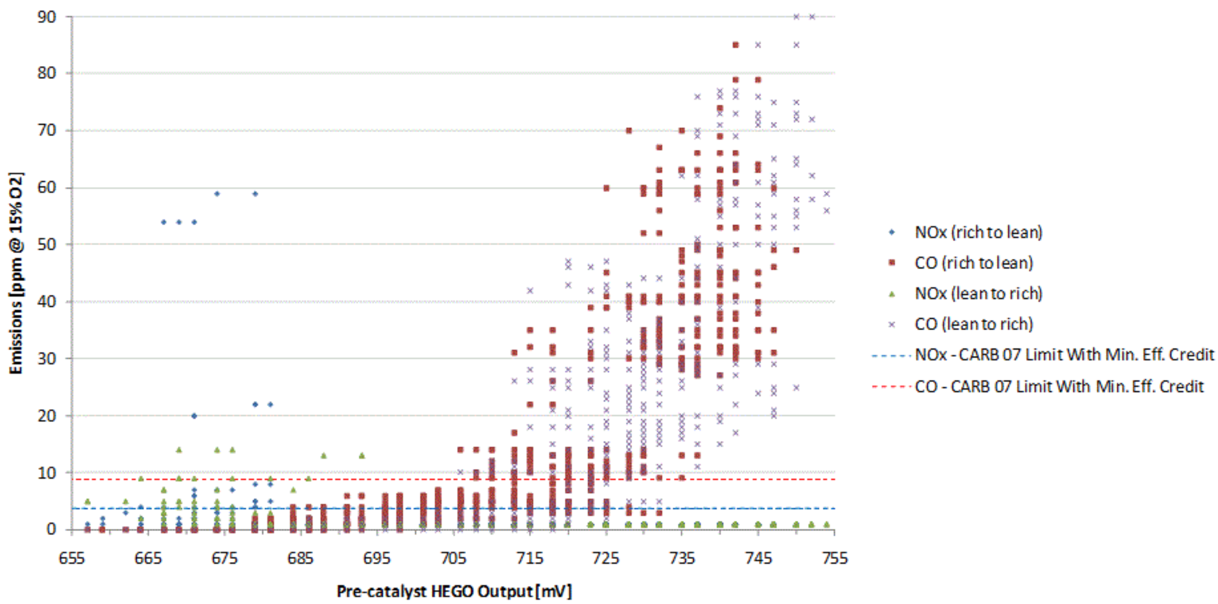
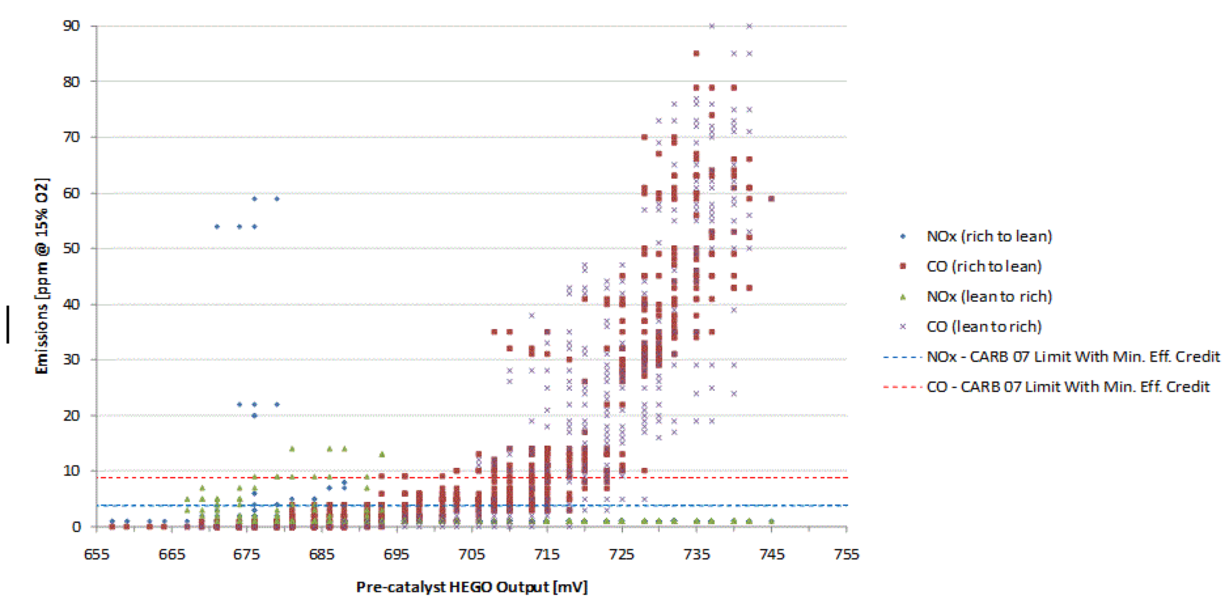
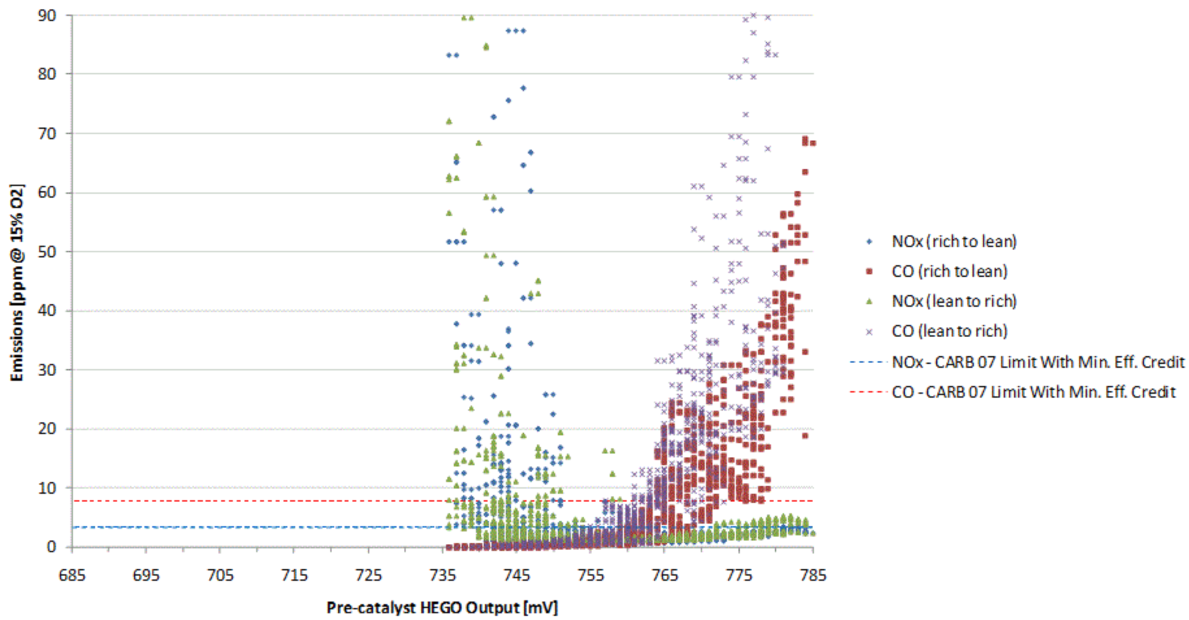


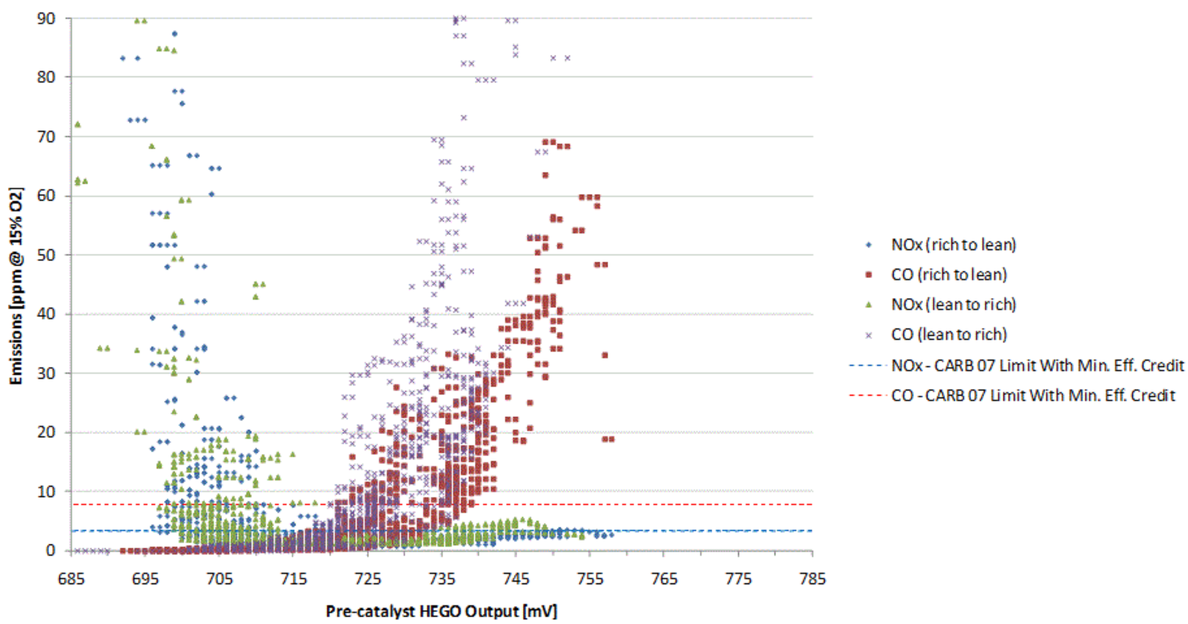

Figure 4-31:  New HEGO-013 AutoSweep



## Figure 4-32: Aged HEGO-010 Auto-Sweep




## Figure 4-33: Aged HEGO-011 Auto-Sweep



### 4.4.3 HEGO Auto-Sweep Discussion

The purpose of characterizing the emissions versus HEGO mV output of four HEGO sensors at new and 50-hour aged conditions, was to create a baseline for comparisons against similar tests to be performed using UEGO sensors. The results of the HEGO auto-sweeps show the traditional $NO_x$ versus CO trade-off inherent to any tuning process with rich-burn engines using TWC after treatment. Even with a statistically insignificant number of sensors tested, the results show an unreliable correlation between HEGO mV and best TWC emissions as a function of sensor age, and also sensor-to-sensor at equivalent age. These results are applicable to AFR control processes using steady-state fuel control, based on a fixed pre-catalyst target. Dithering and post-catalyst feedback strategies have the potential to mitigate the influences of HEGO sensor drift. Independent experience from members of the test team suggest that intelligent HEGO heater controls, which attempt to maintain consistent sensing element temperature provide benefits, do not eliminate the observations stated above.

## 4.5 Universal Exhaust Gas Oxygen Sensors

The intentions of all UEGO sensor testing were defeated by an apparent severe incompatibility between the UEGO controllers and the noise of the InVerde inverter-based generator control system. This section characterizes Tecogen's noise related difficulties during the UEGO efforts, but no tangible ultra-low emissions-related insights were produced by the UEGO program because the UEGO controllers could not be successfully integrated into Tecogen's InVerde equipment.

### 4.5.1 Experimental Setup

The goal of the UEGO sensor testing was to replace the HEGO input to the RMCS pre-catalyst AFR control loop with various UEGO sensor/controller pairs, and perform emissions auto-sweeps based on pre-catalyst UEGO mV targets. Sweeps were to be made with sensors in new and 50-hour aged conditions with data to be compared against similar evaluations with HEGO sensors. The key finding Tecogen hoped to observe was a benefit with UEGO sensors as compared to HEGO sensors, with regards to the correlation between UEGO output and the range of best simultaneous $NO_x$ and CO conversion from the TWC as a function of early sensor aging. The combinations evaluated were:

- Four Bosch LSU4.2 UEGO sensors with two Innovate LM-1 and two LC-1 model controllers
- Four Bosch LSU4.2 UEGO sensors with AEM controllers
- Four NTK UEGO (model) sensors with E-Controls controllers

The RMCS control system could accommodate one oxygen sensor input to be used in the AFR control algorithm, and an additional three analog input channels that could log the outputs of other sensors. Tecogen used this analog input availability to operate the AFR control loop with the standard HEGO sensor while logging one of each type of UEGO combination. This initial effort was expected to be very brief, providing a simple screening for reasonable signal stability and lambda accuracy before switching from HEGO to UEGO-based AFR control.

Figure 4-34 and Figure 4-35 show the equivalence ratio calibration options from the AEM and E-Controls UEGO controllers, respectively. The E-Controls UEGO controller can be ordered with a variety of calibrations developed to fit the needs of specific high-volume customers. Calibration #4 appears odd as a non-linear equivalence relationship in Figure 4-35, but it is actually linear with lambda, again a customer-driven issue.

**Figure 4-34: AEM's UEGO Controller Analog Output Options**

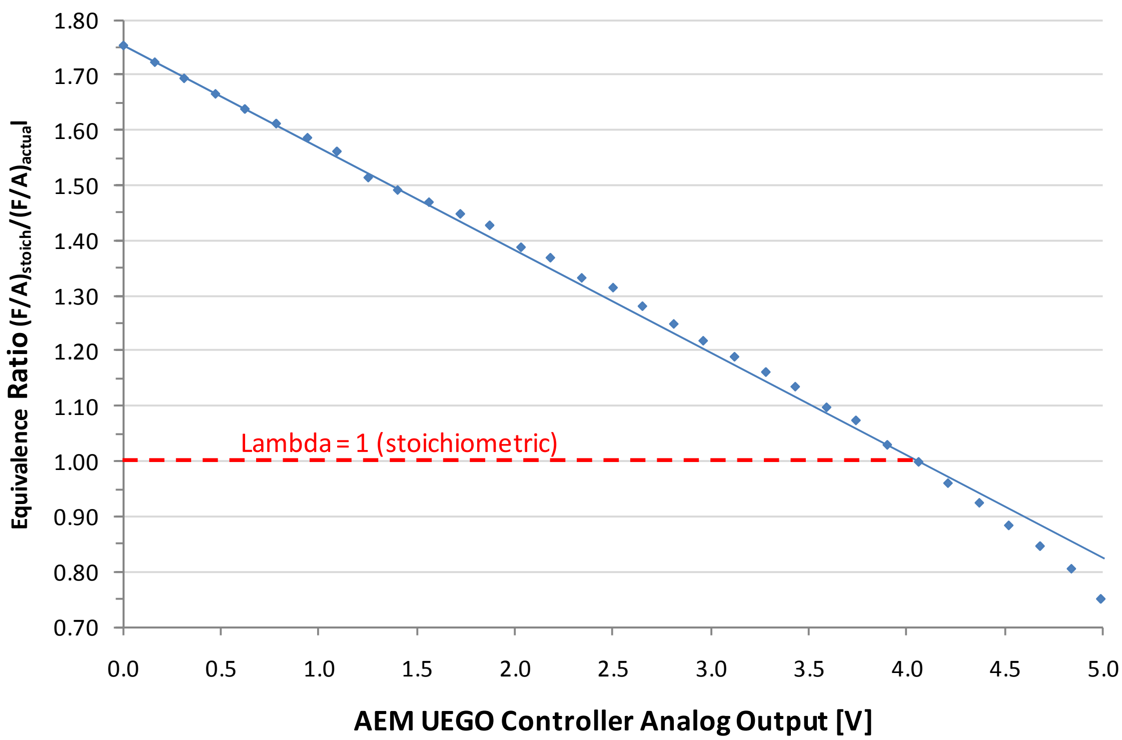
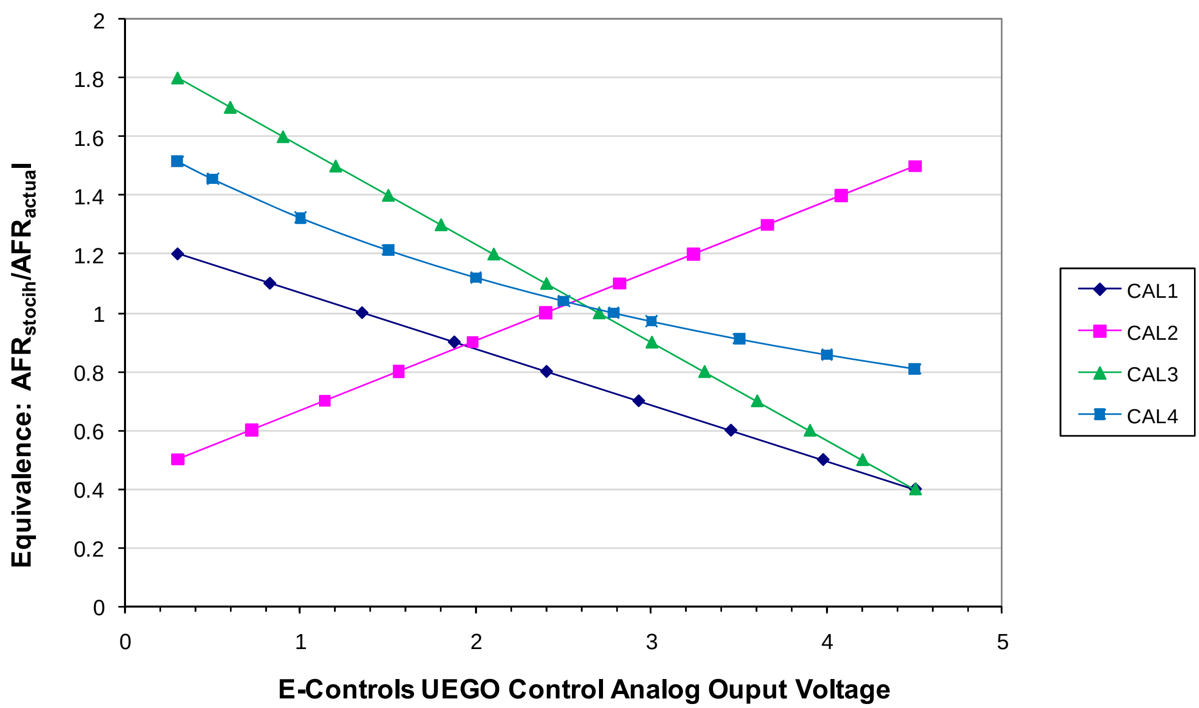


**Figure 4-35: E-Controls' UEGO Controller Analog Output Options**




(Note the non-linear Cal#4 is linear to AFR)

Unfortunately, none of the UEGO systems produced stable enough readings when integrated into the InVerde's control system to be used in the AFR control loop. When UEGO sensor inputs were the driver to the AFR control process, emissions rose considerably in comparison to control based on HEGO sensors. As a result, the UEGO testing program devolved into unsuccessful efforts to reduce UEGO signal variability and achieve UEGO-based AFR control on par with the baseline HEGO sensors. The issues encountered are described below. Unless otherwise noted, observations were made with the InVerde at 100 kW, with stable AFR control provided by Tecogen's standard fixed pre-catalyst HEGO target control, and post-catalyst feedback turned off.

### 4.5.2 Innovate UEGO Controllers Results

The Innovate UEGO controllers produced the most outward indications of InVerde EMI noise-induced complications and were quickly removed from candidacy. Innovate's LM-1 and LC-1 UEGO controller modules have identical UEGO control electronics per the manufacturer, but the LM-1 models also include a digital display such that the user can view the UEGO AFR reading directly without having to interpret the voltage from the analog output (Figure 4-36). Whether through observing the analog outputs or the AFR and lambda readings on the LM-1 LCD display, the values floated more than the width of the estimated size of the control window Tecogen needs to operate within, a problem with the other UEGO controller models as well.  However, a more severe problem was also observed.  The readings (analog and LCD) were frequently observed to fluctuate wildly to values that were far beyond the rich and lean limits of combustion for natural gas.  It was clear the values were nonsense, and evaluation of the heater control circuit with a scope-meter showed the sensors were not being over-cooled or over-heated beyond the capability of the heater circuit's pulse-width modulated control range, a speculated culprit by the manufacturer.

Ultimately, the test team found that it could produce nonsensical readings from the Innovate controllers at will by bringing the controller within about eight feet of the InVerde controls cabinet, even when a dedicated battery was used to provide isolated power to the Innovate devices, with no analog output wires connected to the InVerde electronics, and the sensor operating in free air.  This was a clear indication that EMI produced by InVerde electronics affected the Innovate model controllers in severe and unacceptable ways.

**Figure 4-36:  Innovate's LM1 (left) and LC1 (right) UEGO Controllers**



### 4.5.3 InVerde Noise Characterization

An experiment was designed to differentiate between the common noise produced by electric pumps, fans, and the ignition control system, and the noise produced by the generator's inverter-based power conditioning system.  In the experiment, a voltage was produced with a simple arrangement of alkaline batteries, and this voltage was input to the controls on the same channel where the pre-catalyst HEGO signal normally resides.  The voltage was about 0.78 V to mimic the typical voltage from a HEGO sensor operating at a low-emissions condition.  The RMCS was used to record the battery voltage input over time as the engine and generator system went through various phases of operation.

Figure 4-37 and Figure 4-38 show the raw and heavily filtered signals, respectively.  Figure 4-37 shows the raw battery voltage does not show signs of being influenced by the electrical noise produced by the engine's DC electrical system when turned on, or the AC power to AC powered pumps and fans.  However, the electrical noise is significant when the inverter is engaged to condition the power produced by the generator, starting with the 50 kW condition.  Figure 4-38 shows the same signal as processed through a mathematical filter that Tecogen normally applies to the HEGO sensor inputs because of the enhanced noise observed on those signals on the InVerde platform. The data suggests the filter works very well, but Figure 4-37 identifies the inverter as a very unusual noise source with greater influences than all the other electrical components on the CHP platform. It seemed likely the inverter noise was having an abnormal effect on the UEGO controllers, either through their processing of the UEGO sensor, or through the analog output translation of the AFR condition.

**Figure 4-37: InVerde Noise vs. Operating Condition - No Signal Conditioning**

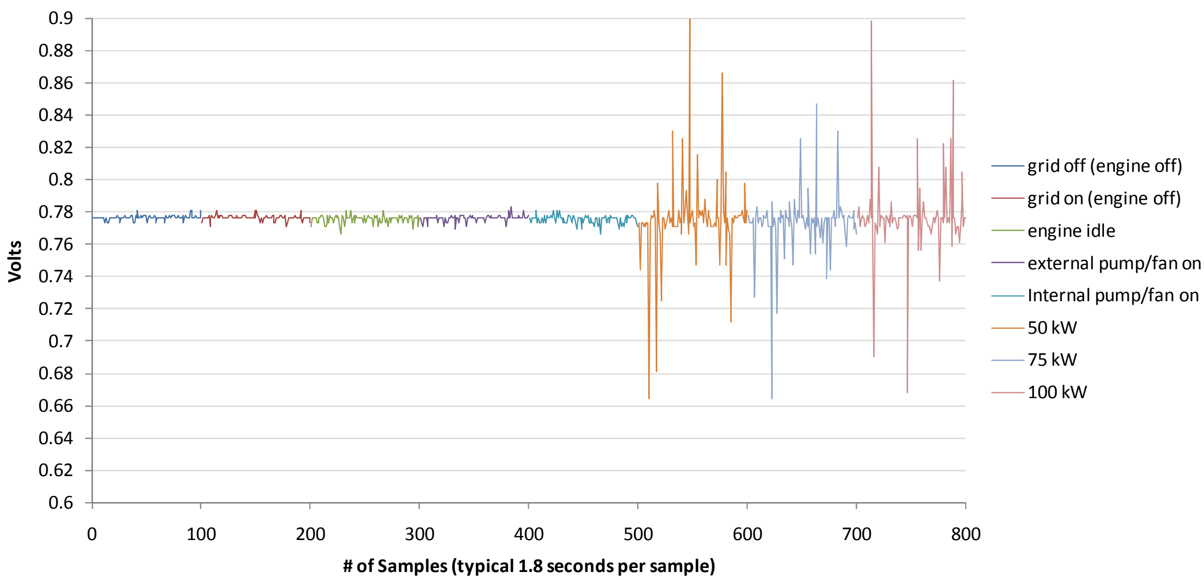


**Figure 4-38: InVerde Noise Attenuation With Heavy Signal Filtering**

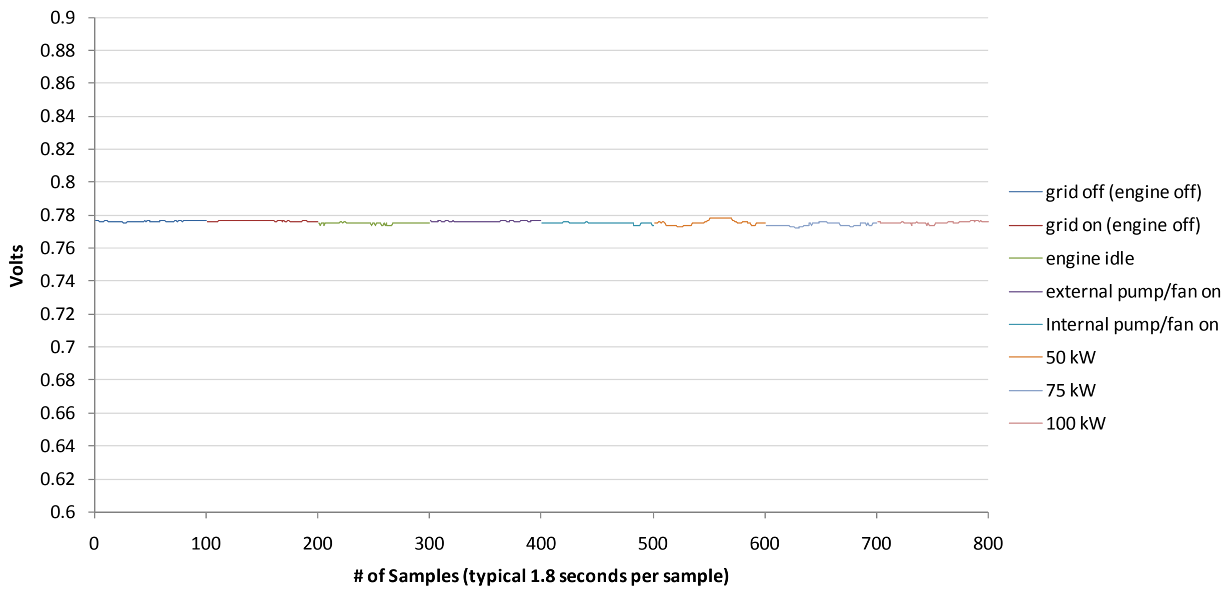
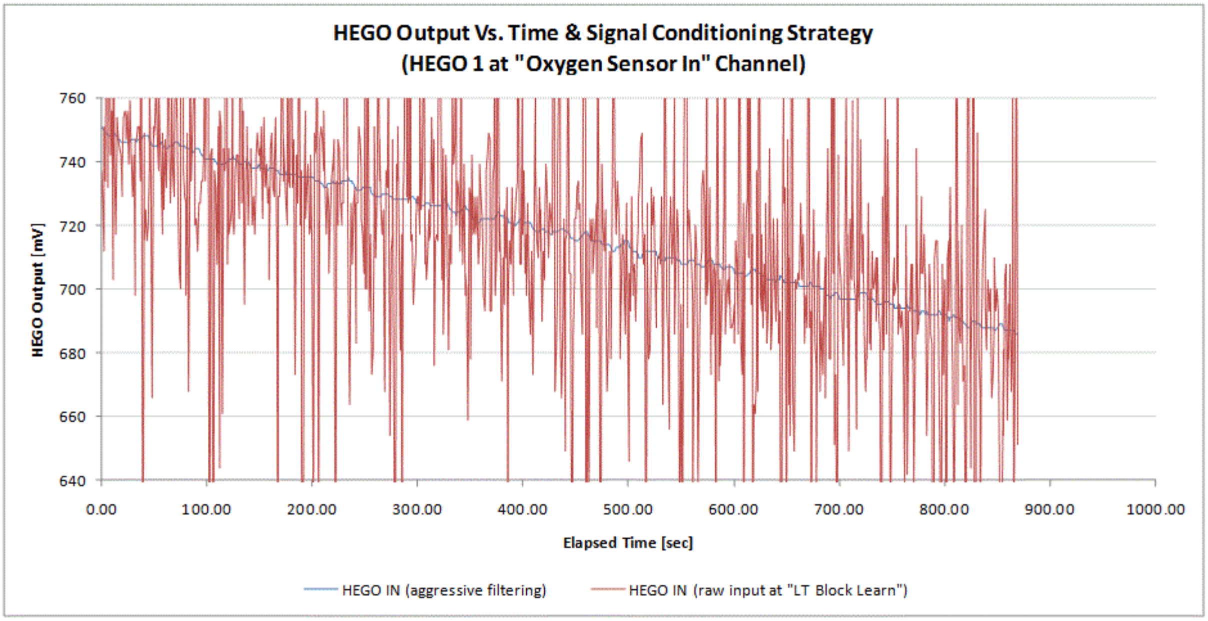



Figure 4-37 and Figure 4-38 showed the effect of inverter noise on a voltage signal produced by a battery. Figure 4-39 shows a recording of the pre-catalyst HEGO signal as recorded during an auto-sweep, with and without Tecogen's aggressive data filtering applied. Tecogen's AFR controls were programmed to continuously modify the pre-catalyst HEGO mV target from a starting richer mV target to an ending leaner mV target over a fifteen minute period. The noise is unmistakable in Figure 4-39, but so is a clean trend of the filtered HEGO mV signal as the auto-sweep progresses. The non-UEGO data seems to indicate that the inverter noise is significant, but manageable with regards to the HEGO signal.

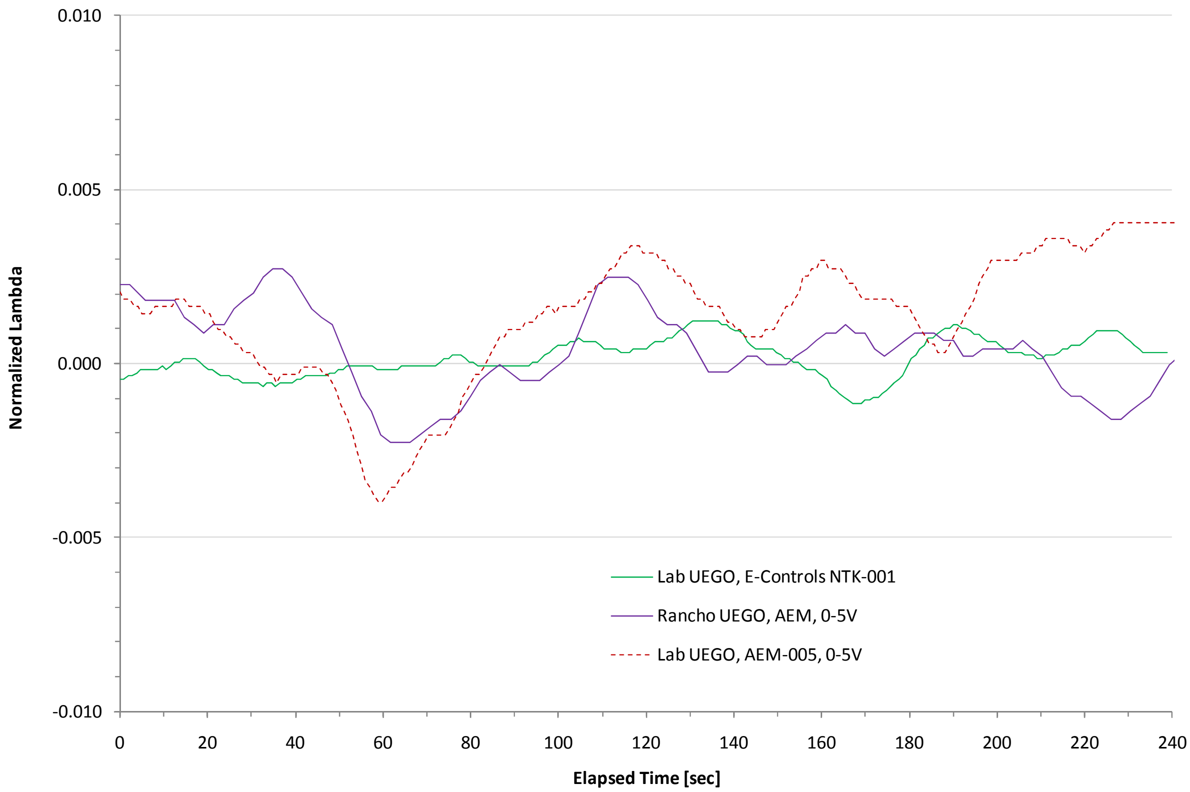
**Figure 4-39: HEGO Signal During Auto-Sweep - Raw and Heavily Filtered**




Ultimately, all UEGO controller analog outputs were processed through electronic chokes before connection to the InVerde control system. Chokes are small electrical devices designed to reduce some noise problems. The chokes were installed to supplement the mathematical functions of Tecogen's data filtering processes. Yet UEGO signal analyses continued to show too much signal deviation, and any attempts to use any of the UEGO outputs for AFR control resulted in unacceptable swings in $NO_x$ and CO emissions that were uncharacteristic compared to the stable emissions ranges that could be achieved with the HEGO input to the AFR control.

Figure 4-40 shows the final status of the UEGO signals before Tecogen discontinued the UEGO program. It shows the lambda translations of the voltage output from three UEGO systems, two running simultaneously on the test cell engine and one providing independent data from the Rancho San Antonio Boys Home field test site, which was equipped with AEM UEGOs in a data gathering mode. In both locations, the UEGO data was recorded while the engine was operating with very stable AFR control set by using standard pre-catalyst HEGO-based feedback control. Both engines were known to be operating with low emissions and with very little fuel valve position movement at the time of the UEGO signal recordings. The lambda data was normalized to show the variation (+/-) of the UEGO signals during this steady-state operation. Ideally, for the lambda scale shown, the UEGO signals should have appeared as perfectly straight horizontal lines because the lambda window for CARB 2007 DG limit compliance is expected to be less than 0.004 lambda wide, or less than +/- .002 lambda. However, the UEGO signals all deviated enough to suggest UEGO-based control would result in AFR control that would be unstable over the entire width of the compliance range and lead to lean NOx spikes one minute and rich CO spikes the next, which is exactly what was seen when UEGOs provided the AFR control input. One would like the AFR system, if using a UEGO input, to have such a stable and exacting control input as to be able to divide the emissions compliance range into several incremental UEGO output targets. This was not the case and it is unfortunate because the issue is believed to be related to the noise.

**Figure 4-40: Normalized UEGO-Based Lambda**




(Above) The engine was operating with AFR control using Tecogen's standard algorithms for pre-catalyst HEGO feedback control, with post-catalyst feedback turned off. The plot shows a distinct lack of signal stability from the UEGO outputs, believed to a function of electronic noise rather than actual lambda deviations.

## 4.6 Air Injection and Supplemental Oxidation Catalysis:

### 4.6.1 Experimental Setup

Tecogen reconfigured the exhaust system on the InVerde system in the test cell to facilitate evaluation of a dual-stage exhaust after treatment strategy using air injection and supplemental oxidation catalysis. The modified arrangement includes a second stage catalyst with an air injection port between the first stage TWC and the second stage oxidation catalyst. The air was fed by a VFD controlled oversized blower assembly that would allow precise tuning of the air injection rate.

The first stage catalyst contained 682 $in^3$ of DCL 400 cpsi TWC. The TWC substrates were previously identified as being capable of reaching CARB 2007 $NO_x$ and CO limits, albeit only in an abnormally tight AFR band of operation. The fact that the 682 $in^3$ TWC substrate volume could achieve the CARB 2007 $NO_x$ limit was the critical aspect of the 1st stage performance because the supplemental oxidation stage would be enlisted to perform secondary CO and VOC reductions. A 10.5" OD x 3.94" length DCL TWC substrate was installed in the downstream 2nd stage catalyst housing. This TWC substrate was originally used in the standard catalyst location to identify the optimum performance of the DCL product with the maximum (1023 $in^3$) that could fit within Tecogen's catalyst housing. Although a TWC was installed in the 2nd stage location, only oxidation reactions were expected in any significance because the air injection process would induce a relatively oxygen-rich atmosphere expected to decimate $NO_x$ reduction reactions.

### 4.6.2 Oxicat Profiling Experiment Methodology

Preliminary investigations into the supplemental oxidation catalyst strategy were designed to investigate the general impacts of oxygen content, and other exhaust conditioning parameters, on final tailpipe emissions.

1. The engine AFR was tuned and stabilized at a slight rich bias to favor CARB 2007 $NO_x$ compliance at the expense of modest CO non-compliance with CARB 2007 limits.
2. The portable emissions analyzer was set to continuously log the key parameters of interest such as $NO_x$, CO, $O_2$, and also the exhaust temperature using the thermocouple located at the tip of the emissions sample probe.
3. Testo data logging was initiated with the Testo probe located in the exhaust stream just before the oxidation catalyst. This location provided adequate mixing of the exhaust gas exiting the 1st stage TWC.
4. After baseline TWC emissions were sampled, the probe was quickly moved from the pre-oxidation catalyst location to the post-oxidation catalyst location. After the probe location was changed, the Testo recorded the exhaust constituents exiting the oxidation catalyst, still operating without the benefit of air injection, and thus operating as a

traditional TWC. It was important to record emissions out of the oxidation catalyst prior to the air injection process to quantify the air injection effect.

5. Next the VFD controlled air blower was started to induce air/oxygen flow into the exhaust stream. The air injection was very quickly adjusted to a predetermined starting rate, typically 0.25 percent $O_2$.
6. After recording the effects of inducing a 0.25 percent $O_2$ exhaust atmosphere, the air injection was subsequently increased to 0.5 percent, 0.75 percent and then 1.0 percent $O_2$ to observe the impacts on the $NO_x$ and CO emissions.[8]
7. This oxidation catalyst technology involved other innovative exhaust conditioning configurations that differed from the conventional systems in the industry. However, due to the proprietary nature of this system, these details are not revealed in this document. A patent application was filed by Tecogen and the information is expected to be public in late 2011.

Figure 4-41 illustrates a profiling experiment with the 2nd stage supplemental oxidation catalyst concept. First, data was captured with the baseline system, which is with the air injection off. In this scenario, all catalysts were acting as TWC in typical rich-burn exhaust with CARB 2007 compliant $NO_x$ and very low, but not compliant CO. At time = 530 seconds, the air injection was enabled and the average $NO_x$ increased above CARB 2007 levels, and perhaps even above non-DG BACT standards (9-11 ppm NOx, corrected). This sharper $NO_x$ formation response was assumed to be the enhanced reformation of $NH_3$ (Ammonia) to $NO_x$. Conversely, the CO was driven to 0 ppm with the introduction of air injection.

At approximately 1660 seconds, a system modification was made to produce evidence that would help support the theory that $NH_3$ was the unmeasured culprit that was leading to $NO_x$ formation in the 2nd stage. The AFR control's pre-catalyst HEGO mV target was adjusted from 680 mV to 700 mV to produce an AFR shift in the rich direction. Standard TWC performance trends suggest that such a shift would be expected to produce higher $NH_3$ and CO levels out of the first stage. Normally, the impact on $NO_x$ in the rich direction away from the point of lowest combined $NO_x$ and CO depends on the magnitude of the rich shift. The $NO_x$ could be expected to decrease, remain the same, or increase slightly if the point of peak $NO_x$ conversion efficiency had been crossed. The result of the rich adjustment at 1660 seconds and 1 percent 2nd stage O2 content was a significant increase in $NO_x$ emissions above typical ICE BACT permitting limits in California. CO remained at 0 ppm. At time = 1950 seconds, the air was turned off to better quantify the magnitude of the rich shift in AFR that had been made. With the air off, the Testo was then sampling standard rich-burn exhaust processed from a 1st stage TWC. With the air

[8] U.S. Patent Application No. 12/816,706, "Assembly and Method For Reducing Nitrogen Oxides, Carbon Monoxide And Hydrocarbons In Exhausts Of Internal Combustion Engines", Joseph B. Gehret, Robert A. Panora, and Ranson Roser

injection stopped, the CO increased dramatically above non-DG ICE BACT standards. The $NO_x$ also decreased significantly in comparison to that which was produced with air injection on, but the $NO_x$ was higher than the experiment starting conditions, and possibly no longer CARB 2007 compliant. The observations made in this test series suggest unmeasured $NH_3$ was converted to produce new $NO_x$ emissions in the 2nd stage catalyst with the aid of the oxidizing atmosphere induced by air injection.

**Figure 4-41: Baseline Oxidation Catalyst Profiling**

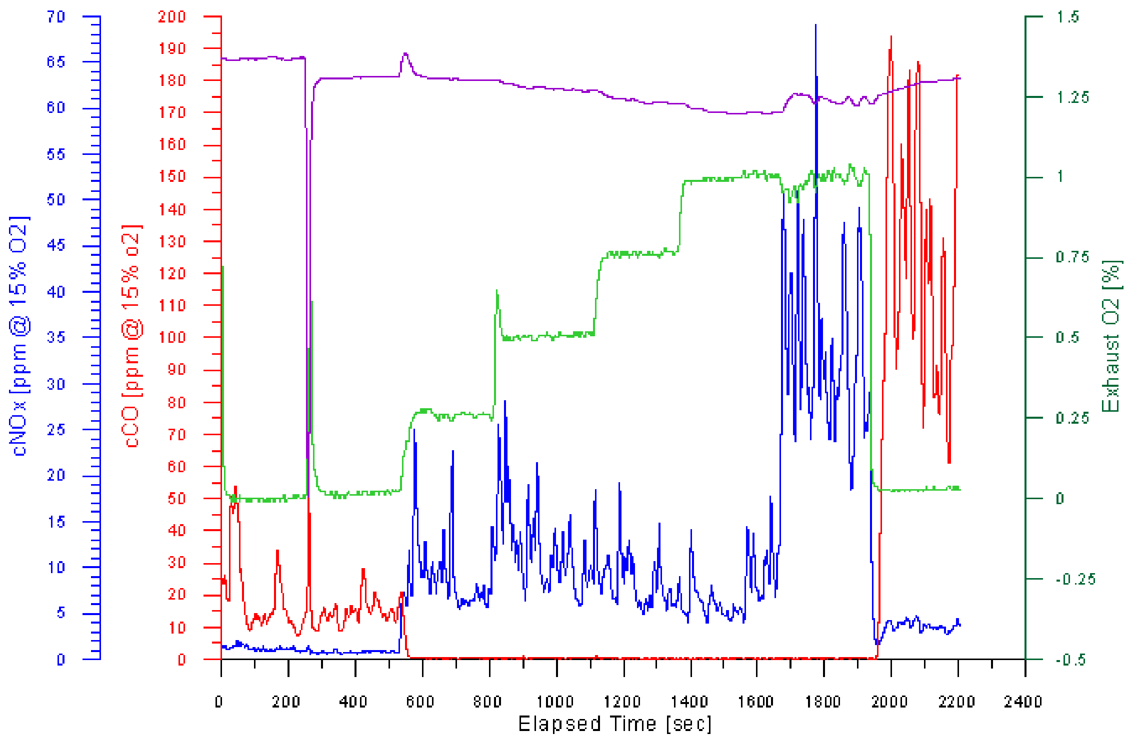
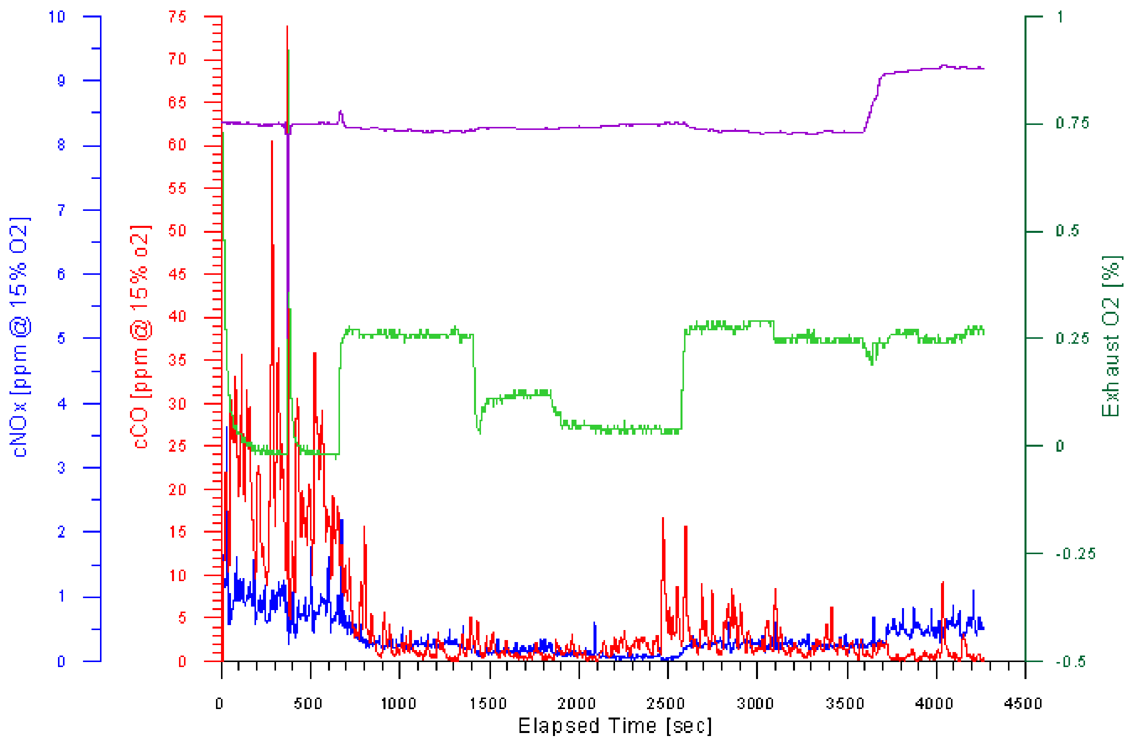



Figure 4-42 shows the results of operating this 2nd stage with the new technology employed. The test series started with the AFR producing CARB 2007 compliant $NO_x$ and low, but non-CARB 2007 compliant, CO out of the 682 $in^3$ DCL TWC 1st stage. Air injection producing 0.25 percent 2nd stage $O_2$ content was turned on at 700 seconds into the experiment. Similar to the results of Figure 4-41, the onset of air injection resulted in a significant reduction in CO to CARB 2007 compliant levels, but also a welcome drop in corrected $NO_x$ from about 0.8 ppm to 0.3 ppm. The air injection rate was reduced at time 1400 seconds to lower the 2nd stage $O_2$ content to 0.1 percent and that did not result in a loss of performance from the supplemental oxidation catalyst. Initially, there was also no loss in performance as the air injection rate was dropped further to 0.05 percent $O_2$, but the CO did start to show signs of spiking before the 0.05 percent section was over. At 2600 seconds the 2nd stage $O_2$ content was increased back to 0.25 percent, which appeared to quiet the CO somewhat. At 3700 seconds, exhaust conditions were modified, resulting in further CO improvement and a slight increase in $NO_x$, suggestive that the $NH_3$ to $NO_x$ conversion reactions start to become active, albeit not unacceptable.

**Figure 4-42: Oxidation Catalyst Profiling – New Tecogen Technology**

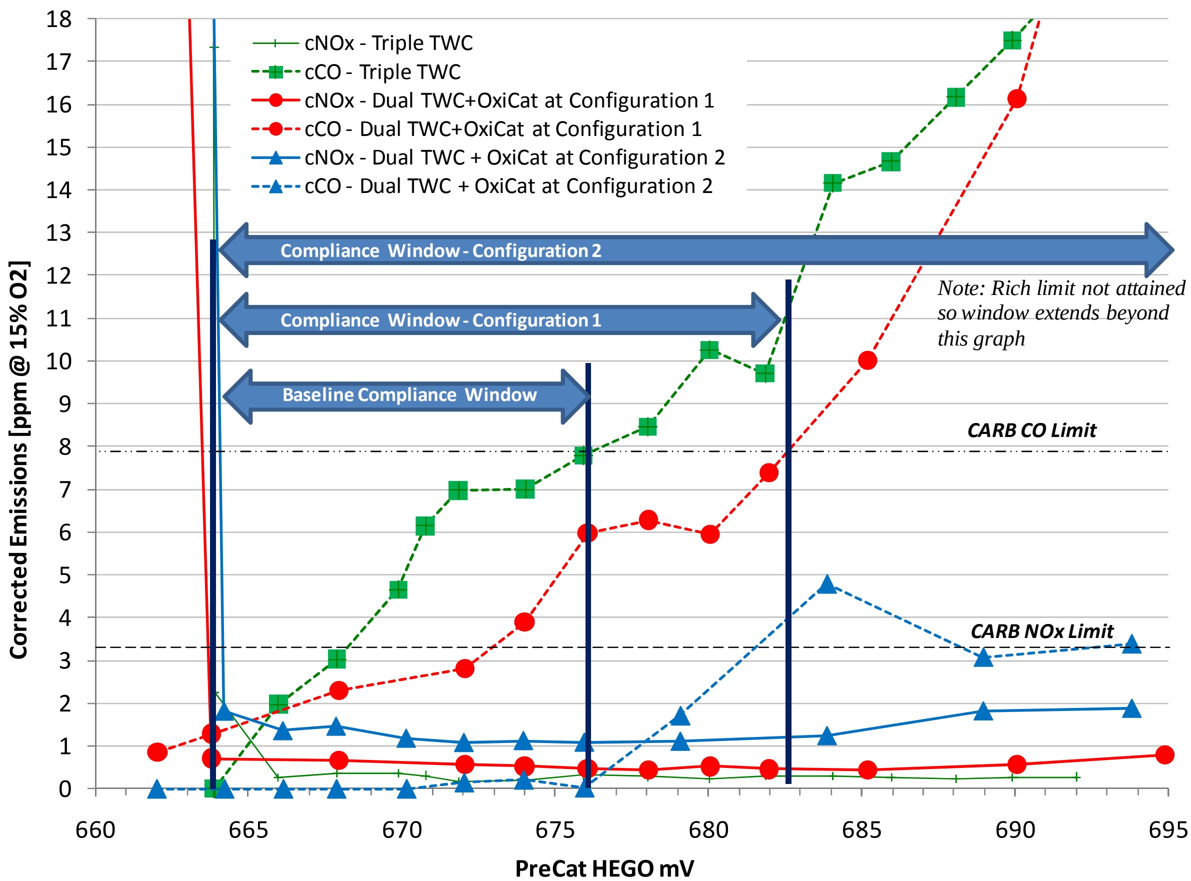



The results of the early supplemental air injection and oxidation catalyst profiling tests described in Figure 4-41, identified that the strategy would actually create unacceptable $NO_x$ emissions. However, the profiling identified very promising results with the new system features enabled. Therefore, the two-stage catalyst program transitioned to characterizing the emissions as a function of the AFR controller's pre-catalyst HEGO mV target, to quantify whether or not the strategy would enlarge the CARB 2007 AFR control range. Several HEGO mV sweep experiments was performed at full 100 kW generator output, air injection controlled to produce nominal 0.25 percent $O_2$ from the $2^{nd}$ stage catalyst, and the activation of the other exhaust conditioning strategies. The two-stage catalyst configuration was still comprised of all DCL 400 cpsi TWCs, with 682 $in^3$ in the first stage and 341 $in^3$ in the second stage. The sweep generally proceeded from the rich-to-lean direction, with each point representing the average of at least five minutes of stabilized data.

Figure 4-43 presents a comparison of the sweep results of the two alternative system configurations versus the baseline. For visual clarity, the HEGO mV data for each series was shifted by a fixed offset to align the location where significant lean-$NO_x$ increases occurred. Figure 4-43 clearly indicates the supplemental oxidation catalyst strategy widens the window of CARB 2007 compliance in comparison to the single-stage strategy by increasing the AFR range of compliant CO conversion in the rich direction. In the case of Configuration 1, the control range improved by more than 50 percent, whereas in the case of Configuration 2, the control

range increased by more than twofold. Since the Configuration 2 experiment did not establish the rich limit, the range is actually somewhat larger that the depiction in the graph.
The $NO_x$ emissions in both configurations are far enough below CARB 2007 to suggest there is at least some margin for catalyst degradation, although only long-term testing will define whether or not it is commercially adequate. The two-stage configurations produced higher $NO_x$ than the TWC-only setup.

**Figure 4-43: Emissions Sweeps With Supplemental Oxidation Strategy**

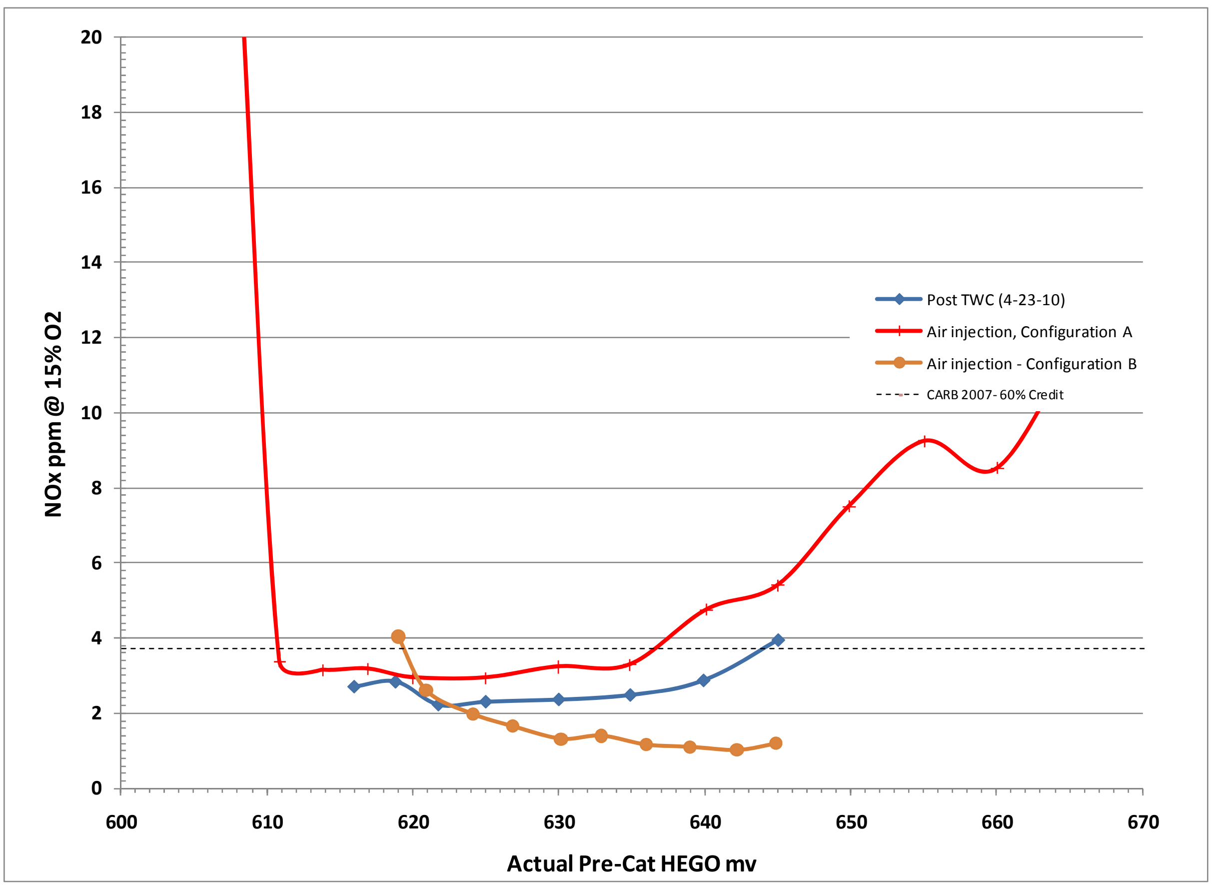



Tecogen later performed additional HEGO sweep evaluations of the two-stage after treatment concept while measuring $NH_3$ concentration. Ammonia measurement apparatus was installed in the test cell by CK Environmental, a local source test company. The $NH_3$ measurement process involved two NO measuring devices and two sample paths, with a $NH_3$ to NO converter in one of the paths. Ammonia was quantified based on the difference between the NO measured directly and the greater NO measured by the sample path that included the true exhaust NO plus the NO created by the conversion of $NH_3$. The converter's NO to $NH_3$ conversion efficiency was calibrated each day with known span gases, such that $NH_3$ concentrations could be correctly calculated from the delta-NO measurements. The other exhaust constituents continued to be measured by Tecogen's Testo 350XL.

Emissions of NOx and $NH_3$ are compared in Figure 4-44 and Figure 4-45, respectively. In these graphs, three conditions are plotted: 1) post TWC, 2) Configuration A, and 3) Configuration B. The two configuration parameters are not necessarily the same as Configuration 1 and 2 in previous experiments. They were selected to compare the relative effect of the technology against the base condition.

The NOx emissions (Figure 4-44) trends show that air injection can reform NOx (Configuration A) so that there is more NOx than the base condition of just a TWC. However, with the new technology properly tuned (Configuration B), the NOx can be reduced to levels below the base condition. This test series did not include measurements with 1023 $in^3$ of TWC volume. Therefore, it is possible that an equivalent TWC total catalyst volume, to that used in the total two-stage configuration would produce equivalent or lower $NO_x$.

**Figure 4-44: NOx Measurements at Various System Configurations**




With regard to the exhaust $NH_3$ concentrations (Figure 4-45), they were generally lowest under the leaner conditions in the sweep, and then increased as a function of HEGO target increments in the rich direction. The trends support the concept that the $NH_3$ concentrations, or formation rates, increase as a function of rich AFR increments, and are highest coming out of the 1st stage TWC, where the $NH_3$ is formed. As the $NH_3$ passes through the oxidation catalyst, the $NH_3$ levels are reduced.

**Figure 4-45: NH3 Measurements at Various System Configurations**

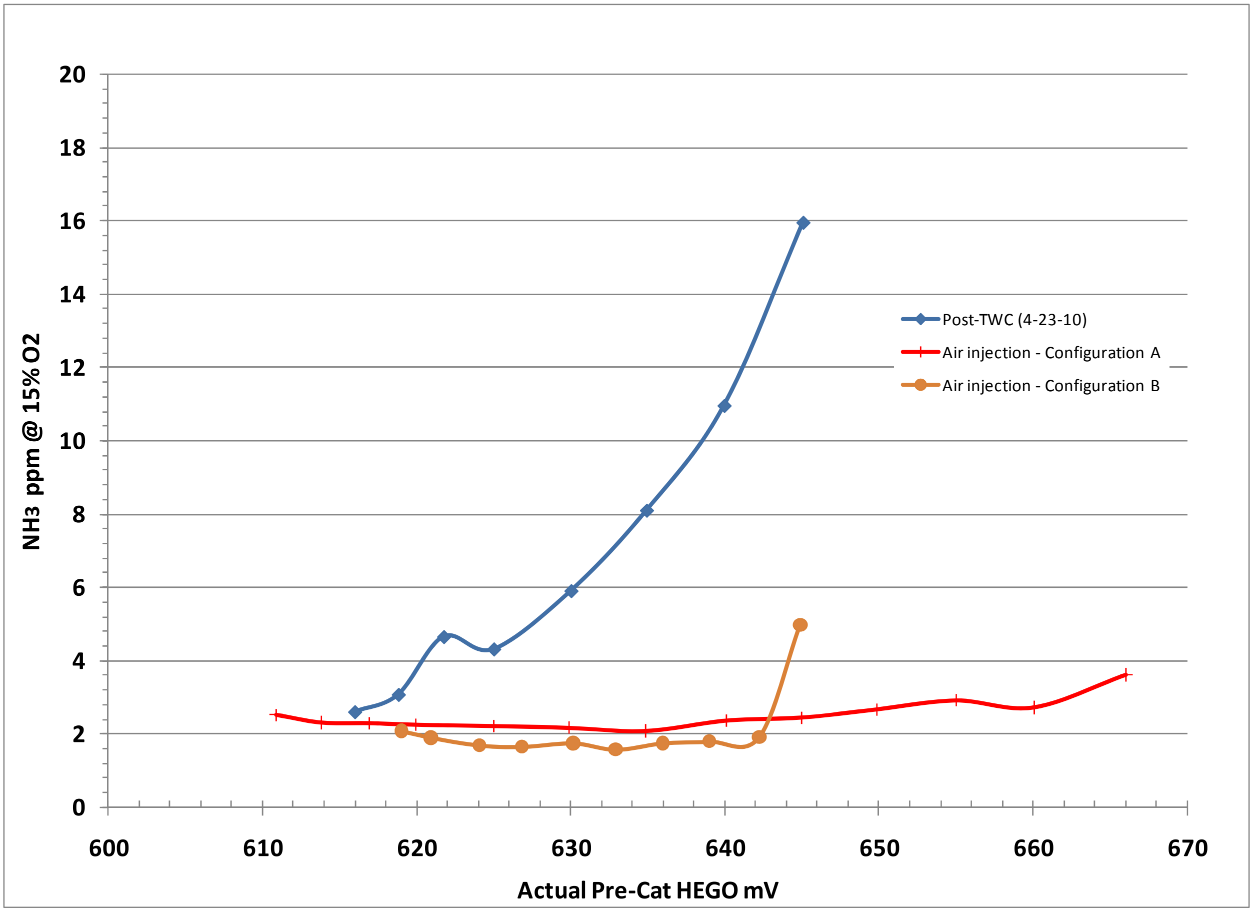
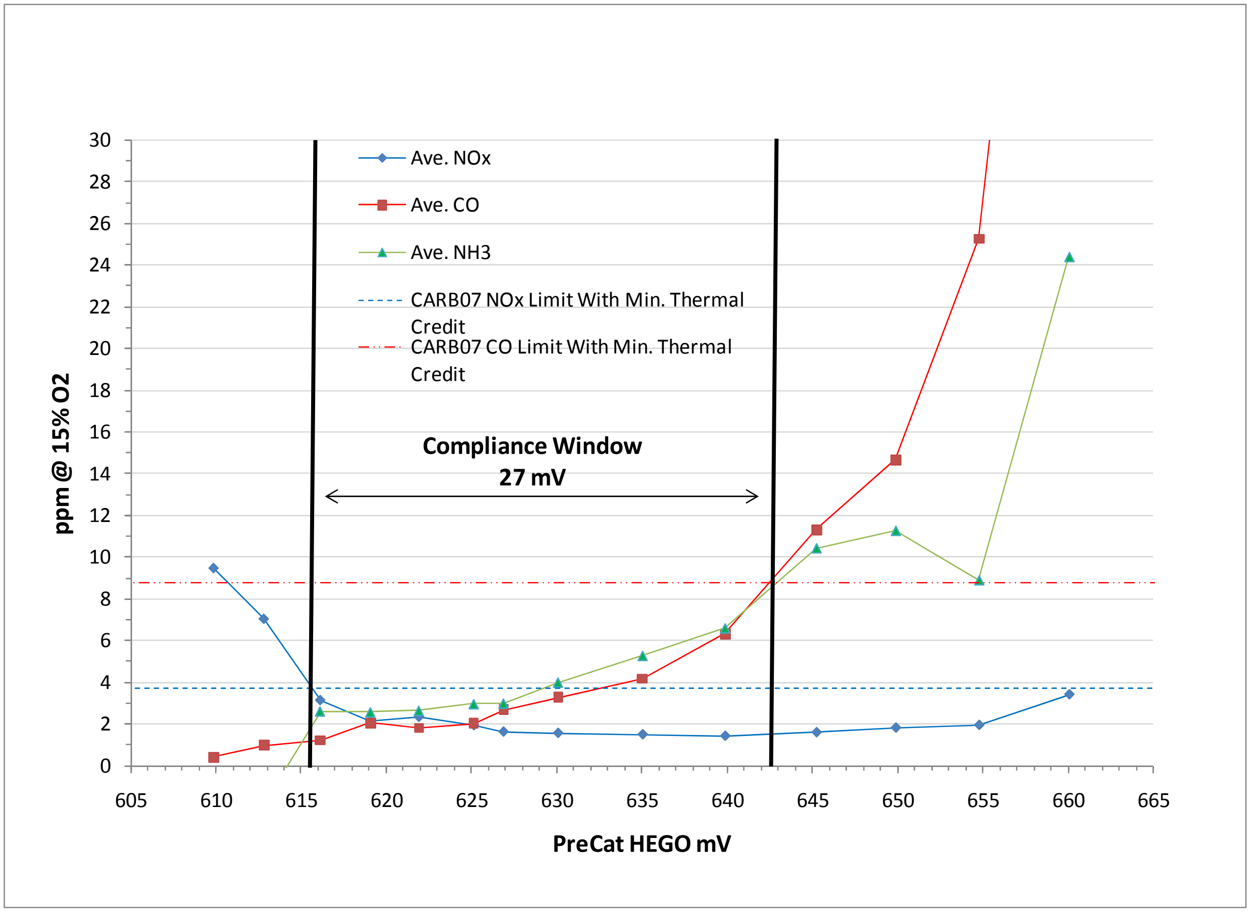



Figure 4-46 presents all three constituents plotted in an AFR sweep with the best tuned configuration of the new technology. As shown, $NH_3$ levels are not prohibitive within the compliance window of control.

**Figure 4-46: NOx, CO and NH3 Measurements at Optimized Configuration**

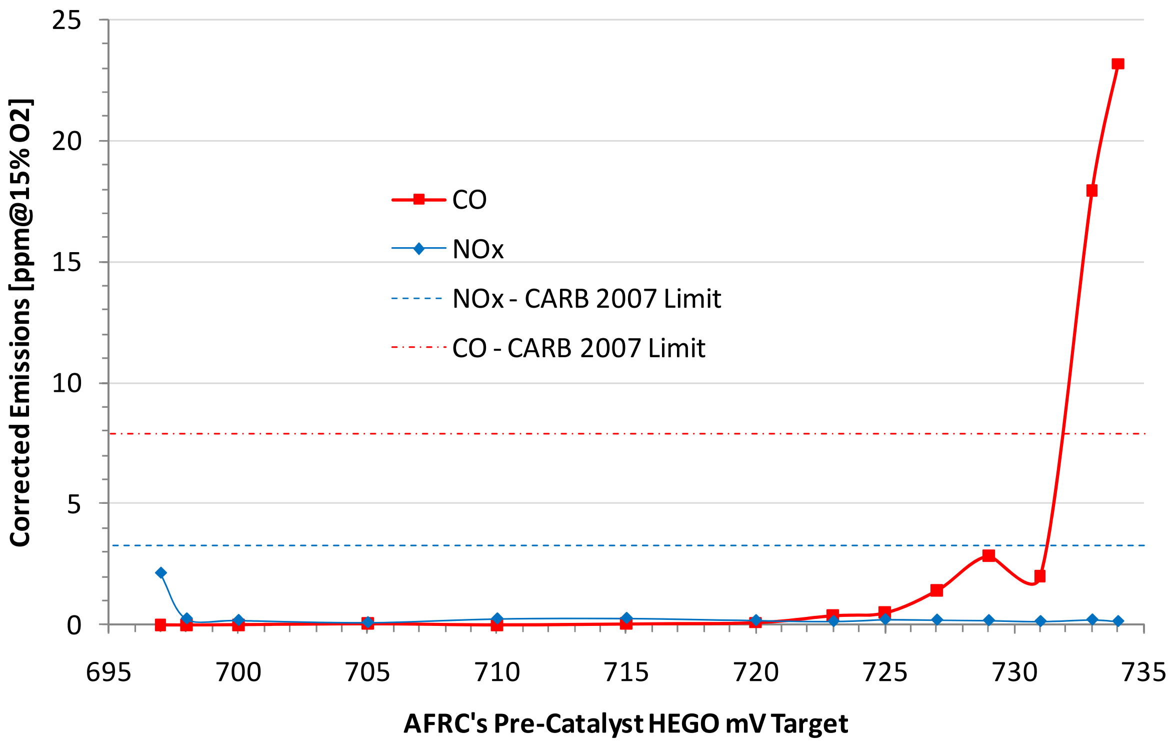



This supplemental air injection and oxidation catalyst strategy results were promising enough to qualify as the strategy of choice to be implemented at the San Fernando Regional Pools Facility field demonstration site in San Fernando, California. The San Fernando pool facility (SFP) operates one of Tecogen's 75 kW Model CM-75 CHP systems. Tecogen prepared a retrofit after treatment assembly for the SFP installation using its standard CM75 Süd-Chemie TWC substrates, with two 7.5" OD x 5.91" length substrates for the 1st stage, and one for the 2$^{nd}$ stage, all with 300 cpsi cell densities. Success with the Süd-Chemie product would mean that Tecogen could evaluate the two-stage after treatment concept in the field while avoiding the complication of supporting and stocking non-standard catalyst inventory or managing a new catalyst vendor relationship.

The two-stage retrofit components, intended to be shipped to the SFP installation, were installed on a newly assembled CM-75 system that was available during its brief post-production verification testing. The unit was operated at full rated output (75 kW) at 1800 rpm. A sweep of emissions, as a function of pre-catalyst HEGO mV AFR control targets, was performed to verify the retrofit could produce CARB 2007 limits using the Süd-Chemie product under CM75 conditions. The test was conducted with 0.25 percent nominal 2nd stage oxygen content from the air injection pump.

Figure 4-47 presents an AFR- emissions sweep for this two-stage retrofit system. The results were quite favorable, with a very wide 35 mV compliance window. It is acknowledged that the results of the experiment may have benefitted from the use of new catalysts that had not been de-greened, and that the total catalyst volume had increased from 10.2 $in^3$/kW to 10.4 $in^3$/kW. Nonetheless, the results fundamentally agreed with the strategy's goals, and proved that the Süd-Chemie product was valid for the field test which would provide more important data over time.

**Figure 4-47: Pre-Shipment Test of Two-Stage Strategy**




### 4.6.3 Discussion – Two-Stage Catalyst Strategy

The laboratory test results Tecogen achieved with a two-stage after treatment strategy were more successful than those produced with just enhanced volumes of TWC operating in typical rich-burn exhaust.

CO reduction in oxidation catalysts performs best if there is 3-5 times more oxygen present than CO (Aleixo). For example, an engine with TWC CO emissions of 500 ppm (raw), would require 5 x 500 ppm $O_2$ (2500 ppm or 0.25 percent) to achieve the maximum conversion possible for the given oxidation catalyst. During 2nd stage profiling, Tecogen found the supplemental oxidation catalyst could produce the final required reductions with much less oxygen, down to 0.05

percent, but that the results were less robust. Operating with modestly higher air injection rates than initially appear necessary can represent an operating hedge against incomplete air-to-exhaust mixing before the second stage. Therefore, Tecogen sized an electric air pump for the field retrofit that will produce a minimum of 0.25 percent $O_2$ in the 2nd stage catalyst at full load.

All two-stage after treatment testing was performed with a TWC in the 2nd stage location to maintain flexibility between single-stage and two-stage experiments, and to minimize special catalyst procurements. Functionally, a TWC operated in the oxidizing atmosphere of the 2nd stage location will operate as an oxidation catalyst, not a TWC. In this manner Tecogen had the flexibility to move TWC between the 1st and 2nd stages as necessary. Likewise in the field, the two-stage concept could be employed with all TWC, or a combination of TWC and downstream oxidation-only catalysts. Using an oxidation-only catalyst, one with Platinum (Pt), Palladium (Pd), or both, would reduce the cost of the second stage in comparison to a TWC with Rhodium (Rh) in addition to the Pt and Pd. However, using a TWC in the 2nd stage offers the advantage of less variation of catalysts to stock at the factory. It also provides the flexibility to rotate a TWC operated in the low temperature 2nd stage, a position that should experience decreased oil-based poisoning and thermal degradation, to the forward location of the 1st stage assembly.

## 4.7 AFR Dithering

### 4.7.1 Experimental Setup

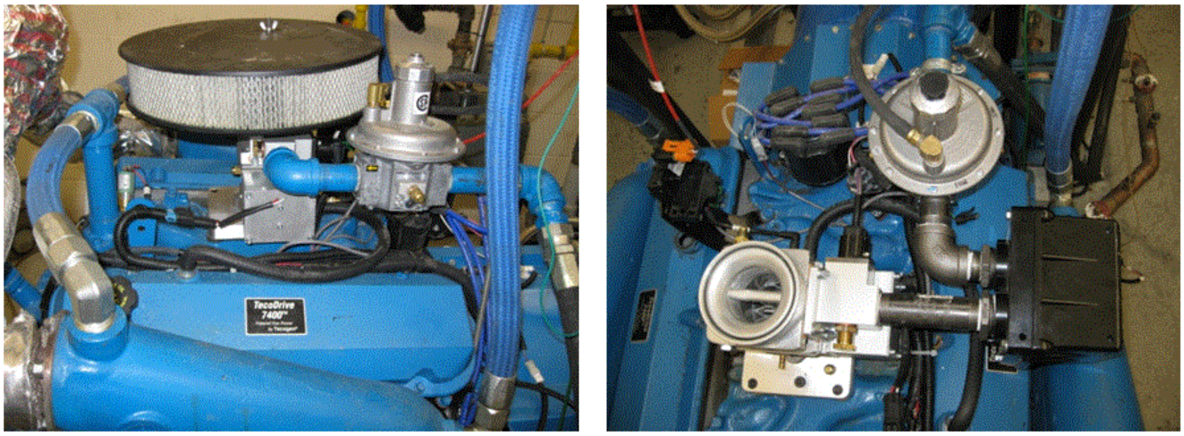
Tecogen's internal AFR controller does not have built in dithering AFR control code, so Tecogen adapted a third-party AFRC with dithering capability to the InVerde platform in the test cell. The test engine was equipped with a 682 $in^3$ volume of DCL TWC in the combined catalyst/EHRU housing. The AFR controller was a Compliance Controls Model MEC-R, capable of being configured to operate in steady-state or dithering fuel control modes, either using just the pre-catalyst HEGO for closed-loop control, or both pre-catalyst and post-catalyst HEGO sensors. Although the controller was available to Tecogen and had been used by a member of the test team on other commercial applications, it was not supported by the manufacturer or distributor with regards to this Tecogen test program. That is, neither entity had a commercial obligation to provide technical support if difficulties were experienced, especially with the dithering functionality, since this option is rarely applied by Compliance Controls' customers in the stationary power market. The dithering strategy requires the use of a post-catalyst oxygen sensor to continuously adapt the pre-catalyst dithering waveform if very low emissions, such as ICE non-DG BACT or CARB 2007 DG limits, are to be maintained. This would prove to be a troublesome issue during Tecogen's efforts to compare dithering and non-dithering strategies because the MEC-R controller's post-catalyst HEGO feedback function often deactivated for reasons that could not be understood.

On the InVerde engine in the test cell, the valve portion of the stock stepper motor fuel control valve was removed such that the full bore of aluminum valve mounting block was open to gas flow. An E-Controls Megajector electronic fuel control valve was then inserted in the gas path between the zero pressure regulator and the Woodward venturi-mixer (Figure 4-48). The Megajector is best described as an electronic pressure control valve used for light-duty mobile natural gas engine applications, such as on pickup trucks or forklifts. Internally, the pressure control valve uses an electronically controlled butterfly valve, but also includes an internal pressure transducer such that pressure can be controlled on a closed-loop basis. The MEC-R controller also required engine speed and manifold absolute pressure inputs to function. The MEC-R uses engine displacement, # cylinders, manifold absolute pressure, and engine speed to estimate the load of the engine in terms of the mass of air per liter of displacement. A table is then built by the user, guided by testing, to correlate the engine load to a fuel delivery pressure target from the Megajector to the fuel mixer. In this way, the combined AFR control system can be programmed to deliver approximately desired AFR mixtures as a function of engine speed and load. With closed-loop HEGO feedback algorithms engaged, the fuel delivery pressure can be modified further in response to deviations between equivalence targets and equivalence values reported by the HEGO sensors.

Under steady-state engine conditions and in steady-state fuel control mode, the fuel delivery pressure is very stable. In a dithering fuel control mode, the controller is programmed to create rich-lean fuel perturbations by wave shaping the pressure command signal. Configurable parameter inputs allow the user to specify the perturbation frequency, magnitude, and ramp rates of the rising and falling edges of the pressure waveform. Figure 4-49 gives an example of a dithering fuel pressure waveform with the parametric elements noted above. It shows the dithering fuel pressure target, the actual pressure response, and the pre-catalyst and post-catalyst HEGO responses to the fuel perturbations. Note that the pre-catalyst HEGO sensor shows the cyclic trans-stoichiometric crossing of the HEGO voltage from rich (~ 0.8 V) to lean (~0.2 V) indicative of dithering AFR control. The wave-shaping inputs are not defined in direct AFR-related units, meaning that the user does not have the luxury of specifying an AFR, equivalence ratio, or lambda shape. Rather the wave-shaping influences these parameters, but then results in a net effect characterized by a resultant equivalence (phi) waveform with instantaneous and average values derived from pre-catalyst and post-catalyst HEGO sensors. The controller then adjusts the entire waveform richer (an offset increase in fuel pressure), or leaner (an offset decrease in fuel pressure) to achieve the average pre-catalyst and/or post-catalyst equivalence targets that have been programmed as a function of engine speed and load.

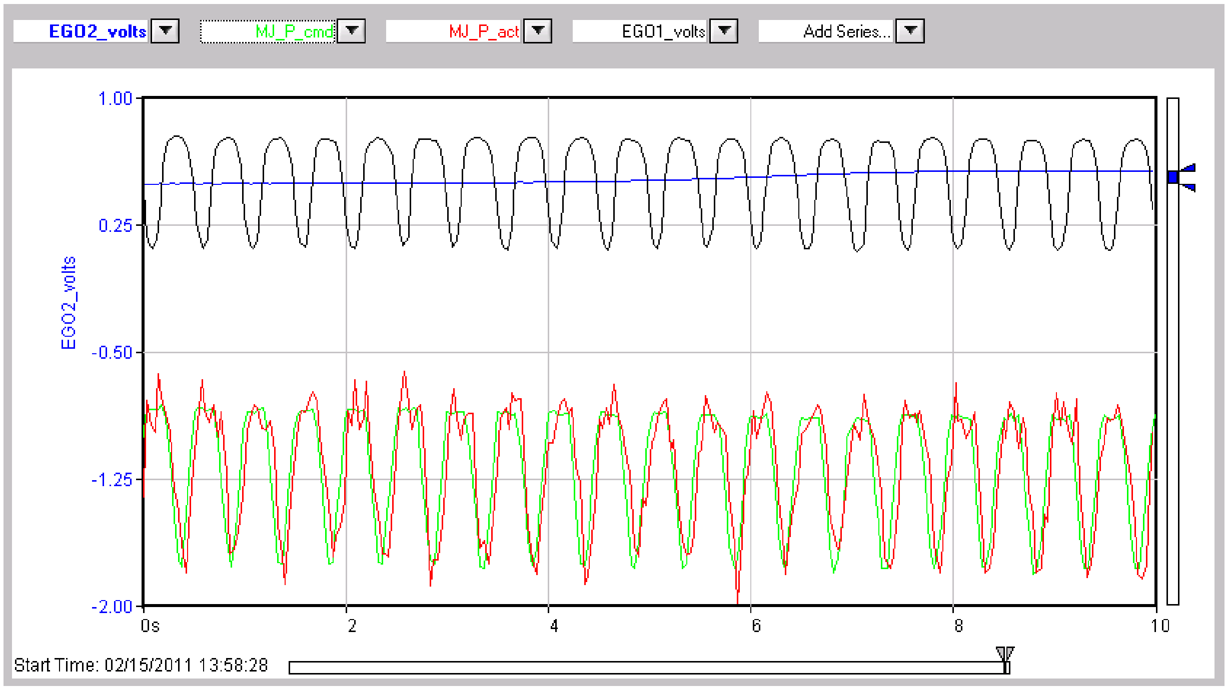
The dithering fuel control was engaged with closed-loop control to post-catalyst equivalence targets entered by the user. Post-catalyst targets were swept from rich to lean values to define the optimum performance of the catalyst (2 DCL), similar to pre-catalyst HEGO characterizations made earlier in this report. Each data point represents the average of at least five minutes of stabilized engine operation at a target condition. Figure 4-50 shows the results of the dithering AFR sweep with the x-axis represented by the average post-catalyst HEGO mV as measured by a Tecogen's Delphi –model HEGO sensor, which was independent of the MEC-R AFR control system. The $NO_x$ emissions were never observed to be compliant with the CARB 2007 limits, although both $NO_x$ and CO could achieve ICE non-DG BACT limits. Although the dithering tests were not exhaustive, Figure 4-50 was consistent with some researchers' claims that the AFR control window for acceptable TWC performance could be widened at the expense of peak conversion performance. It was reasonable for Tecogen to conclude that such was the cast being demonstrated within Figure 4-51, that $NO_x$ conversion performance, in particular, had suffered just enough to defeat compliance with the CARB 2007 limits.

**Figure 4-48: Stock vs. Dithering Capable Fuel System**



(Left) Tecogen's standard fuel train and layout. (Right) Top view of the electronic pressure control system inserted between the zero pressure regulator and he fuel venturi/mixer with the air filter removed. The AFR control system using the electronic pressure control device as steady-state and dithering fuel control options.

**Figure 4-49: Dithering Waveforms and Waveform Shaping**




(Above) Black and blue traces are pre-catalyst and post-catalyst HEGO voltages, respectively, and use the y-axis voltage scale displayed. The green and red traces are the "commanded" fuel pressure and "actual" fuel pressure from the electronic pressure control valve during dithering operation. The y-axis scale and units are not shown for the pressures. (Below) Same trace, but with expanded view.

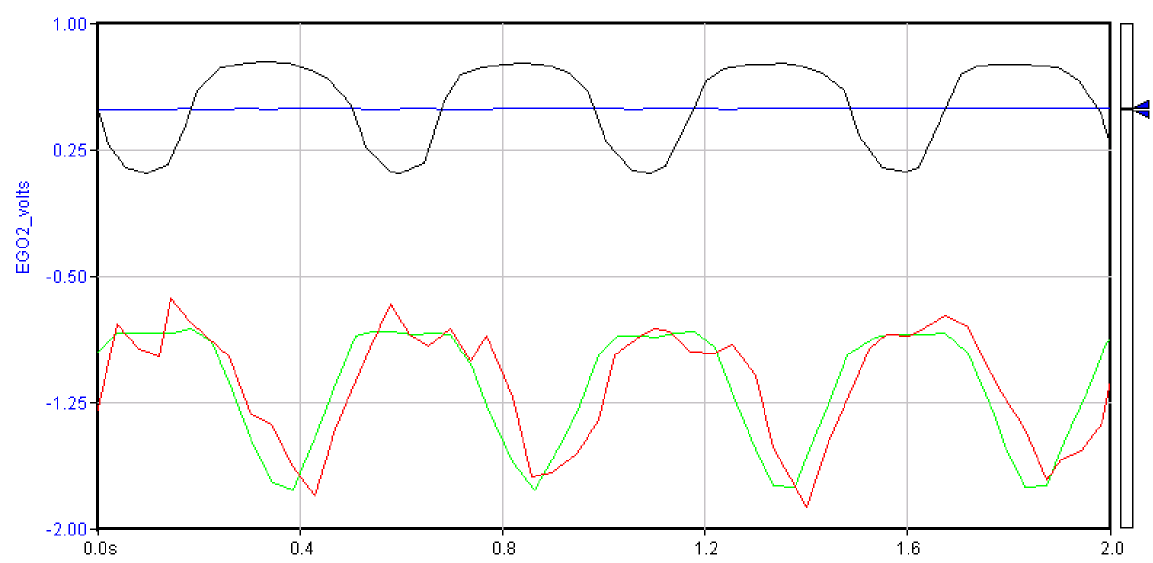
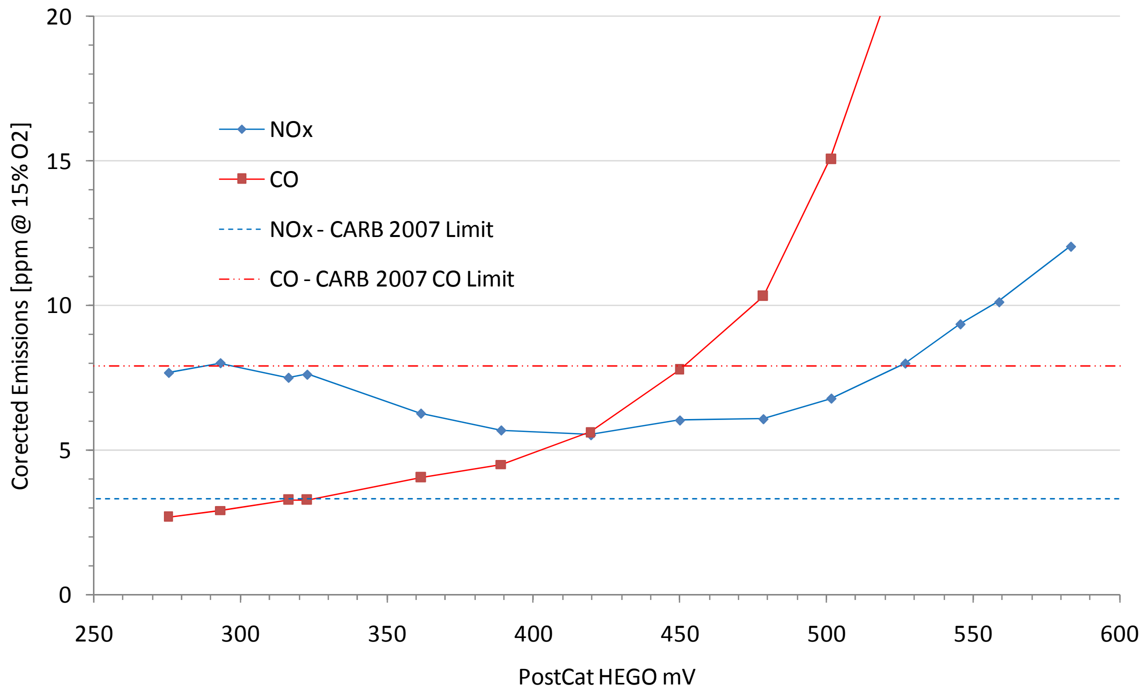


**Figure 4-50: Dithering Emissions Sweep Results**




## 4.7.2 Dithering Discussion

The results from the dithering emissions sweep were not compliant with the program goals, so Tecogen continued to focus increasing attention on the promising two-stage exhaust after treatment strategy as well as other program initiatives. However, it would not be appropriate to declare AFR dithering was proven to offer no value to Tecogen's future interests in an exhaustive manner. It is possible that the results were influenced by degradation of the DCL TWC in the test cell. Figure 4-51 shows the dithering AFR sweep in comparison to two other test series in which 682 $in^3$ volumes of DCL TWC were tested using steady-state AFR control to pre-catalyst HEGO mV targets. Both steady-state series show $NO_x$/CO operating points that are mutually compliant with the CARB 2007 limits, whereas the dithering series does not. However, the steady-state series collected April 30, 2010 shows higher $NO_x$ than the steady-state series on March 8, 2010. If this reduction in maximum $NO_x$ conversion is a sign of catalyst degradation, then perhaps the peak $NO_x$ conversion performance capability of the catalysts were further degraded by the May 13, 2010 dithering testing. Later in the program, the DCL TWC substrates were removed due to a tangible reduction in peak performance.

The dithering control parameters have further room for optimization as applied to the 7.4L GM engine which could improve emissions performance. The exhaust chemistry variations that occur with AFR dithering should be achieved without impacts on engine operation that are perceivable by basic human observation. The user should not hear audible sound pitch variation with load or speed variations as a result of AFR dithering. This was not always the case with the dithering testing on the InVerde engine. The dithering waveform could be manipulated to eliminate non-electronic evidence that dithering was occurring, but sometimes this also resulted in an undesirable effect in which the MEC-R disabled the post-catalyst feedback control. Therefore, the sweep shown in Figure 4-52 represents a dithering waveform that was probably more aggressive in differential lambda amplitude than is appropriate for best emissions.

**Figure 4-51: Lower Dithering Performance or Degraded Catalysts?**

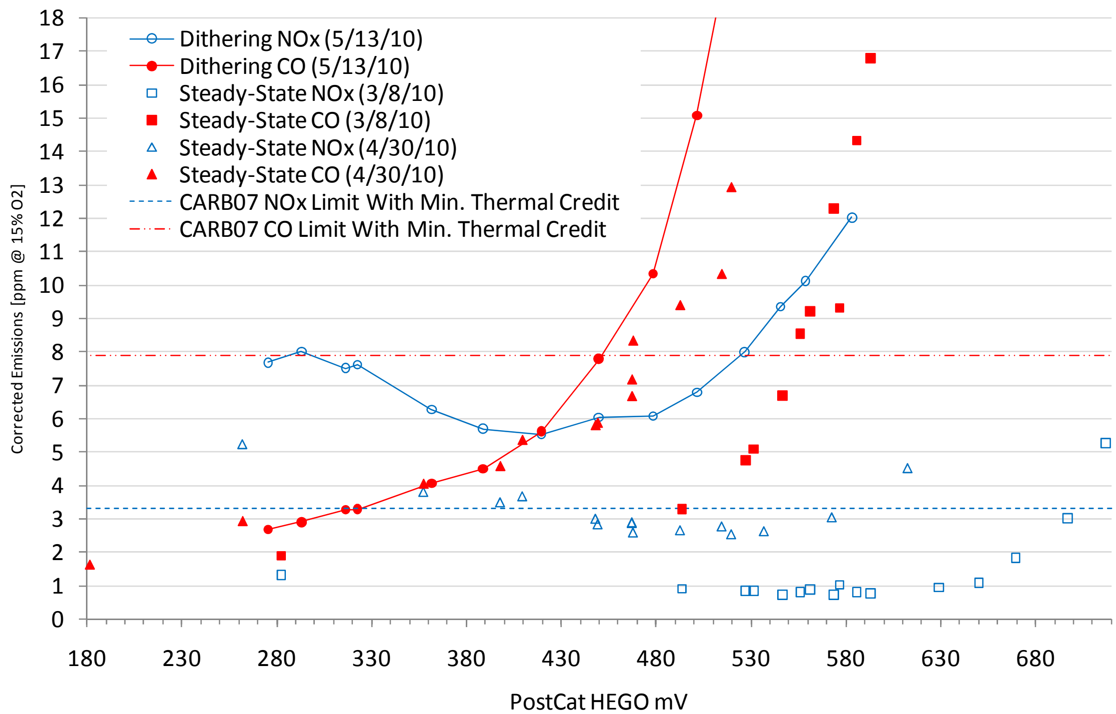
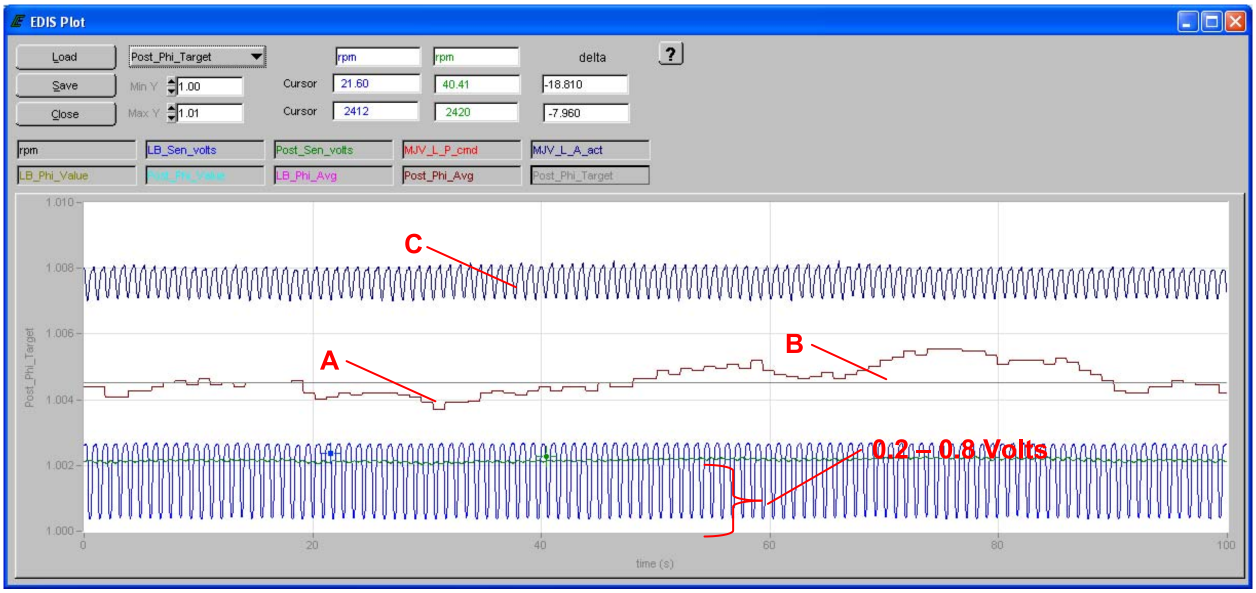



Figure 4-52 gives an example of the post-catalyst feedback control process during the dithering AFR control. It shows the valve position oscillations, the pre-catalyst and post-catalyst HEGO voltages, the post-catalyst equivalence target, and the actual post-catalyst equivalence value as the dithering waveform is imperceptibly driven richer and leaner to achieve the control targets. The post-catalyst feedback is important for achieving best performance out of the TWC, especially in the context of aggressive emissions standards. It should be evident from the discussions above that the AFR control window for optimum TWC emissions reductions is very small and gets smaller with tighter limits. Cycling the AFR rich and lean of stoichiometric does not ensure that the average chemical condition in the catalyst will produce the desired $NO_x$ or CO emissions. The net effect of the dithering could be a catalyst condition that is either marginally rich or lean and result in unacceptable CO or $NO_x$ emissions, respectively. Although the AFR controller can average the pre-catalyst HEGO voltage, the resultant pre-catalyst average will not be as indicative of the net chemical composition of the catalyst as the post-catalyst HEGO voltage. In addition, the post-catalyst HEGO location is less subject to signal biasing errors as mentioned earlier in this report (errors from high pre-catalyst CO and $H_2$ levels). It is for these reasons that the post-catalyst HEGO sensor feedback can play an important role in enhancing the emissions performance of a dithering AFR control strategy.

**Figure 4-52: Dithering AFR Control and Post-Catalyst Feedback**




(Figure Explanation) Y-axis scale represents equivalence ratio (phi) based on the air/fuel ratio controller's interpretation of the post-catalyst HEGO voltage. The Y-axis corresponds to only the post-catalyst phi target (A), the straight horizontal line in the center, and the actual post-catalyst phi (B) measured by the post-catalyst HEGO sensor, the burgundy line that fluctuates above and below the target. The top waveform (C) is indicative of the fuel valves flow area, which fluctuated rapidly to produce rich and lean perturbations in the air/fuel ratio. The pre-catalyst and post-catalyst HEGO voltages are shown at the bottom of the plot on a scale that is not shown, but the blue pre-catalyst HEGO trace fluctuated between about 0.2 and 0.8 volts, while the post-catalyst HEGO stayed nearly constant.

## 4.8 High Energy Ignition and EGR

### 4.8.1 Experimental Setup

Exhaust and intake modifications were made to the InVerde system in the test cell to allow the flow of cooled exhaust gas into the intake as shown in Figure 4-53. In comparison to the standard layout (Figure 4-54), an EGR venturi-mixer assembly was installed between the fuel venturi-mixer and the electronic throttle/governor. Piping extensions were used between the throttle, EGR venturi, fuel venturi, and air filter to assure complete EGR/fuel/air mixing. With an ideal air/fuel mixing venturi arrangement, the fuel delivered is in direct proportion to the load without the aid of electronically controlled adjustments. to maintain the best mechanically metered fuel flow, the fuel venturi was raised upstream of the EGR venturi such that the nominal fuel flow from the zero pressure regulator would be based on the response to venturi's throat pressure effect induced by air flow only, rather than the flow of both air and EGR.

A piping tee was added to the cooled exhaust gas exiting the EHRU and then EGR piping connected the tee to the EGR venturi. A flanged interface allowed 0-100 percent restrictive inserts to be installed in the cooled EGR line so the experiment could transition from no EGR to various increments of EGR. Furthermore, the experimental setup included an EHRU bypass that allowed cooled EGR temperatures to be increased, although the need never materialized. Emissions were sampled after the 1st stage catalyst assembly which consisted of 1023 $in^3$ of 300 cpsi Süd-Chemie TWC.

Two ignition systems were used during the EGR evaluations, Tecogen's stock GM inductive ignition and Altronic's Model CDA-6 capacitive discharge ignition system. Combining ignition system observations with EGR evaluations provided certain advantages to the test team. First, the charge-dilution provided by EGR would create additional stress on the ignition system in comparison to standard stoichiometric combustion without EGR. If no differences occurred between EGR efficiency and emissions observations with the stock inductive ignition system versus the CDI system, then it would be unlikely that Tecogen would be able to observe any short term benefits in the test cell when observing the same parameters with standard stoichiometric combustion, which does not pose a particular challenge for ignition systems. Conversely, using a CDI system with multiple spark discharge per combustion cycle would help to ensure than EGR findings were not unfairly compromised by inadequate ignition capabilities.

### 4.8.2 Test Methodology

All EGR testing was performed by first achieving rated 100 kW power with zero EGR by inserting a blocking plate at a flanged junction in the cooled EGR piping. Once at 100 kW, the EGR blocking plate was slowly removed with an upstream EGR throttling butterfly valve at its minimum position. The EGR throttling valve did not have positive closure capability and the resultant EGR had an obvious and measurable impact on engine operation as indicated by a change in the engine rpm required to maintain 100 kW and in the ignition timing required to achieve best fuel efficiency. This resultant EGR was identified as EGR Rate 1 since the test cell was not equipped to define EGR flow rates quantitatively.

Once the transition to EGR operation at minimum flow (Rate 1) was established, the EGR rate was increased by opening the EGR throttling valve. The intent was to increase EGR rate until increases in engine speed could not recuperate lost power without exceeding a system speed limitation of 2900 rpm (based on limits of the generator voltage regulator followed closely by maximum generator speed limits), or until obvious charge dilution limits had been reached as evidenced by engine misfiring. Ignition timing was advanced as necessary to ensure the limits above were not reached due to inadequate ignition advance. This process led to the engine being operated with the EGR throttling valve wide open, and was identified as EGR Rate 2.

A third and final EGR rate was achieved by increasing the area of the flow orifices in the EGR venturi and repeating the procedures above. With the modified venturi, EGR flow reduction had to be employed using the EGR throttling valve to prevent engine misfires caused by charge dilution beyond the limits for the engine's combustion chamber design. Thus a maximum EGR rate, although not quantified, was established and referenced as Rate 3. In summary, Tecogen establish three EGR rates to test, with flow rates characterized as Rate 1 < Rate 2 < Rate 3.

Sweeps of ignition timing advance versus gross electric efficiency were performed with the engine running with no EGR and EGR Rates 1-3. These sweeps were important to identify "MBT" timing, the minimum ignition advance for best torque or efficiency, to identify optimized operating conditions for non-EGR versus EGR comparisons on the InVerde engine. These ignition timing sweeps were performed with both the stock inductive ignition system and the CDI system. Electric efficiency was quantified with timed measurements of volumetric gas consumption using the test cells pressure and temperature compensated positive displacement meter. The lower heating value of gas was assumed, and thus could induce some error in the absolute efficiency values, but this error would not impact the relative comparisons between configurations.

The defining of MBT timing points was used to select the ignition timing that would be used during emissions sweeps for the following three cases:

- No EGR, stock inductive ignition,
- EGR Rate 2, stock inductive ignition,
- EGR Rate 2, capacitive discharge ignition.

EGR Rate 2 was selected for the EGR emissions sweeps because the timing sweep data, discussed below, suggested it was the highest level of EGR the engine could accommodate without operating on the ragged edge of dilution-induced misfire. The emissions sweeps were performed by recording data at fixed pre-catalyst HEGO targets for at least five minutes per point with engine stabilization and Testo air rinsing in between points. Sweeps proceeded in rich-to-lean directions.

**Figure 4-53: EGR Experimental Setup**

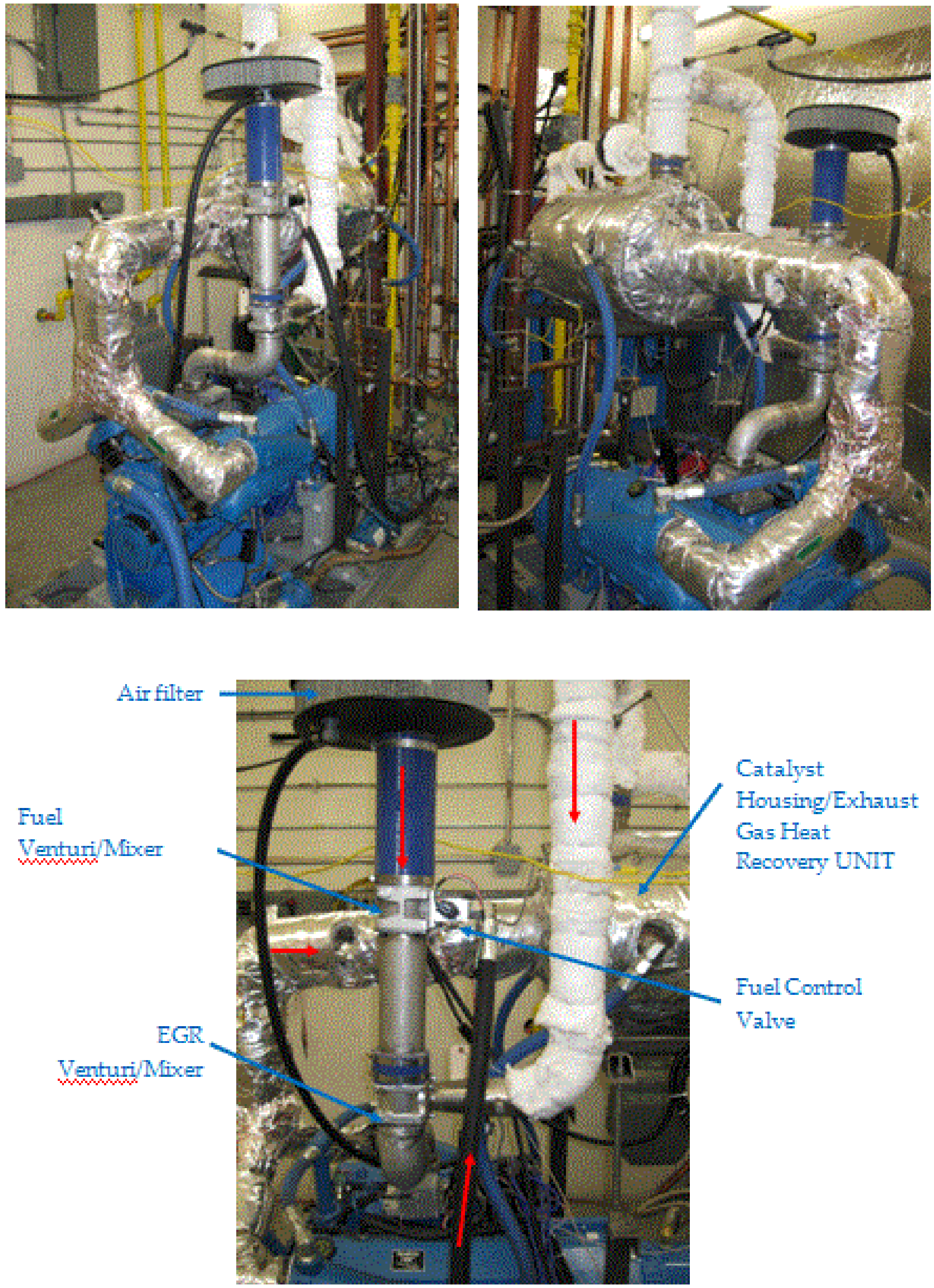
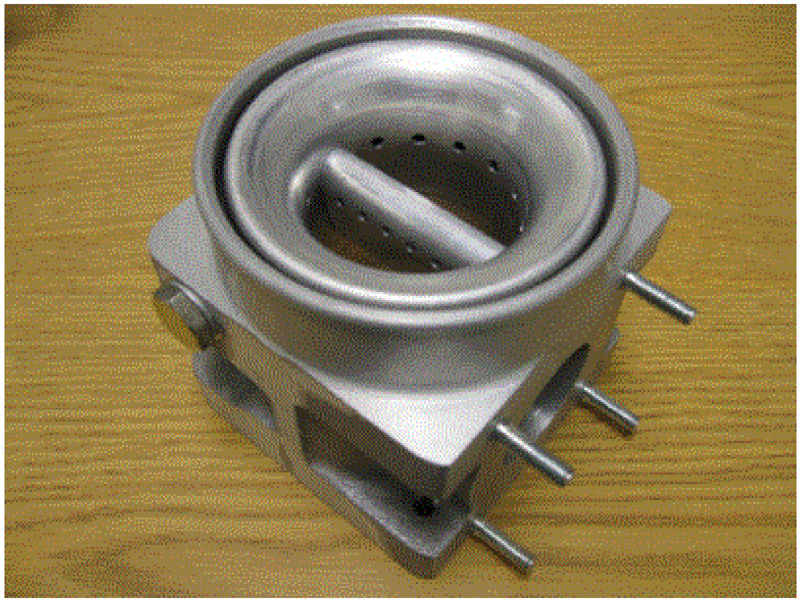
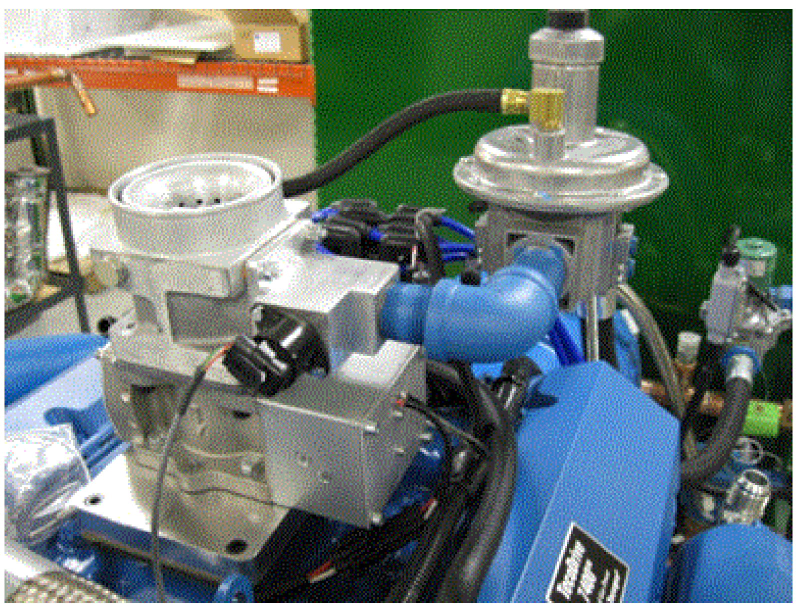


**Figure 4-54: Fuel Venturi and Its Standard Location**





### 4.8.3 Results

Figure 4-55 shows the results of the ignition timing sweeps with no EGR, three different EGR rates, and one repeated EGR rate with the CDI ignition system instead of the stock ignition. The highest efficiency (30.6 percent) was achieved without EGR at Tecogen's standard 35° BTC full load ignition timing. As expected, increases in EGR required advances in MBT timing to counteract the decreasing combustion flame speed that come with any form of charge dilution. However, even with MBT timing set for all configurations, incremental increases in EGR rate resulted in incremental penalties in engine efficiency with 29.9 percent, 29.3 percent, and 28.7 percent peak efficiency for EGR Rates 1, 2, and 3, respectively. Table 4-4 shows the nominal engine speed increases that were necessary to achieve the 100 kW set point for each configuration at MBT timing, and the resultant exhaust temperatures. EGR Rate 2 produced the lowest pre-catalyst exhaust temperature at 1217 °F, while the exhaust temperature at EGR Rate 3 actually climbed again. It is believed that the combustion speed at EGR Rate 3 was so slow that partial misfires and late burns led to an increase in exhaust temperature despite the increase in charge dilution.

**Figure 4-55: Ignition Timing Sweeps – EGR, No EGR and Ignition Types**

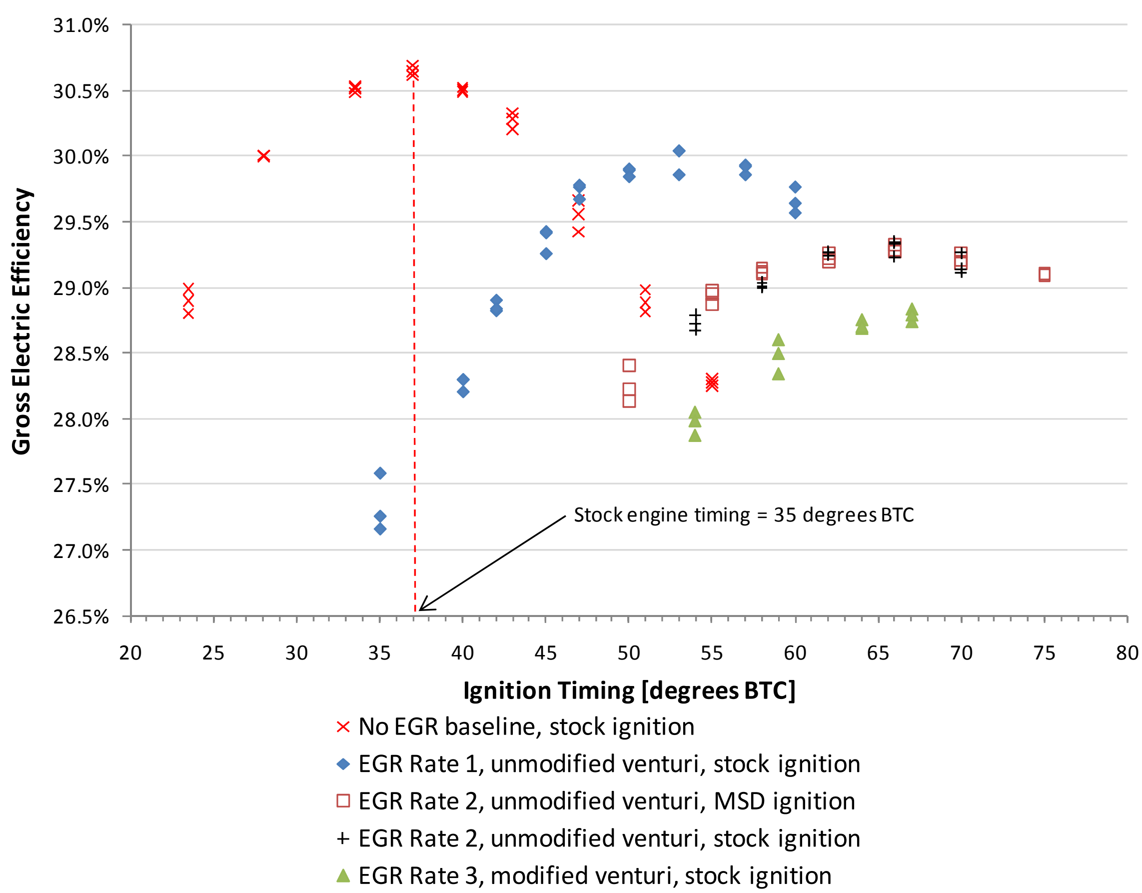
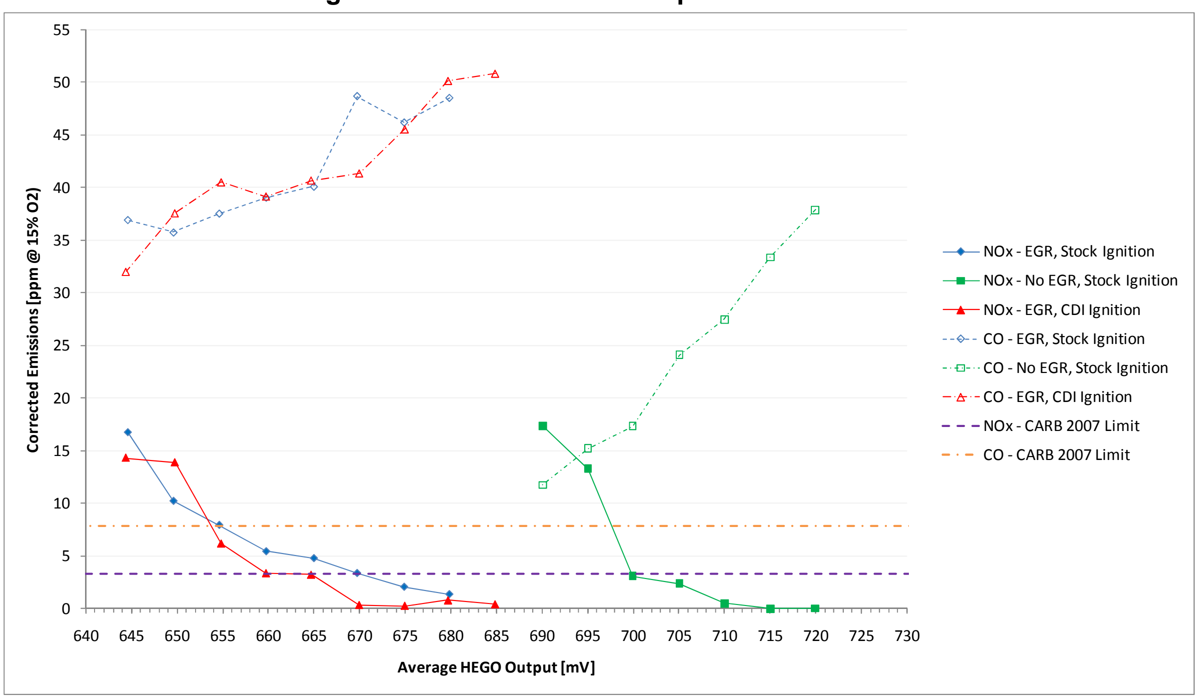


**Table 4-4: Influence of EGR**

| EGR Configuration | MBT Timing | Exhaust Temperature At MBT Timing | Engine Speed At MBT Timing |
|---|---|---|---|
| No EGR | 37 °BTC | 1260 °F | 2257 rpm |
| EGR Rate 1 | 52°BTC | 1230 °F | 2600 rpm |
| EGR Rate 2 (> Rate 1) | 62°BTC | 1217 °F | 2670 rpm |
| EGR Rate 3 (> Rate 2) | 67°BTC | 1230 °F | 2850 rpm |

Figure 4-56 shows the emissions sweeps performed at select conditions. First one sees that the choice of ignition system, stock inductive versus capacitive discharge, did not have an influence on the $NO_x$ and CO emissions results just as it had no effect on the electric efficiency. The emissions between no-EGR and EGR conditions are best compared by looking at the CO emissions for each configuration at a common $NO_x$ level, such as the point where the $NO_x$ emissions cross the CARB 2007 limit. This comparison shows CO without EGR at about 17 ppm and about 40 ppm with EGR (all corrected to 15 percent $O_2$). This significant increase in CO using EGR was produced without any offsetting benefits, suggesting EGR to be an unfruitful option for the InVerde platform.

**Figure 4-56: Emissions Sweeps With/Without EGR**



The CDI ignition system provided two sparks per combustion cycle as observed with a handheld ignition scope that provided a quantitative look at the ignition waveforms (Figure 4-57 and Figure 4-58). The peak ignition voltage was very erratic as is somewhat normal for spark ignition engines, but the peak ignition voltage was generally observed to be higher with the CDI ignition than the stock inductive ignition. Spark durations were about 1000 microsecond for the inductive system and 220 microseconds per spark from the CDI system.

**Figure 4-57: Capacitive Discharge Ignition With 220 Microsecond Spark Duration**

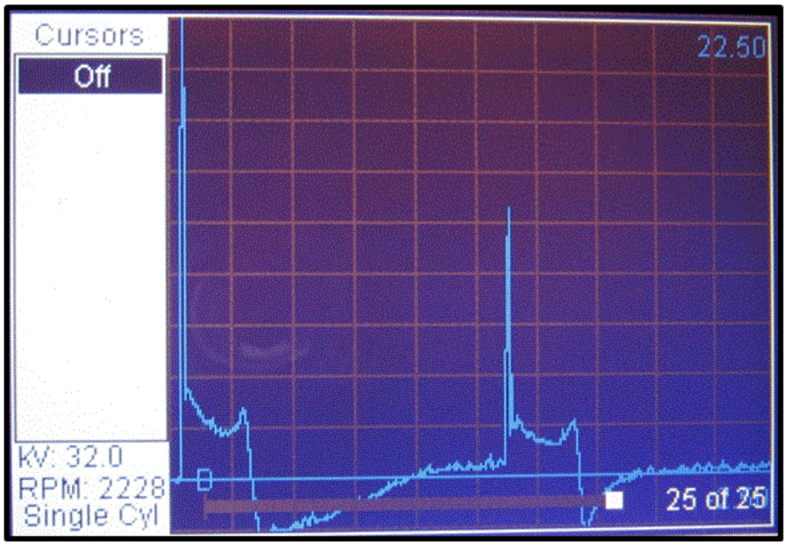
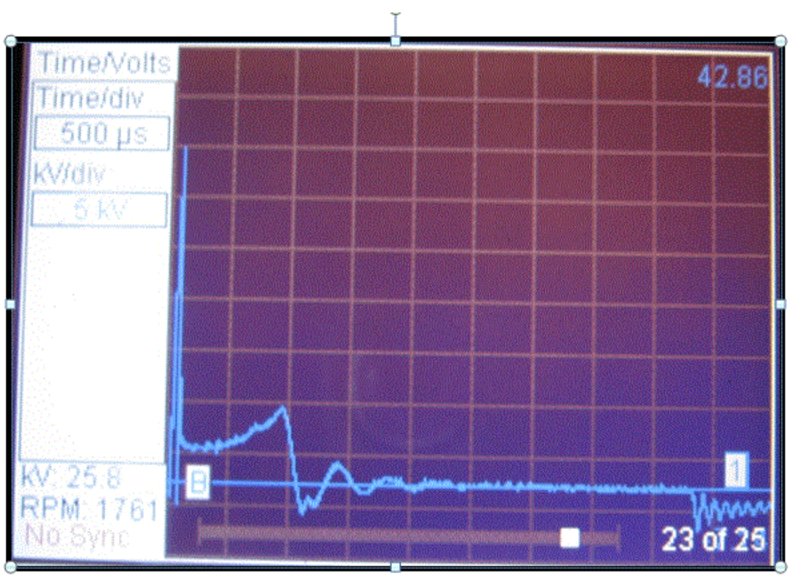



**Figure 4-58: Stock Inductive Ignition With 1000 Microsecond Spark Duration**



### 4.8.4 Discussion

Implementing EGR on the GM 7.4L InVerde engine did not produce any benefits of a magnitude that that would entice Tecogen to pursue it further for its CHP products. EGR implementation is often associated with lower peak combustion temperature for lower engine-out NOx formation and increased engine efficiency. It was a positive observation that engine speed increases were capable of maintaining 100 kW rated power even though the fresh charge air density decreased with the introduction of cooled (290 °F) EGR. However, at full load conditions, the electric efficiency decreased with each incremental addition of cooled EGR. Pre-catalyst NOx emission reductions due to EGR were likely present, but were not measured. More importantly, the post-catalyst emissions results at equivalent No-EGR/EGR $NO_x$ levels showed > 200 percent increase in CO emissions. Another potential EGR attribute that the InVerde engine could have benefited from, if achieved, was to reduce the pre-catalyst exhaust temperature to 1000-1200 °F, which is below common catalyst industry limits for continuous operation and decrease thermal aging degradation. However, the lowest pre-catalyst temperature reached with EGR was 1217 °F, only a modest reduction.

The cylinder head and combustion chamber shape employed by Tecogen does not have outward indications of being designed to provide high levels of swirl which often enhance the charge turbulence in the combustion chamber and make the engine more conducive to forms of charge dilution such as EGR. Therefore, the mechanical design of Tecogen's GM 7.4L is thought to be less than ideal for the implementation of EGR.

The challenges against successful EGR implementation are also compounded by the almost exclusive operation at rated power with the throttle nearly wide open. In Tecogen's duty-cycle there are effectively no throttle-based pumping losses to recuperate or to induce EGR flow. The addition of a second mixing venturi into the intake air path increased pumping losses in comparison to the stock engine without EGR. Also, frictional losses increase with engine speed and it was increases in engine speed, rather than throttle position, which were used to maintain power targets when EGR was employed. Whatever thermodynamic benefits in efficiency can be derived from the implementation of EGR in other applications, were more than offset on the Tecogen application by combustion that was too slow (very advanced MBT timing), by higher engine speed, and by increased pumping losses.

The CDI ignition system produced no measureable benefits among the measured variables. This indicates the stock ignition system adequately initiates a kernel of combustion in the stoichiometric charge mixtures of the Tecogen product such that normal and reliable combustion occurs. Even with EGR, which increases the difficulty of igniting combustible mixtures through dilution of reacting constituents, the CDI ignition system showed no benefit. It is a valid point to question whether or not CDI systems will universally provide an advantage to a particular inductive system in those conditions that do challenge the capabilities of the ignition systems, such as very high load, fouling atmospheres, poor mixing, and heavy charge dilution. Capacitive discharge systems can provide much higher secondary delivery voltages, but the spark duration is so short that even with multiple sparks, it is questionable whether or not greater ignition energy is provided to the combustion process than with a particular inductive system. In the case of these tests, even with two sparks per combustion event, the combined CDI spark duration was less than half that of the inductive components. The results observed in the brief nature of the laboratory testing do not eliminate the possibility that other benefits may exist with one ignition approach versus another with regards to the durability of the ignition delivery through the spark plugs as a function of time and fouling in the combustion chamber. However, no unacceptable ignition systems characteristics were identified by Tecogen with regards to general engine operation, and thus such longer term studies were not performed.

The InVerde engine has different mechanical and application characteristics than other engine systems that derive attractive benefits from implementing EGR. Automotive spark ignition engines operate a significant portion of their duty-cycle at part load, characterized by large intake vacuums and high pumping losses. If the engine has a cylinder head and combustion chamber design that can induce enhanced levels of swirl or tumble (specific forms of combustion chamber air motion), then it can accommodate the introduction of EGR, which can offer emissions and efficiency benefits. Under part load conditions, the manifold vacuum is a natural force by which to induce EGR to flow into the intake system. As EGR is admitted to the intake manifold, it displaces air. This results in an increased throttle position to maintain the part-load power needed by the user. The increased throttle position leads to lower pumping losses. The net result for a part-load spark ignition engine is lower peak combustion temperature and lower fuel consumption for a given load.

## 4.9 Conclusions

Tecogen has conducted several areas of investigation that relate to the control of rich-burn engine emissions including the use of oversized three-way catalysts, two-stage after treatment with TWC followed by air injection and a supplemental oxidation catalysts, universal exhaust gas oxygen sensors, dithering fuel control, exhaust gas recirculation, and a comparison of stock induction versus capacitive discharge ignition systems. From this work, Tecogen has drawn the following conclusions or opinions:

1. Süd-Chemie's 300 cpsi TWC product, Tecogen's standard catalyst for commercial applications, does not provide a reliable option for compliance with the CARB 2007 DG limits, even when it is used to fill the available volume inside Tecogen's combined catalyst housing and EHRU assembly. Although one compliant engine operating condition was demonstrated, there was very little margin for error both in terms of catalyst degradation and AFR control variability. Also, a replacement set of Süd-Chemie catalysts could not repeat the task.
2. Süd-Chemie predicted CARB 2007 DG compliance with half the catalyst volume tested. This suggests their sizing program has important flaws with regards to predicting compliance with such low limits.
3. DCL's 400 cpsi outperformed the Süd-Chemie product and could demonstrate compliant engine operate with 682 $in^3$ and 1023 $in^3$ substrate volumes. The smaller volume had a very narrow AFR control compliance range. The width of the compliance

window was increased with additional DCL TWC, but the increase, although critical, did not seem on par with the magnitude of volume increase.

4. The performance of the DCL product qualified it for field testing where longer term emissions characteristics could be observed. As such, 1023 $in^3$ of DCL TWC was installed in the catalyst assembly at Rancho San Antonio Boys Home for such observations.
5. The most promising aspect of the laboratory work evolved out of the air injection and supplemental oxidation catalyst testing. This two-stage after treatment approach demonstrated a significant increase in the width of the AFR compliance window, primarily by reducing the CO during rich-biased conditions.
6. The two-stage strategy has definite limitations due to the propensity for NH3 to oxidize into new NOx in the second stage, but the formation mechanism and temperatures to avoid are understood. The inherent exhaust temperature reduction associated with the heat recovery, found with most CHP systems, makes the two-stage after treatment process particularly suitable for CHP applications. This after treatment process earned a place into the field test program on a CM75 unit at San Fernando Pools.
7. AFR dithering was explored, but did not demonstrate emissions benefits in comparison to the standard steady-state fuel control process during a dithering performance sweep. The commercial product used to employ the dithering functionality did not perform flawlessly, and it is possible the results were unfairly compromised by imperfect adjustments of the many non-intuitive variables in the AFR controller.
8. UEGO sensors are still a subject of interest to Tecogen, but the InVerde platform may be too noisy an environment to make fair inroads into their use. Three different UEGO controllers, using two different UEGO sensors, failed to provide Tecogen's AFR controller with signals stable enough for precise closed-loop fuel control.
9. EGR lowers engine efficiency on the Tecogen engine, and increases post-catalyst CO, without any offsetting benefit. Tecogen's naturally aspirated engine operates at high load and is not conducive to EGR operation.
10. No changes were observed when operating the engine with a capacitive discharge ignition system, even when tested with EGR. The stock ignition system and the capacitive discharge system produced mirrored results during timing sweeps for identifying best efficiency and during emissions sweeps.

The emphasis of future work will be to demonstrate the longevity and operational nuances of the two-stage exhaust after treatment approach.

# CHAPTER 5: Field Testing

The objective of this task is to document the results of long term emissions monitoring of two Tecogen CHP customer installations that were retrofitted with different exhaust after treatment strategies, both of which were developed and characterized during the laboratory test phase of this program.

Both field test host sites are located in the greater Los Angeles area. The first host site to receive an emissions system upgrade was the Rancho San Antonio Boys Home in Chatsworth, CA. At this facility, Tecogen's 100 kW CHP system (Model INV-100) was retrofitted with a robust but traditional three-way catalyst (TWC) after treatment strategy for rich-burn engines, using a catalyst assembly that demonstrated the capability to achieve program goals during the laboratory phase of testing. Subsequently, Tecogen's 75 kW (Model CM-75) CHP installation at San Fernando Municipal Pools, in San Fernando, CA, was retrofitted with a novel two-stage after treatment approach that demonstrated excellent results in the laboratory. During the field tests, the emissions at both locations were monitored on a semi-continuous basis for several months to document the durability of the emissions reduction strategies and components. Both after treatment strategies demonstrated admirable compliance with program goals initially, but within an unacceptable period of time, the performance of the traditional TWC approach degraded to such an extent that the program goals could no longer be met. However, the two-stage emissions reduction concept at San Fernando Municipal Pools continues to look promising as a viable solution for achieving the goals of this program.

## 5.1 Data Collection Methodologies

The objective of the field verification test is to monitor the ultra-lean emissions system over a 6-month period, in the true operating environment, to subject the system to real uncontrolled parameters. The field test sites, test instrumentation and test sequences were detailed in a Field Test Plan. Test sequences and methods were followed according to the approved Test Plan except where adjusted as warranted by interim test results

The field data presented in this report was collected in a variety of ways to address different purposes. Data was collected:

- automatically through Tecogen's generator control system for a two-minute period at a 15 minute frequency during normal operation using one dedicated portable analyzer per location
- through on-site and remotely controlled R&D investigations using the same dedicated portable analyzers
- through regular service personnel visits to comply with SCAQMD Rule 1110.2 requirements to perform periodic portable analyzer tests, typically using an alternate analyzer

- by an independent source testing contractor with true CEMs equipment to validate particular R&D activities.

An overview of the data collection apparatus and methodologies is provided in the paragraphs below.

Tecogen's proprietary engine and generator control system is managed by its Remote Monitoring and Control System (RMCS) product. RMCS allows Tecogen to monitor the unit via a modem and phone line, as well as provide limited remote control capability (stop, start, change set point, and so forth). The remote interface also allows for factory downloading of customized control software modifications, such as modified air/fuel ratio (AFR) control algorithms or data processing tools. RMCS also has data logging functionality. The data logging features can operate in modes that capture period-averaged data automatically or capture nearly second-by-second data, during focused observations, based on start/stop logging commands from users linked to RMCS.

Each field test installation was equipped with a dedicated Testo 350XL portable emissions analyzer. The Testo 350XL analyzer uses chemical cell technology to measure NO, $NO_2$, CO, and $O_2$. This type of technology is not appropriate for continuous emissions monitoring, but it can be used in a semi-continuous mode as long as the analyzer's chemical cells are purged with air after limited-duration exhaust sampling cycles. Each Testo analyzer was configured with an optional four-channel analog output device, such that the four gas parameters could be transmitted to Tecogen's RMCS control system through 0-10V analog signals. Furthermore, the Testo was configured to accept an externally-supplied electronic trigger signal to start and stop emissions sampling, with all stop commands followed by a three minute air rinse. In this fashion, the Testo could be activated to transmit emissions data into the RMCS system with all the other engine and generator management parameters normally monitored and recorded by RMCS.

By default, all commercially operating Tecogen products with RMCS are programmed to monitor all system parameters at three Hz, and then transmit an average value for each parameter to a centralized Tecogen database every 15 minutes. For the field test efforts, this inherent data collection process was augmented with Testo emissions data by initiating a start-sampling trigger command 13 minutes into each 15 minute cycle. The analog emissions values were then sampled at the same three Hz rate for the final two minutes. The resultant emissions data were then averaged at the end of the cycle and included with the rest of the 15 minute averages of all the other non-emissions operational data. Finally, the Testo would follow each emissions sampling cycle with a three minute air rinse, and so on. Further programming prevented emissions sampling and recording when the engine was off, during transient operation such as startup, or before the system reached normal operating temperature. Using this methodology, a 24 hour running period would produce 96 averaged values of two minute data, representing 3.2 hours of active emissions sampling every day. This semi-continuous cycle provided a high degree of assurance that an accurate portrayal of the emissions characteristics could be made over an extended period of time, while also protecting the sensitivities of the Testo given its limitations as a portable analyzer. An example of a portion of the data recorded at 15 minute intervals is shown in Table 5-1.

RMCS's flexible data gathering capabilities were used for field investigations as well. On several occasions, the test team traveled to the San Fernando Pools (SFP) test site to perform field investigations of system performance by altering physical aspects of the after treatment retrofit. During these investigations, the $NO_x$ and CO emissions were characterized over a broad range of air/fuel ratio set points to characterize the size and shape of the emissions compliance zone under different second-stage catalyst operating temperatures, identical to techniques performed in the laboratory program. During such investigations, the test personnel bypassed the standard RMCS control algorithms to force the AFR to desired conditions, whether compliant or not, and then used RMCS to capture emissions data for each stabilized condition. During field R&D, data was captured at a higher resolution (~1.8 seconds per sample) such that real time emissions variability could be observed. On one day, such investigations were augmented at SFP by performing a series of performance characterization tests using three independent data sources, specifically the Testo, a second portable analyzer manufactured by LAND instruments, and traditional source test equipment operated by an independent emissions source testing company, Air X. Collectively, such investigations enhanced the understanding of the two-stage after treatment characteristics as a function of age and other discretionary operating parameters.

### Table 5-1: Sample of RMCS Data Collection

| TimeStamp | Hour Meter | Minutes Run | kWAvg | NO ppmvd (Uncorr) | NO2 ppmvd (Uncorr) | CO ppmvd (Uncorr) | O2% | O2 In [mV] | O2 Out [mV] | UEGO In [mV] | UEGO Out [mV] | O2 Bounce Hi | O2 Bounce Lo | O2 Adjust | MAP [in Hg] | Catalyst In Temp [°F] | Catalyst Out Temp [°F] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5/12/09 3:30 PM | 166 | 15 | 99 | 0.90 | 0.1 | 17.8 | 0.61 | 626 | 324 | 4008 | 4049 | 8 | 11 | 1 | 25.2 | 1235 | 1261 |
| 5/12/09 3:15 PM | 166 | 15 | 99 | 3.90 | 0.1 | 25.1 | 0.6 | 626 | 392 | 4014 | 4053 | 12 | 13 | 1 | 25.2 | 1234 | 1262 |
| 5/12/09 3:00 PM | 166 | 15 | 99 | 0.50 | 0.1 | 36.8 | 0.6 | 624 | 385 | 4016 | 4045 | 12 | 12 | 0 | 25.2 | 1234 | 1262 |
| 5/12/09 2:45 PM | 166 | 15 | 99 | 1.60 | 0.1 | 32.2 | 0.6 | 623 | 350 | 4002 | 4051 | 14 | 11 | 0 | 25.4 | 1235 | 1262 |
| 5/12/09 2:30 PM | 164 | 15 | 99 | 0.50 | 0.1 | 36.6 | 0.6 | 626 | 470 | 4007 | 4041 | 15 | 12 | 1 | 25.4 | 1236 | 1261 |
| 5/12/09 2:15 PM | 164 | 15 | 99 | 0.70 | 0.1 | 34.4 | 0.6 | 623 | 207 | 3999 | 4047 | 10 | 8 | 0 | 25.4 | 1229 | 1257 |
| 5/12/09 2:00 PM | 164 | 15 | 99 | 10.20 | 0.1 | 19.2 | 0.58 | 624 | 433 | 4016 | 4053 | 9 | 14 | 0 | 25.2 | 1237 | 1262 |
| 5/12/09 1:45 PM | 164 | 15 | 99 | 0.50 | 0.1 | 64.2 | 0.58 | 631 | 383 | 4008 | 4043 | 12 | 11 | 6 | 25.4 | 1233 | 1256 |
| 5/12/09 1:30 PM | 164 | 15 | 99 | 0.70 | 0.1 | 59.5 | 0.56 | 630 | 403 | 4011 | 4045 | 12 | 11 | 6 | 25.4 | 1228 | 1257 |
| 5/12/09 1:15 PM | 164 | 15 | 99 | 0.40 | 0.1 | 45.1 | 0.54 | 628 | 343 | 4011 | 4051 | 16 | 11 | 2 | 25.2 | 1229 | 1259 |
| 5/12/09 1:00 PM | 164 | 15 | 99 | 0.70 | 0.1 | 26 | 0.55 | 627 | 408 | 4005 | 4042 | 13 | 10 | -21 | 25.2 | 1234 | 1259 |
| 5/12/09 12:45 PM | 164 | 15 | 99 | 63.70 | 0.1 | 3 | 0.56 | 627 | 355 | 4016 | 4054 | 11 | 13 | -21 | 25.4 | 1230 | 1258 |
| 5/12/09 12:30 PM | 162 | 15 | 99 | 1.60 | 0.1 | 23.7 | 0.54 | 626 | 309 | 4017 | 4051 | 10 | 11 | -22 | 25.2 | 1232 | 1258 |
| 5/12/09 12:15 PM | 162 | 15 | 99 | 0.70 | 0.3 | 32 | 0.53 | 627 | 393 | 4012 | 4047 | 20 | 15 | -20 | 25.2 | 1232 | 1258 |
| 5/12/09 12:00 PM | 162 | 15 | 99 | 10.90 | 0.1 | 10.3 | 0.53 | 629 | 412 | 4016 | 4048 | 17 | 14 | -19 | 25.4 | 1230 | 1256 |
| 5/12/09 11:45 AM | 162 | 15 | 99 | 5.90 | 0.1 | 23.3 | 0.53 | 630 | 369 | 4010 | 4055 | 14 | 16 | -18 | 25.4 | 1230 | 1256 |
| 5/12/09 11:30 AM | 162 | 15 | 99 | 0.60 | 0.1 | 43.9 | 0.53 | 631 | 281 | 4010 | 4049 | 15 | 9 | -17 | 25.4 | 1227 | 1254 |
| 5/12/09 11:15 AM | 162 | 15 | 99 | 16.80 | 0.1 | 8.3 | 0.52 | 629 | 356 | 4009 | 4054 | 11 | 13 | -19 | 25.4 | 1229 | 1254 |
| 5/12/09 11:00 AM | 162 | 15 | 99 | 1.10 | 0.1 | 27.7 | 0.53 | 632 | 339 | 4011 | 4049 | 12 | 9 | -16 | 25.4 | 1226 | 1252 |
| 5/12/09 10:45 AM | 162 | 15 | 99 | 43.60 | 0.2 | 6.2 | 0.52 | 633 | 370 | 4011 | 4053 | 12 | 13 | -15 | 25.4 | 1221 | 1249 |
| 5/12/09 10:30 AM | 160 | 15 | 99 | 6.80 | 0.2 | 16.2 | 0.53 | 644 | 504 | 4017 | 4059 | 13 | 8 | -4 | 25.4 | 1220 | 1240 |

## 5.2 Field Test Results

### 5.2.1 Rancho San Antonio Boys Home Field Test

Rancho San Antonio Boys Home (RSA) operates a 100 kW INV-100 marketed under the "InVerde" name. This CHP system was commissioned with Tecogen's standard emissions after treatment system in March 2009. The CHP installation provides base load electricity and heat to reduce net utility operating costs. About four months after the system began commercial operation, the standard catalyst substrates from Süd-Chemie were replaced with 1023 $in^3$ of TWC substrates manufactured by DCL International, Inc. This volume of DCL's 400 cells per square inch cpsi TWC had demonstrated the capability to achieve program goals during laboratory testing. The RSA CHP system provided the opportunity to evaluate the robustness of the catalyst substrates and Tecogen's latest AFR control algorithms. The actual length of the field test fell short of the six month period originally planned due to an inability to maintain CARB 07 levels and a subsequent, unrelated destruction of the DCL catalyst, perhaps caused by engine misfires.

Official monitoring of the enhanced after treatment system performance started July 1, 2009 with the CHP system operating 8-16 hours per day. Figure 5-1 shows the daily averages of $NO_x$ and CO monitored by the Testo 350XL from July to mid-November. These daily averages encompassed all the two-minute sampling averages recorded throughout the day and night on 15 minutes intervals as discussed earlier. During the first three weeks of operation, the $NO_x$ and CO results were compliant with CARB 2007 DG limits with the application of the minimum thermal credit for CHP applications, which require documented operation at 60 percent overall electric and thermal efficiency (HHV). However, by late July, the CO results degraded to levels that were typically above the 60 percent efficiency CARB limits. Throughout September, the daily CO averages were above the CARB limits even if maximum thermal credit was applied.

Tecogen implemented an AFR control algorithm change in October 19, 2009 to try to achieve better results. The daily averages in Figure 5-1 suggest the effect was a decrease in CO at the expense of an allowable increase in $NO_x$ emissions, but the AFR control change did not result in a return to common compliance with the 60 percent efficiency CARB limits.

With such low $NO_x$ emissions throughout the performance period, it would be valid to question whether CO increases over time were merely a consequence of an AFR controller shift towards a rich operating bias, a bias that could be retuned for better results. However, close inspection of Figure 5-1 provides evidence that this was not the case and that the decrease in TWC conversion performance was a degradation of the catalyst itself. In July and in October there were some daily $NO_x$ averages that approached the 3.3 ppm $NO_x$ limit identified in the Figure. This would indicate the AFR was being controlled with as much of a lean bias as possible and should have resulted in the lowest possible CO emissions. In July, these highest $NO_x$ averages were associated with < 5 ppm CO, whereas similar $NO_x$ averages in October were associated with 8-9 ppm CO, a small but critical increase given the extremely tight standards. Furthermore, the general trends in the transition between the months of August and September show a clear increase in CO emissions even while the $NO_x$ emissions increased slightly, another indication that the general CO degradation was a function of catalyst degradation rather than unwanted AFR deviation.

**Figure 5-1: RSA Field Test, Daily $NO_x$ and CO Averages**

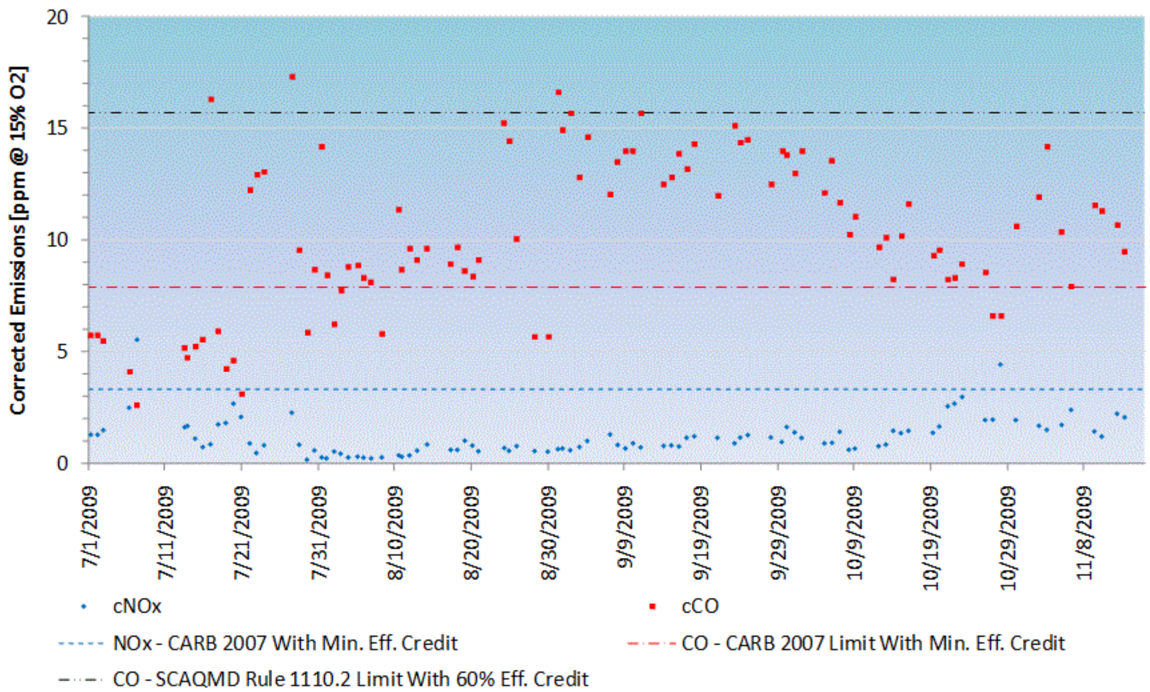
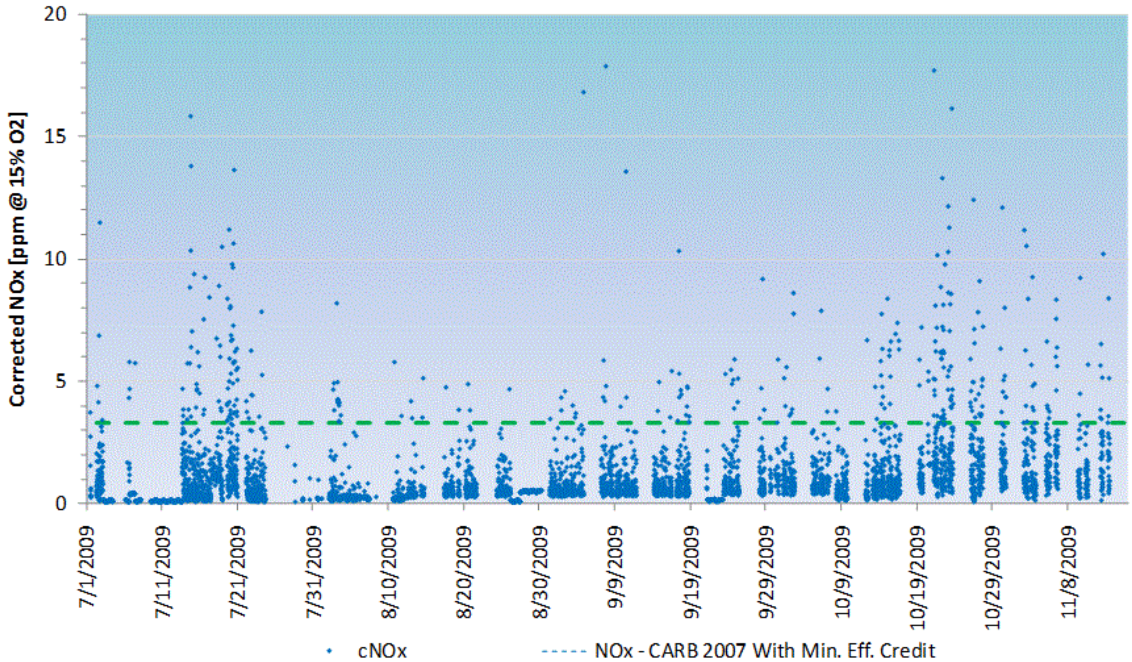



Figure 5-2 and Figure 5-3 provide additional insight into the DCL TWC performance at RSA and will aid in the appreciation of much improved results achieved with the alternate after treatment approach evaluated at the San Fernando Pools field test site, to be discussed later in this report. Figure 5- 2 and Figure 5-3 plot the individual two-minute averages for $NO_x$ and CO, respectively, that were acquired on 15 minute intervals and represent the basis for the daily averages shown in Figure 5-1. It should be readily accepted that the daily averages, often based on over two hours of active sampling (two minute sampling every 15 minutes for a 16 hour operating day), are far more indicative of the general performance of the after treatment strategy than any of the individual two-minute averages in Figures 5-2 and 5-3. In this light, the results at RSA suggest the DCL TWC retrofit appears suitable for the commercially-relevant limits posed by South Coast AQMD's Rule 1110.2, which has somewhat relaxed CO limits. However, it is also valid to suggest that the result of any individual 2 minute sample average could be indicative of the results that would have occurred during the same period if the sample time length had been increased to 15 minutes, the sample period specified by South Coast AQMD when performing periodic portable analyzer testing for compliance with Rule 1110.2. With this concept in mind, Figures 5-2 and 5-3 further suggest that it would not have been surprising for the DCL assembly at RSA to have failed a 15 minute compliance test against the CARB or SCAQMD DG, during any random period of the RSA field test.[9]

**Figure 5-2: RSA NOx, Two-Minute Sample Averages**




[9] It is important to note that the permit limits for the Rancho San Antonio site are11 ppm NOx and 73 pm CO @ 15 percent O2. Therefore, although the unit was not meeting the program goals, it was in compliance with the local AQMD air permit.

**Figure 5-3: RSA CO, Two-Minute Sample Averages**

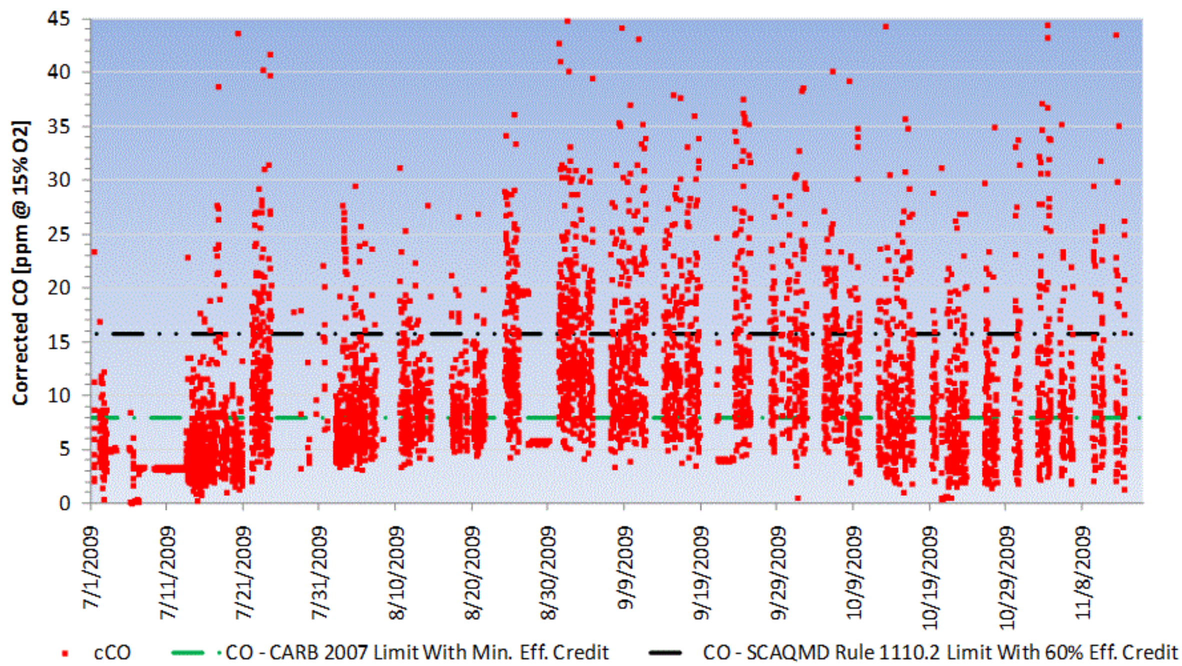



Figure 5-4 and Figure 5-5 consider the potential importance of each individual two-minute sample and reorganize the two-minute average sample data into histograms that show the percentage of results that complied with various CARB/SCAQMD thresholds. The monitoring program was broken into three periods. The July-August period represents the DCL TWC in a low-hour state. September-October represents the DCL with moderate run time, and October-November represents the results after an October 19 AFR algorithm change was implemented. Figure 5-4 compares the results to CARB 2007 DG limits, for program relevance, while Figure 5-5 references SCAQMD's Rule 1110.2, which has more practical commercial relevance.

The histogram data suggest the following conclusions with regards to the collection of individual two-minute samples taken over 1838 hours of CHP operation.

- The histogram data supports Figure 5-1 in the conclusion that the performance of the DCL TWC degraded, regardless of AFR control algorithm changes.
- The mid-October software change produced a tangible improvement in the compliance rates with CARB limits. Figure 5-1 suggests the effect of the software change was to induce a slightly leaner AFR tendency such that CO decreases came at the expense of an allowable level of $NO_x$ increases.
- The mid-October software change helped improve the compliance rates, but could not overcome general TWC degradation.

- By the end of the observation period, even with maximum thermal credit applied, the CARB 2007 compliance rates were < 60 percent, and the SCAQMD Rule 1110.2 rates were about 80 percent, not enough to claim success with program goals.

It was unfortunate that the RSA field test of a traditional rich-burn after treatment approach, with a TWC that was 50 percent larger than the manufacturer's original sizing analysis predicted was required, began demonstrating non-compliance with program goals after just two months of operation. However, by November the TWC was still reducing average $NO_x$ and CO emissions by an estimated 99 percent, so the failure to achieve the program goals was more of a testament to the extremely stringent nature of the regulatory limits than a statement against the durability of the TWC product. There is simply very little margin for degradation.

**Figure 5-4: Histogram Plot of RSA Compliance With CARB 2007 DG Limits**

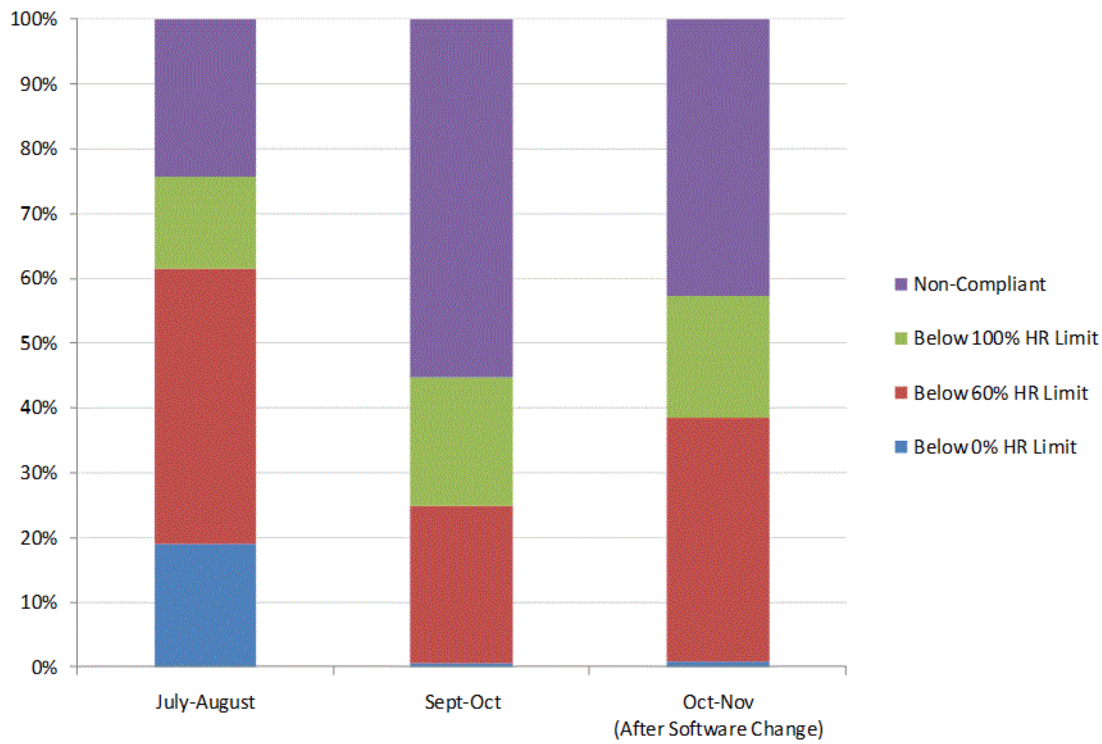
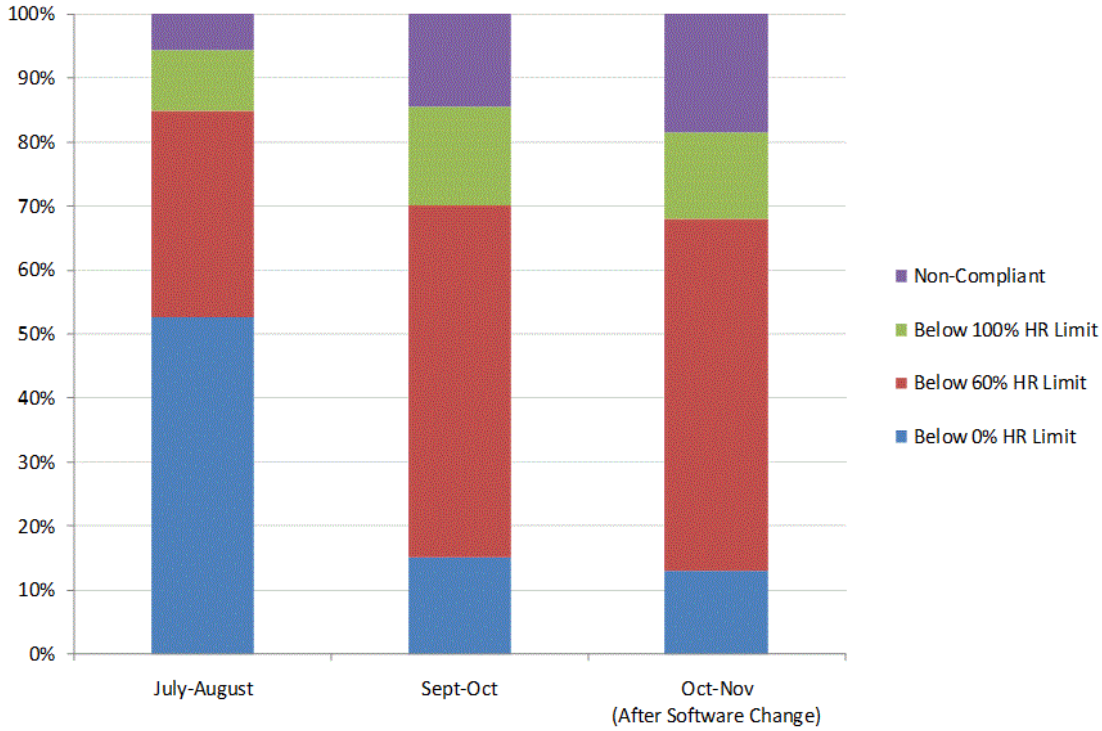


**Figure 5-5: Histogram Plot of RSA Compliance With SCAQMD Rule 1110.2 DG Limits**




Despite the November status with respect to program goals, Tecogen intended to carry on with the semi-continuous emissions sampling for longer-term documentation of the TWC's degradation characteristics. However, various events led to November 2009 being the effective end of the RSA field test program and the end of any substantially useful emissions data from the DCL catalysts. On November 16, 2009 the host facility discontinued operation of the CHP plant while it worked out disputes between the facility and the utility regarding the nature of the electrical interconnect agreement. The CHP plant was not placed back on-line until July 2010, by which time all attention and resources had been directed to the San Fernando Pools field test site, which was retrofitted with Tecogen's alternate after treatment strategy as of June 2010. The on-going plan for RSA was simply to accumulate more operating hours on the DCL catalysts for deeper characterization of the DCL TWC performance at a later date.

Unfortunately, the DCL catalyst substrates were destroyed before useful aging results could be documented. Operational anomalies, including sudden increases in emissions to levels far removed from the goals of this program, led to the discovery of extremely worn engine camshaft lobes. After replacement of the camshaft, the emissions continued to be exceedingly high regardless of AFR tuning and other diagnostic measures. In February 2011, the catalyst substrates were removed from the catalyst housing, and the third substrate was found to have suffered major thermal damage as shown in Figure 5-6. The DCL substrates had been provided by DCL in two modules. The first module consistent of two 3.94" length elements butted together by welding stainless steel sleeves in very close proximity, such that there was a very small gap between the gas-exiting face of substrate #1 and the entrance face of substrate #2. Substrate #1 was relatively clean and had no visual signs of abnormal operation. The majority of the channel entrances on the face of substrate #2, however, were completely clogged with what might have been ash accumulation (Figure 5-7). The entrance to the third element also had some channel blockage, but to a much lower degree. Part way into the depth of the third element, a significant portion of the stainless steel substrate was found to have reached a molten condition (5- 8). Given the normal appearance of the first element, this could only have occurred via large amounts of unburned air/fuel mixture reacting in the catalyst assembly, such as from cylinder misfiring.

**Figure 5-6: Inspection of Failed DCL Three-Way Catalyst**

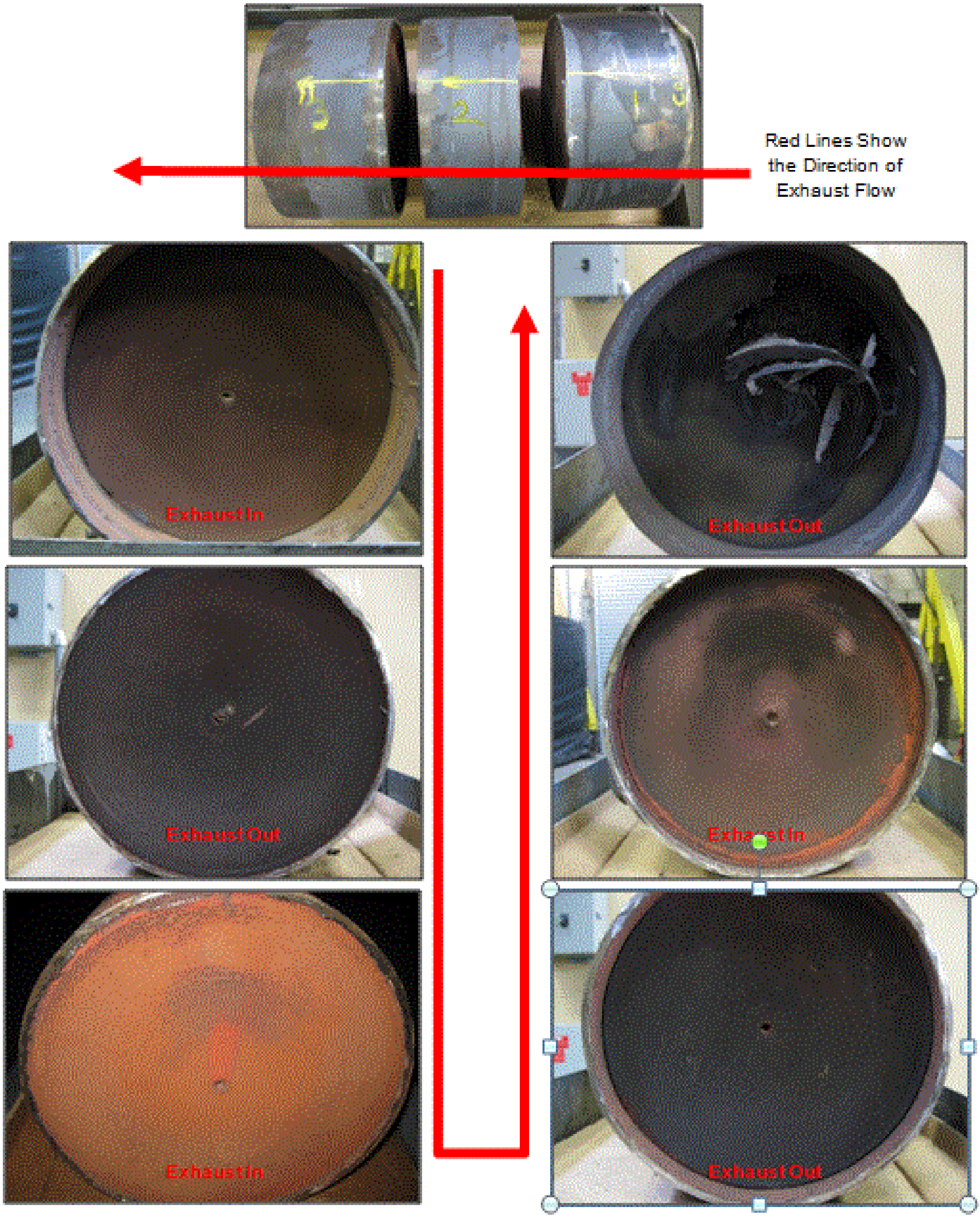


**Figure 5-7: Close-Up View, Face of Clogged DCL Substrate**

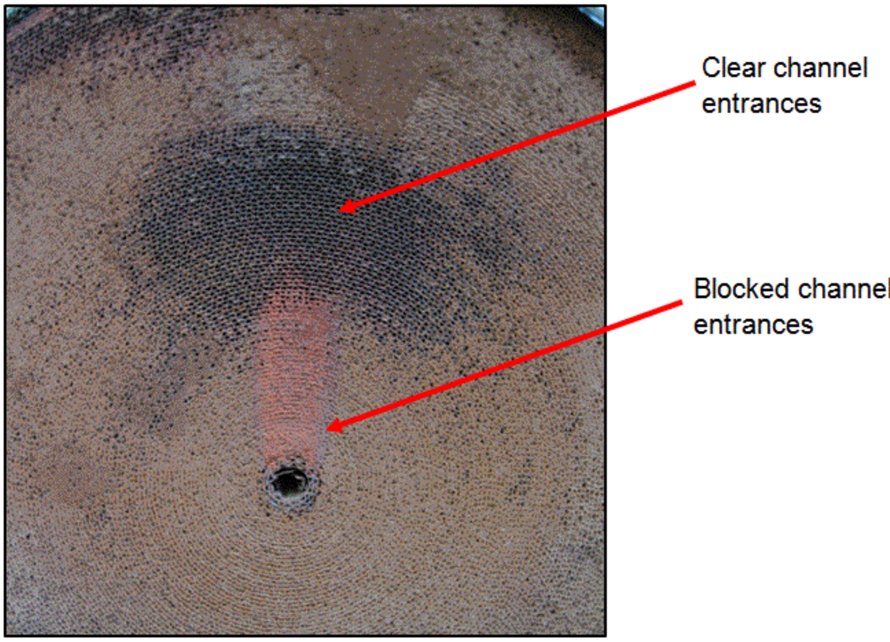



**Figure 5-8: Close-Up View, Molten TWC Substrate**

The root cause of the catalyst failure has not been determined. It has been speculated that, as the camshaft lobes continued to erode and the reduction in valve travel increased, the amount of residual burned gases remaining in the cylinder after each combustion event grew to such an extent that misfires occurred. The misfires could have then caused exothermic reactions in the catalyst that were severe enough to reach the melting temperature of the stainless steel monolith. It could also be speculated that the exhaust restriction caused by the progressive catalyst flow blockage was the mechanism for inducing poor cylinder scavenging, and hence misfires.

Another surprising aspect of the thermal portion of the catalyst's failure was a lack of a CHP shutdown associated with the level of material failure. High temperatures can deactivate catalysts enough to render them incapable of achieving high conversion efficiencies without leaving visually discernible evidence, but the RSA failure was beyond simple deactivation. By default, Tecogen's engine systems have pre-catalyst and post-catalyst thermocouples for exhaust temperature monitoring. The exhaust temperatures are linked to control processes, such as automatic power reduction and shutdown functions, depending on the severity of the temperature excursion. Furthermore, shutdown protections are coupled with email notifications of the event and logs within the RMCS data capturing process. Despite these functions and the logged data archives, the RSA unit never indicated a post-catalyst exhaust temperature problem. This has led to the assumption that the exothermic reactions that were intense enough to melt a portion of the third substrate were only occurring in a highly localized portion of the substrate at any given instant. Under such a scenario, the bulk exhaust temperature could have remained below the various system reaction triggers as the volume of thermally-destroyed material grew over time.

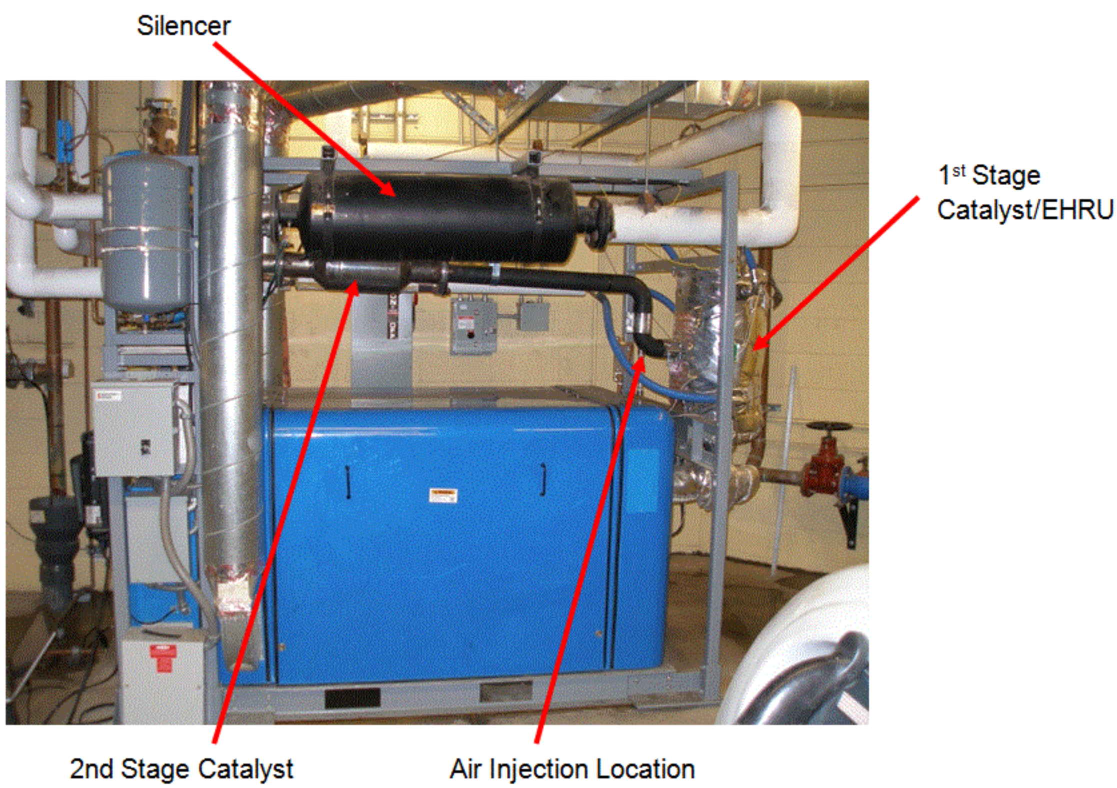
The final oddity of the DCL catalyst failure was the collection of ash at the face of the second catalyst. Catalyst poisons and fouling agents are not typically distributed evenly along the length of the catalyst. Rather, such agents are concentrated in the forward section of the first substrate. Neither Tecogen nor the catalyst manufacturer has observed such a fouling characteristic before and no further speculation is offered in this report.

The DCL catalyst assembly was replaced with Tecogen's standard Süd-Chemie configuration and the field test program and Rancho San Antonio Boys home formally ended, although it was effectively over when the host site stopped operating the CHP system for several months starting in November 2009.

### 5.2.2 San Fernando Municipal Pools Field Test

San Fernando Municipal Pools (SFP), in San Fernando, CA, operates a Tecogen Model CM-75 CHP system. This 75 kW CHP system was commissioned in November 2008 and provides base load electricity and heat to reduce net utility expenditures. The heat is used to heat three outdoor swimming pools. The SFP installation was chosen to demonstrate a novel exhaust after treatment approached explored during the laboratory phase of the program. In June 2010, SFP's original TWC and exhaust gas heat exchanger were replaced with a two-stage after treatment retrofit (Figure 5-9). The first stage of the retrofit consisted of two 300 cpsi Süd-Chemie TWC (522 $in^3$ total volume). The second stage catalyst assembly was installed downstream of the TWC. The 261 $in^3$ catalyst substrate in the second stage housing was identical to individual TWCs elements in the first stage. A small electric air pump was installed to inject ambient air between the first and second stage catalysts. Although the second stage catalyst was a TWC model, the air injection would limit its functionality to that of an oxidation catalyst. The system installation also included hardware for a proprietary exhaust conditioning system, which at the time of this report, could not yet be disclosed, but is expected to be made public in late 2011.[10] Finally, a Testo 350XL was mounted directed on the machine and wired into Tecogen's data management system (Figure 5-10) as discussed in Section 3.0.

**Figure 5-9: CM-75 Retrofitted With Two-Stage After Treatment Concept**




[10] U.S. Patent Application No. 12/816,706, "Assembly and Method For Reducing Nitrogen Oxides, Carbon Monoxide And Hydrocarbons In Exhausts Of Internal Combustion Engines", Joseph B. Gehret, Robert A. Panora, and Ranson Roser

**Figure 5-10: Dedicated Testo 350XL Mounted to San Fernando CHP System**


Semi-continuous emissions monitoring of the SFP CHP system began in April 2010, prior to the two-stage after treatment retrofit in June 2010. The monitoring of the two-stage after treatment performance was still active as of the May 2011 writing of this report. Figures 5-11 and 5-12 show the daily average NOx and CO, respectively, throughout the monitoring period. The timing of major events, AFR control setting changes and field R&D activities are identified in Figure 5-11 for reference. It was common for the SFP system to operate 24 hours per day with the Testo sampling the exhaust for two minutes every quarter hour. On this interval, the emissions sampling typically captured over three hours of data per day for each daily average. Figures 5-11 and 5-12 do not include data for days when the Testo was not available or when field R&D activities took place. The automatic Testo triggering process also did not allow sampling when the unit was off, was not at operating temperature, or was in a highly transient mode such as start-up and shut-down.

**Figure 5-11: Daily NOx Averages from San Fernando Pools Field Test**

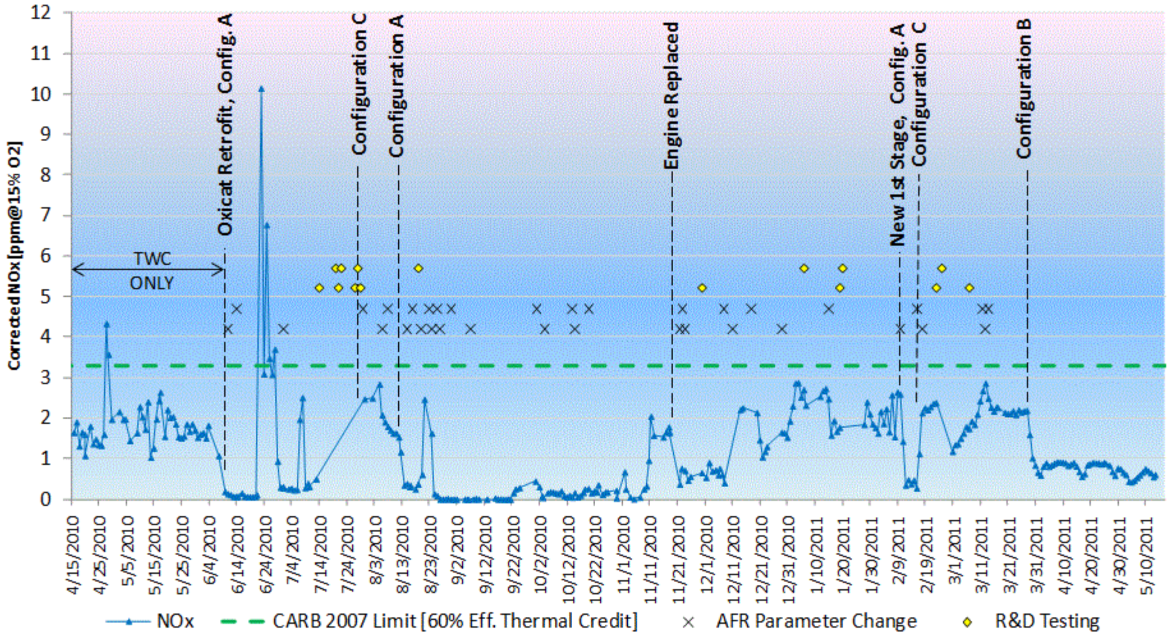



**Figure 5-12: Daily CO Averages from San Fernando Pools Field Test**

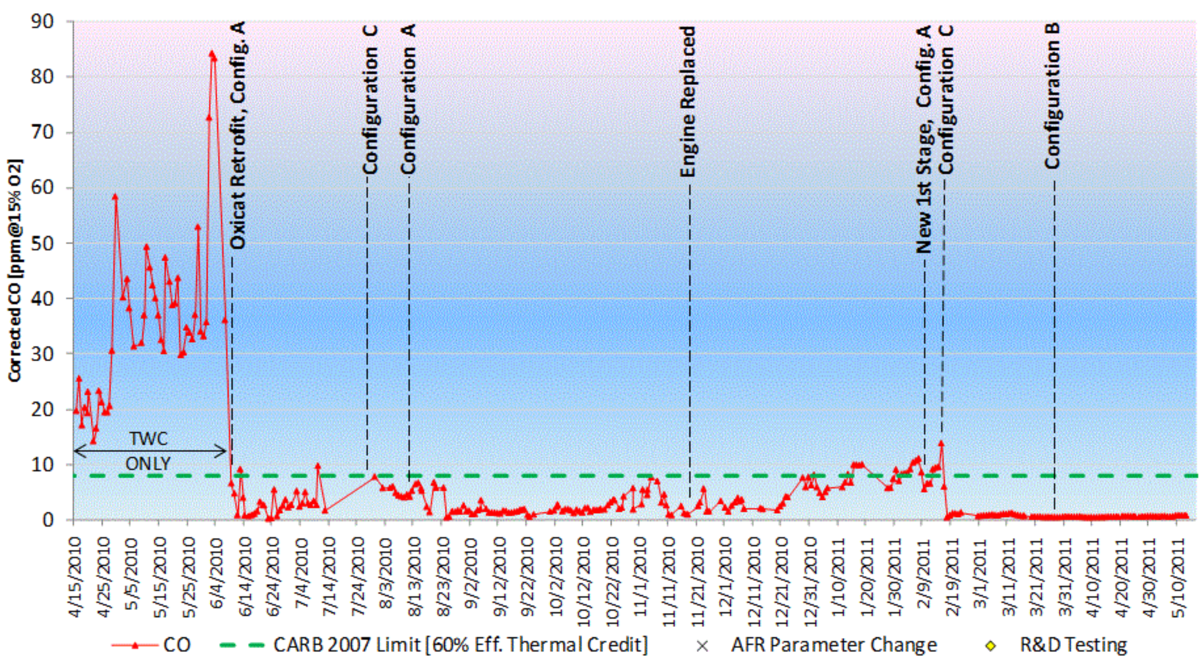
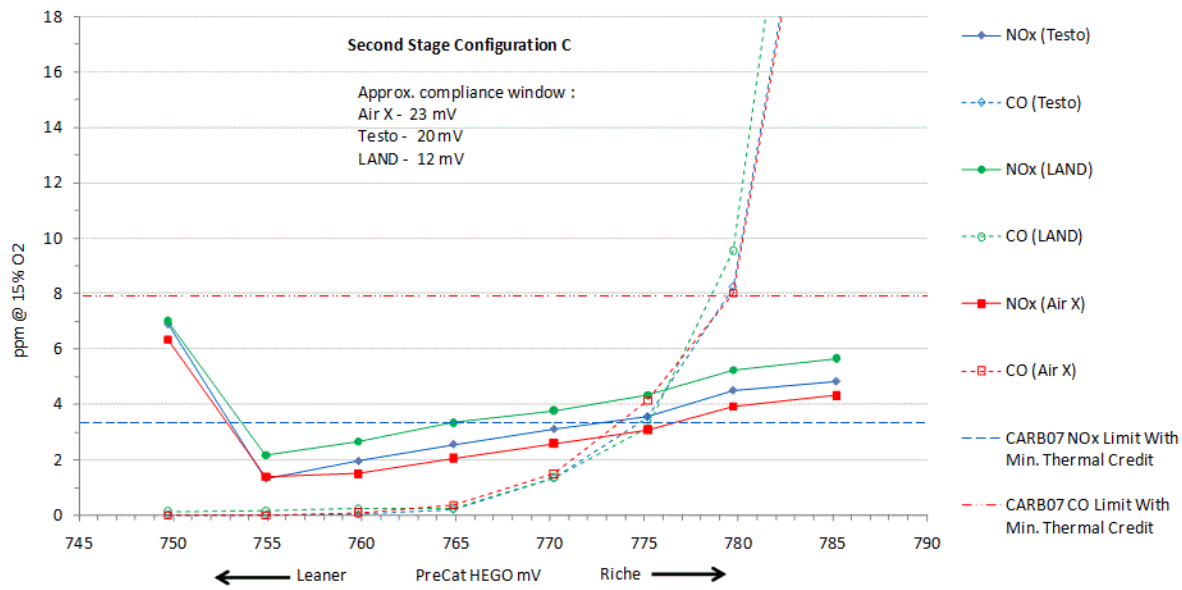


Figure 5-11 shows that the daily average corrected $NO_x$ emissions were generally below the CARB 2007 DG limits of 3.3 ppm (60 percent efficiency) throughout the entire monitoring period, including the time before the two-stage after treatment retrofit, other than a few averages shortly after the retrofit was first installed. These non-compliant $NO_x$ points immediately preceded a cylinder head replacement, although it is possible the two issues were unrelated. Even when daily $NO_x$ and CO averages were compliant with the program goals, Tecogen was compelled to experiment with the AFR control settings and the conditioning parameters (i.e. Configuration A, B, And C). At times the changes may have been in response to undesirable trends, such as an increase in the number of individual two-minute sample averages that were exceeding the program goals, even if the daily averages were compliant. In other cases, changes were enacted to produce more data at variable control conditions than could be generated in the laboratory. Such changes had the effect of altering the balance between AFR-controlled $NO_x$ versus CO reduction in the first stage, or CO reduction versus $NO_x$ production in the second stage. Despite all these changes, Figures 5-11 and 5-12 show the average daily $NO_x$ and CO emissions to have stayed under the CARB 2007 DG limits from July to December 2010.

Occasionally, on-site field investigations were performed using AFR versus emissions sweeps to supplement the understanding of the system performance, or its degradation, beyond what could be derived from the systematic collection of data during normal operation. Figure 5-13 shows a $NO_x$/CO sweep investigation that was performed in August 2009. Note that such sweeps intentionally drive the AFR (as represented by the oxygen sensor's mV output) too lean and too rich, thus driving the $NO_x$ and CO out of compliance with the program goals. This method helps to define the range of operation that can achieve the limits and the $NO_x$/CO trade-offs. The intent of this August field effort was to complement data from the Testo portable emissions analyzer with traditional CEMS equipment operated by an independent and certified source test company, and to produce the first quantification of VOC emissions. Air X was contracted by Tecogen to perform the independent source test measurements consistent with the regulatory test requirements of the South Coast AQMD for permitting stationary power equipment in addition to recording data during the sweep tests presented in this report. Air X's primary equipment consisted of chemiluminescent and non-dispersive infrared analyzers for $NO_x$ and CO measurement, respectively. Other gas samples were collected in Tedlar bags for laboratory quantification of VOC emissions for each run condition. A third instrument, a LAND portable analyzer using chemical cells like the Testo, was also included in the measurement apparatus.

The two-stage after treatment sweep data in Figure 5-13 was generated by operating the AFR control in a mode that allowed test personnel to set the nominal AFR richer or leaner, as indicated by the heated exhaust gas oxygen (HEGO) sensor. Each condition was first stabilized, and then maintained for at least a five-minute sample period. The results were then averaged into a single data point for each condition. Figure 5-13 shows that the three data sources agreed reasonably well, especially between the Testo and the Air X CEMS equipment. The LAND device had a $NO_x$ offset that increased the overall $NO_x$ at each point, the interpretational influence of which was exacerbated by such low limits. In practical terms, though, the LAND data matched the trends of the other equipment very well.

**Figure 5-13: Field Investigation, NOx/CO Sweeps With Independent CEMS Verification**




Besides providing further confidence in day-to-day field test results, the Air X services provided Tecogen with the first verification that the after treatment's VOC emissions were also in compliance with CARB 2007 limits, as shown in Figure 5-14. The sweep in Figure 5-14 was conducted at an alternative exhaust configuration than the sweep of Figure 5-13, and consequently should have been subject to more difficult CO and VOC conversion conditions. Yet the data shows VOC emissions were well below the CARB limits even as AFR ratio was adjusted to richer conditions that drove the CO emissions out of compliance. These were critical findings since the program's semi-continuous Testo monitoring does not otherwise provide VOC data.

A cross-section of numerous sweeps that were performed at various times during the program is given in Figure 5-15. Each sweep set consists of a $NO_x$ and CO curve, with the lean boundary of the AFR compliance zone defined by high $NO_x$ and the rich boundary by high CO. The key attributes Tecogen surveyed from each sweep set included:

- the width of the compliance zone as bounded by CARB $NO_x$ and CO limits
- second-stage exhaust conditioning trade-offs between rich-bias NOx formation and improved CO reduction
- abnormalities in the general shapes of the sweep curves to identify system or instrument problems.

The individual conditions and circumstances that led to each profile in Figure 5-15 will not be explained in this report, except to further illustrate the type of field activities that were used to supplement regular data collection. As an example of general usefulness of the $NO_x$/CO sweeps, note on the CO plots in Figure 5-12 that the CO increased closer to the CARB limit in January 2011. The associated January $NO_x$ data in Figure 5-11 suggested the increase was not simply a function of the AFR control operating with a rich bias. In response, a field testing effort was initiated to perform emissions sweeps for $NO_x$/CO comparisons against earlier data. In Figure 5-15 there are four pairs of "Configuration A" $NO_x$ and CO sweeps plotted for time periods between July 23, 2010 and January 6, 2011. The shapes of these sweeps over time indicated a reduction of the width of the compliance window and a degradation of the best case $NO_x$/CO to be expected from the AFR controller. Thus by characterizing the after treatment performance with $NO_x$/CO sweeps, long term changes in the results from automatic semi-continuous sampling were, in some cases, more accurately interpreted as being dependent on catalyst condition rather than on the performance of the AFR control algorithms. There were other times when the results of such sweeps produced very strange results, leading Tecogen to the discovery that the portable emissions analyzer was starting to experience problems that required instrument repair.

**Figure 5-14: VOC Quantification During Emissions Sweep, Air X Data**

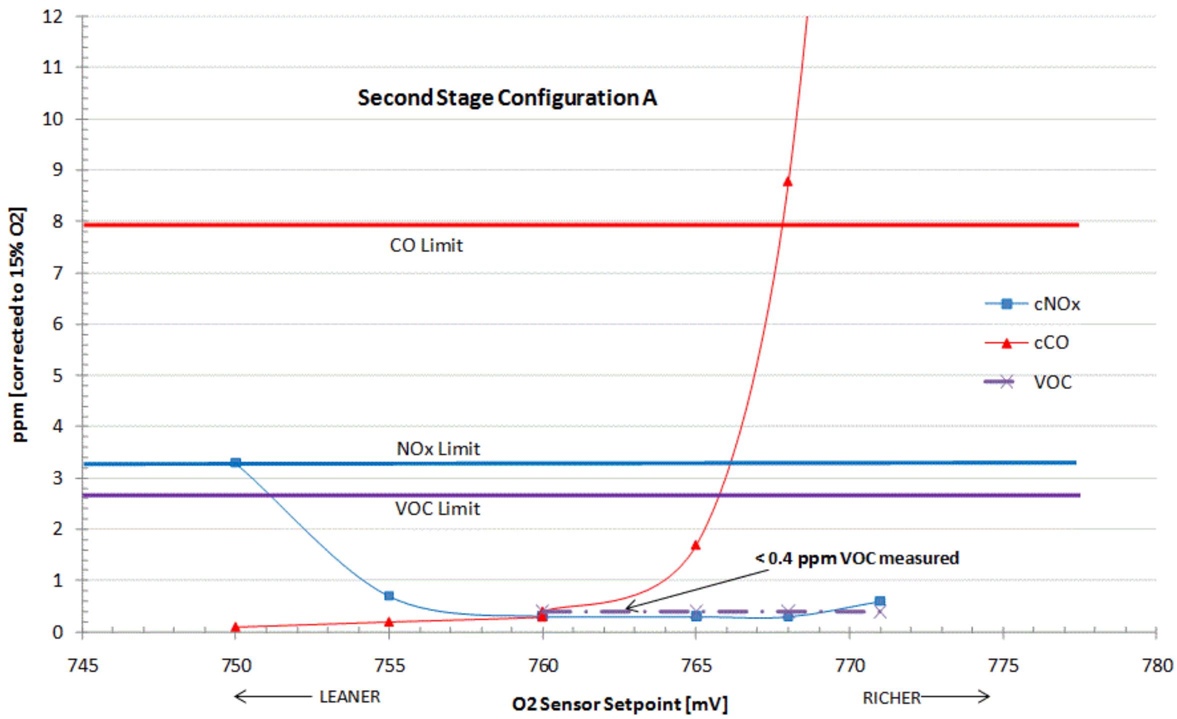
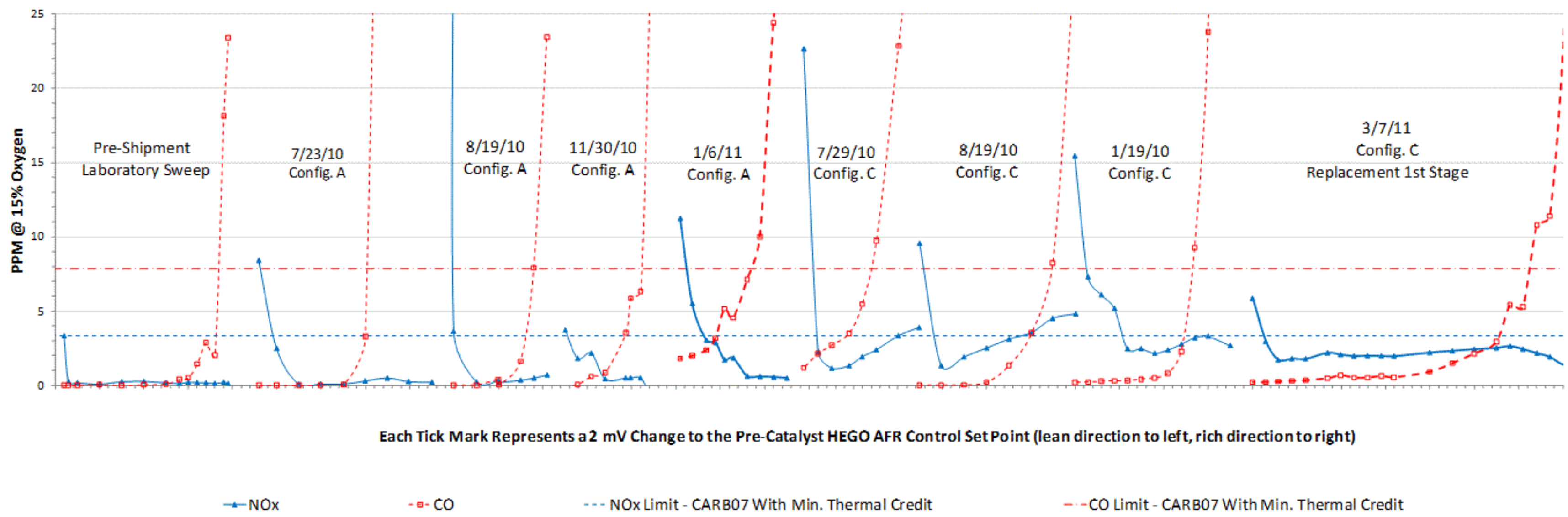


**Figure 5-15: Emissions Sweep Investigations over Time**



The consistency of CO compliance with CARB 2007 limits continued to decrease in January 2011. Also, the field investigations described above produced evidence that the results were degrading as a function of the exhaust after treatment rather than the AFR control algorithms or the engine, which was replaced in November 2010. Therefore, the decision was made to replace the first stage TWC February 10, 2011 despite the fact that the worst daily CO averages still represented about 99 percent catalytic reduction. However, replacing the TWC did not have the immediate effect of returning the system to operating well under the CARB limits as was the norm earlier in the program.

In February 2011, the system was modified to allow the second stage catalyst to operate at an alternative configuration. This was expected to reduce CO emissions at the expense of $NO_x$, but the CO reduction was dramatic. More importantly, the corrected CO reduction to < 1 ppm daily averages was distinctly improved from the system performance when the same conditions were in effect earlier in the program. A March 2011 field investigations produced the $NO_x$/CO sweep shown at the far right of Figure 5-15, which clearly indicated a definitive increase in the width of the AFR compliance window, even in comparison to the original assembly when tested in new condition at the laboratory (far left of the figure).

In March 2011, another configuration change was made with the intent of balancing the trade-off between $NO_x$ and CO. The effect was to provide an attractive reduction in $NO_x$ while maintaining the excellent CO performance. As of May 2011, the performance has continued to be excellent without any further manipulations of the AFR algorithms or set points, changes to the after treatment setup, or invasive field investigations. What really caused the distinct improvement in performance is not known. Installation of the new catalyst did not produce instantaneous benefit. The fact that the configuration change had directional effects on $NO_x$ and CO was not a surprise. Rather the surprise came from the magnitude of the effect given earlier data from the same engine. The second stage had, earlier in the program, operated at identical conditions to the configuration adjustment that resulted in the profound improvements and produced CARB 2007 compliant results, but not to the degree of what has been realized since February 2011. The most plausible explanation to date is that the original first stage catalyst was not adequately sealed and allowed enough raw emissions to slip passed the first stage that it affected the results of the second stage. The installation of the new catalyst could have resulted in better sealing, not immediately, but after some operational settling. Even this scenario, though, is compromised by the fact that the change occurred dramatically with a simple change to the second stage configuration.

Figures 5-16 and 5-17 display $NO_x$ and CO results over the entire SFP field test program using the perspective of all the individual two-minute sampling averages, comprised of over 23,600 sample averages. As the case was made earlier with the Rancho field test data, the daily averages of all two-minute data are the best indicator of the overall results, but the individual two-minute averages are also indicative of what the after treatment system may be doing at any particular time of day when a regulatory entity might perform an unannounced enforcement check of the system. What is most dramatic about Figures 5-16 and 5-17, is the performance of the system since February 16, 2011, shortly after the first stage catalyst was replaced and the configuration was changed. The CARB 2007 compliance rate, with the 60 percent total efficiency thermal credit, was 99.9 percent since that time based on over 7200 individual sample periods. It should be noted that around December 2010, when questions were being raised as to whether or not catalyst degradation was being observed, Tecogen turned the air injection off on two separate days. In Figure 5-17, these days are seen as two significant columns of CO increases above the CARB limits in the December time period. The purpose of turning the air injection off was to validate that the second stage catalyst was still performing a significant oxidation role. Clearly it was.

Even with no thermal credit applied to the CARB 2007 limits, the compliance rate has been 99.9 percent over the 3900 sample averages taken since April 1, 2011, after the final operating parameter modification was made to the second stage catalyst (Figures 5-18 and 5-19). The intent of that modification was to strike the final balance between $NO_x$ and CO goals for best compliance with the CARB limits without the benefit of a thermal credit. These results are significant and promising for the two-stage after treatment concept.

Plotting all two-minute averages provides a compelling visual reference for the evolution in system performance that occurred, but this representation also has limits. Most importantly, the thousands of data points that are below the limits get visually lost because of plotting overlap while the number of points above the limits stand out. The histogram plots in Figures 5-20 and 5-21 supplement the two-minute average data by classifying the percentage of time the two-minute $NO_x$/CO averages fell within distinct compliance categories for CARB 2007 and SCAQMD Rule 1110.2, respectively. The histograms were divided into three field test periods. Period #1 is based on the first seven months of operation and does not differentiate between various AFR settings or second-stage catalyst configurations. This is the period that would be the most difficult to interpret through Figures 5-16 and 5-17, other than to say the performance was not as consistent as it was in the latter stages of the program. Period #1 demonstrated very high compliance frequency, about 89 percent compliance with CARB limits and 94 percent with Rule SCAQMD Rule 1110.2 limits (each with minimum thermal credit). Period #2 starts with the February 2011 system modification to Configuration B. The last histogram period includes the data from the end of March 2011 when the second-stage was modified to Configuration C.

**Figure 5-16: SFP Field Test $NO_x$ History, Two-Minute Sample Averages**

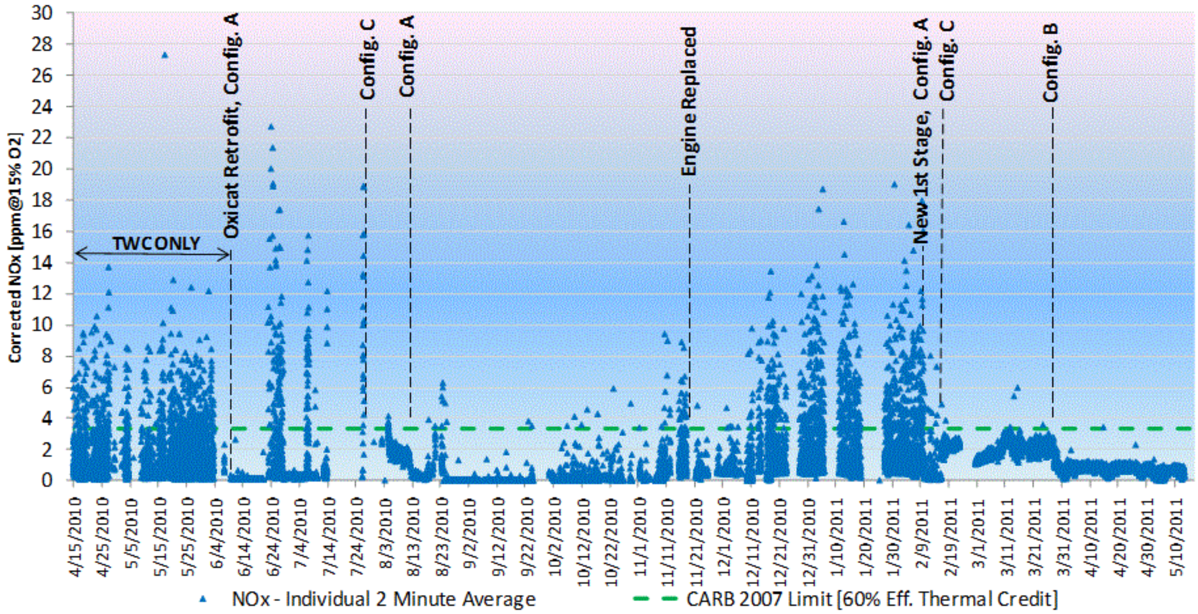



**Figure 5-17: SFP Field Test CO History, Two-Minute Sample Averages**

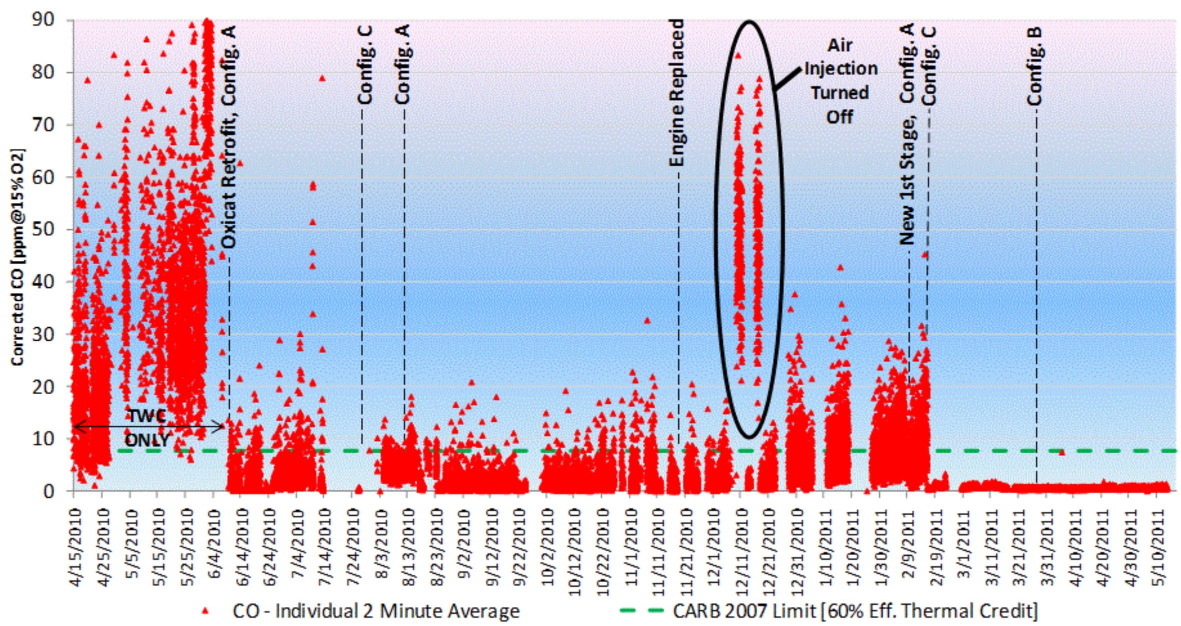


**Figure 5-18: $NO_x$ History After Last After Treatment Configuration Change (3/28/11)**

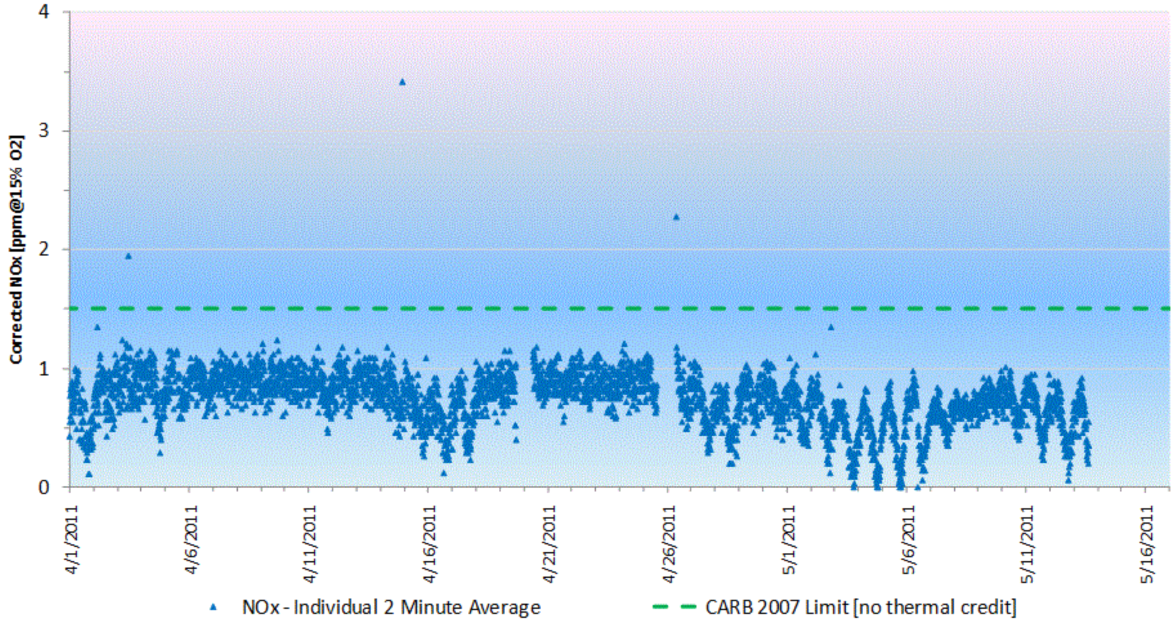



**Figure 5-19: CO History After Last After Treatment Configuration Change (3/28/11)**

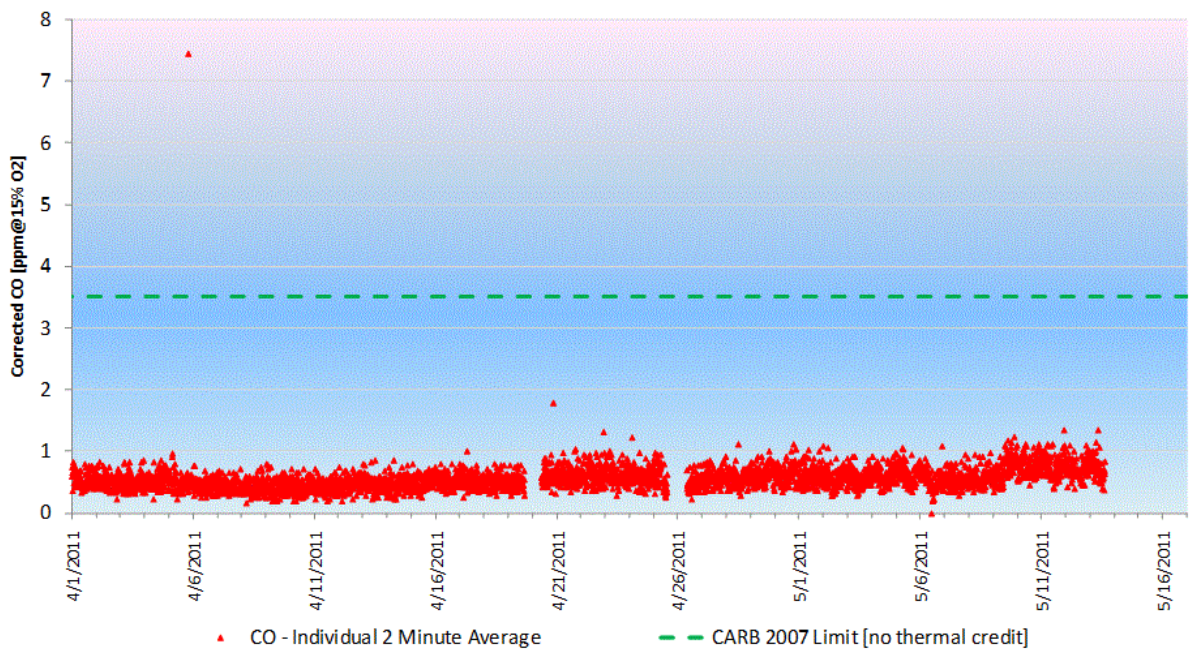


**Figure 5-20: CARB DG Limit Compliance Histogram for SFP Field Test**

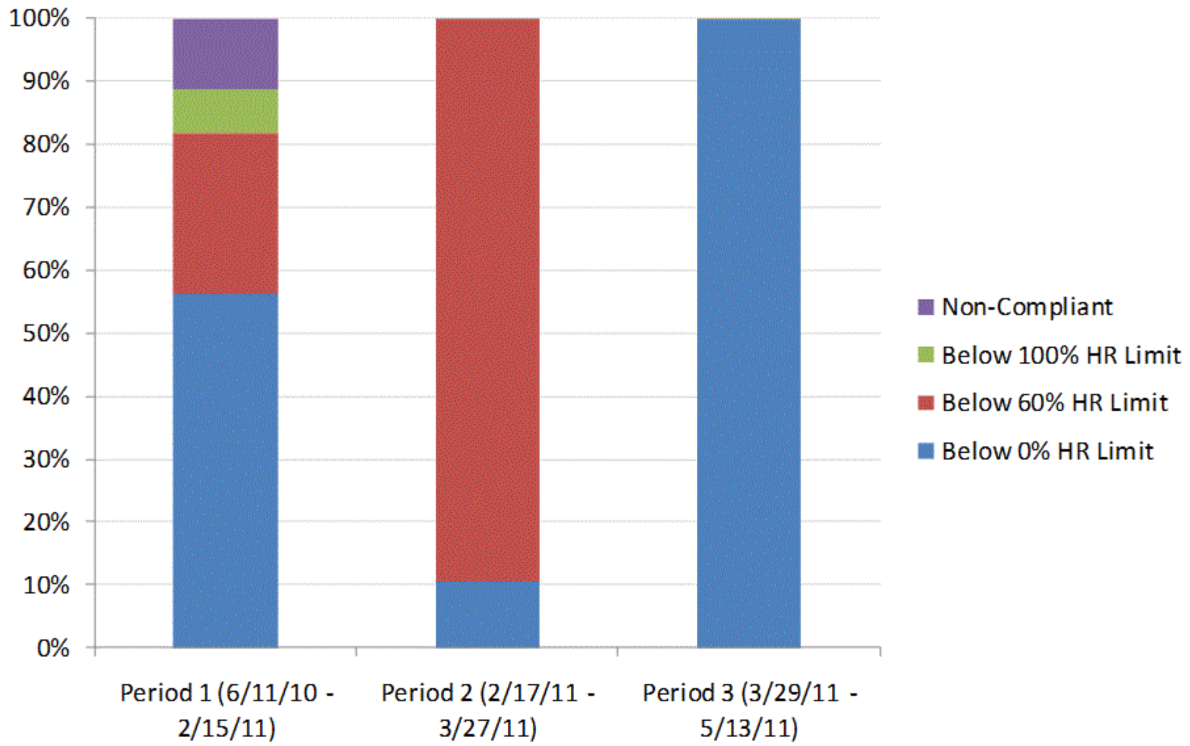
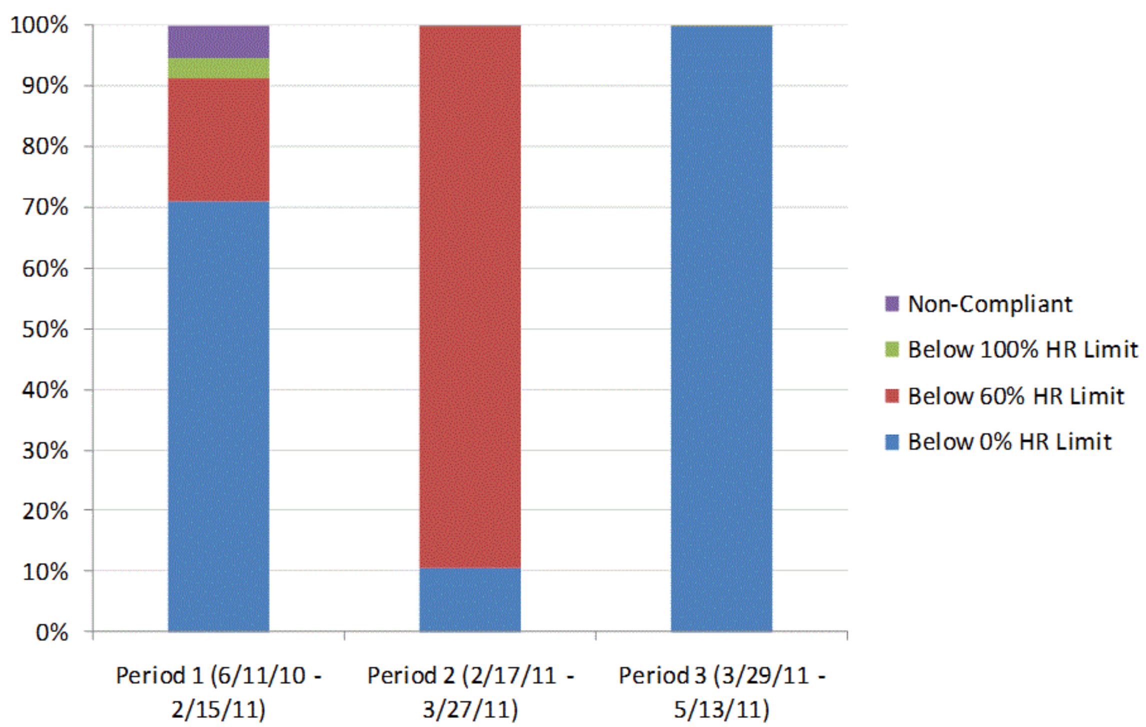



**Figure 5-21: SCAQMD Rule 1110.2 DG Limit Compliance Histogram for SFP Field Test**



## 5.3 Conclusions

Tecogen performed long-term field monitoring of the emissions from two CHP customer host sites retrofitted with enhanced exhaust after treatment equipment designed and laboratory tested to be capable of achieving the CARB 2007 Distributed Generation limits. The Rancho San Antonio Boys Home field demonstrated the capabilities of a traditional TWC assembly in a test period that lasted from July-November 2009. The San Fernando Municipal Pools field test began collecting data from a two-stage after treatment approach in June 2010 and continued to demonstrate positive results through the writing of this report in May 2011. The conclusions from the field test program are listed below.

1. The traditional TWC approach with a DCL TWC could not produce CARB compliant emissions, assuming a maximum CHP thermal credit, for more than a few months of engine operation (~1838 hours), despite the total catalyst volume being oversized by 50 percent according to DCL's most aggressive product sizing performance predictions.
2. It is reasonable to suspect the DCL performance degradation was somewhat accelerated by exhaust gas operating temperatures that were always near, and frequently over, DCL's commercial operating limit of 1250°F (677°C). Tecogen's INV-100 post-catalyst exhaust temperatures were commonly 1260-1280°F (682-693°C) over the course of the monitoring period. Therefore, this report does not conclude that a traditional TWC approach cannot achieve the limits over a commercially viable term. Rather, such an approach did not produce long-term success during the RSA field test.
3. The two-stage after treatment approach, with supplemental oxidation reactions provided by air injection and additional catalyst material downstream of a traditional TWC, as well as a proprietary strategy for exhaust conditioning, has produced promising results for CARB DG compliance on Tecogen's 75 kW product at San Fernando Municipal Pools.
4. Performance conclusions are most appropriately described for the time period starting March 28, 2011, after which no corrective or investigative modifications have been made (the first stage TWC was replaced in February 2009).
5. Since March 28, 2011, over 3900 two-minute emissions samples have been recorded and 99.9 percent of the $NO_x$/CO samples have been compliant with CARB 2007 DG limits, even without the CHP thermal credit. This is a testament to both the two-stage catalyst approach, which widens the tight AFR compliance window, and Tecogen's AFR control algorithms, which must still maintain very tight and consistent AFR control.
6. Testing at SFP has demonstrated that VOC emissions from the two-stage after treatment are also CARB 2007 compliant and are less of a challenge than CO emissions.
7. Monitoring continues beyond the dates covered by this report and will be critical towards understanding the prospects or limitations of the two-stage approach.

However, Tecogen's overall perception of the performance is best illustrated by the fact that three new 100 kW CHP modules have been shipped to Northern California equipped with this new approach.

# CHAPTER 6: Technology Transfer

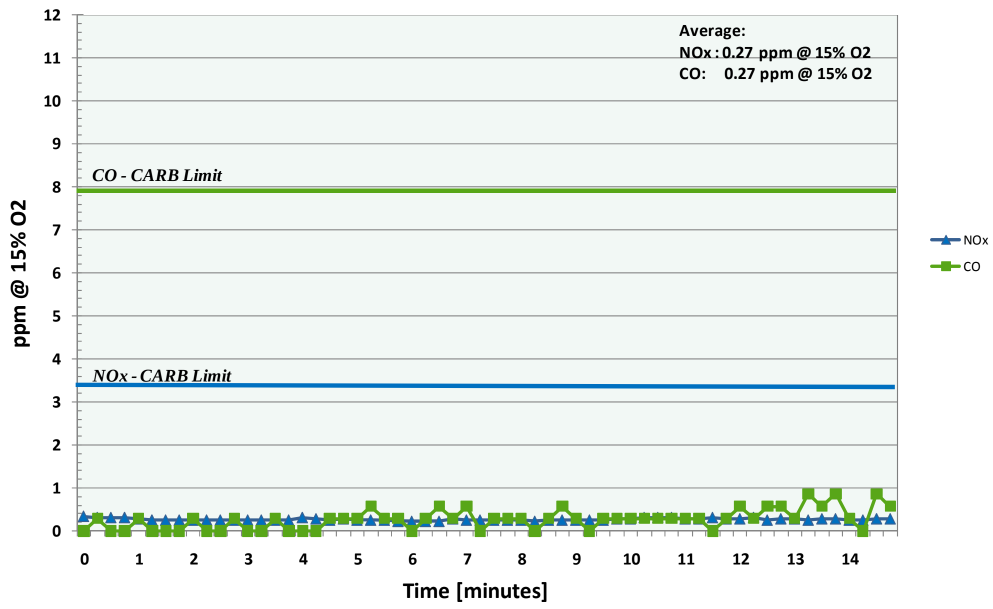
## 6.1 Ultra-Low Emission Products

Tecogen's 100 kW Premium Power CHP unit which was commercialized in 2008 and named the InVerdẽ 100 (Figure 6-1) was considered to be the best choice of the Tecogen products for the initial commercial application of the advanced emissions control system. It already contained Tecogen's most recent innovations in emission control technology, including AFR control using pre- and post-catalyst oxygen sensors. The InVerdẽ 100 represents the future in CHP technology for Tecogen in California and elsewhere, which makes it an ideal platform for introducing the ultra-low emissions technology.

**Figure 6-1: In Verde 100**


In late 2010, assured by thousands of hours of successful field operation at the San Fernando site, Tecogen advanced the commercialization effort of the ultra low emissions system with its implementation on three InVerde 100 kW CHP units for a demonstration project for SMUD (Sacramento Municipal Utility District). With support from the CEC, this project is for the implementation of a 300 kW base-loaded Microgrid at the utility's headquarters in Sacramento, CA. It was considered an excellent high-visibility stage to showcase this innovative emission control technology.

**Figure 6-2: Emission Data**




Adaptation of the ultra low emissions system to the InVerde product required the inclusion of some additional components, as well as packaging modifications. Each unit had to undergo a factory test prior to shipment, where an industry-

standard fifteen minute emissions test, was also incorporated. The results of these emission tests showed robust compliance with CARB 2007. Representative data from one of the SMUD units is shown in
Figure 6-2. This graph shows the emission levels of both NOx and CO (regulated pollutants) versus time. The measurements are well below the CARB compliance limits, with the averages nearly zero.

**Figure 6-3: InVerdẽUltra100**


In late 2011, Tecogen plans to formally introduce, and brand the model equipped with the new emissions technology, as the InVerdẽ®Ultra100 (Figure 6-3). It will be the first and only natural gas engine-driven CHP system able to operate below CARB 07 and SCAQMD regulated pollutant levels. The InVerdẽUltra100 emissions not only meet, but exceed the stringent CARB 2007 regulations.

With the development of the InVerdẽUltra100, Tecogen improves upon CHP technology leaving an even smaller ecological footprint. The cost premium for the InVerdẽUltra100 is estimated at $3,000 or less than 3 percent of the cost of a currently available InVerde 100 unit. In addition to the Premium Power InVerdẽ CHP module, Tecogen has induction-based, 75 kW and 60 kW electrical generation CHP products. In fact, the San Fernando field test system was implemented on a CM-75, so the technology has already been proven on this model. The hardware packaging and adaptation is very similar to the InVerdẽ, so the ultra low emissions technology is also expected to be available for the smaller CHP product line in 2011.

An effort is also underway to incorporate the advanced emission control system into the chiller product line (50 – 400 Tons). Tecogen has also developed a prototype heat pump heating module, using a small 2.3 L Ford engine that will also include this technology.

## 6.2 Target Markets

Tecogen's ultra-low emission technology, although developed initially for the InVerdẽUltra100, can be cost effectively applied to nearly all stationary rich burn engines – new and old. Even on retrofit and new systems not requiring CARB 07 emission performance, this technology is much more forgiving and provides compliance assurance without the expense and nuisance of frequent measurements with a portable emission analyzer. Rich burn engines are dominant in sizes < 1 MW and are commercially available in sizes up to 1.5 MW. With multiple engines per site, rich burn engines can easily serve applications up to 5 MW. The markets for engine CHP systems < 5 MW in size are abundant and span a variety of applications including hospitals, nursing homes, recreation, multi-unit housing, schools, colleges, military, and light industrial facilities. In addition, there is a plentiful market for engine driven gas compression, water pumping, chillers and refrigeration equipment.

The CEC funded CHP Market Assessment identified the remaining CHP technical market potential and the projected market penetration from 2010 through 2029 based on proactive State legislative and regulatory support. The results for CHP system sizes up to 5 MW are summarized in Table 6-1.

**Table 6-1: New CHP Applicable Market**

| | 50-500 kW | 0.5-1 MW | 1-5 MW | Total < 5 MW |
|---|---|---|---|---|
| Remaining Technical Potential (MW) | 5,020 | 1,787 | 4,084 | 10,891 |
| Projected Penetration 2010-2029 (MW) | 684 | 454 | 1,279 | 2,417 |
| Est. Percent Rich Burn Engines (MW basis)[11] | 75% | 75% | 50% | 62% |
| Rich Burn Engine Penetration (MW) | 513 | 340 | 640 | 1,493 |
| Est. Number of Rich Burn Engines[12] | 2,500 | 480 | 320 | 3,300 |

With cost effective emission technology, the projected California market for new rich burn engines over the next twenty years is quite large.

The existing engine population is also sizeable. SCAQMD data on natural gas stationary engines with permit applications in process, permits to construct and permits to operate, is recapped in Table 6-2. Per Southern California Gas Company[13], there are 565 operating rich burn engines in SCAQMD. With approximately 40 percent of the State's population residing in SCAQMD territory, a rough estimate of the State-wide stationary rich burn engine population was extrapolated based on population. This significant engine population is potentially addressable with the subject advanced emission technology.

[11] Rough estimate of rich burn engine penetration (2010–2029) developed by DE Solutions.

[12] Based on assumed average engine size of 200 kW in the 50-500 kW size range, 700 kW in the 500 kW-1 MW range, and 2 MW in the 1-5 MW range

[13] Conversation with Steve Simons, Southern California Gas Company, on June 1, 2011

These engines are used in a variety of applications including CHP, municipal water pumping, agricultural water pumping, natural gas compression, chillers and refrigeration.

**Table 6-2: Existing Population of Rich Burn Engines**

| | Number of Engines | | |
|---|---|---|---|
| Size | SCAQMD<br>Natural Gas | SCAQMD<br>Rich Burn | California<br>Rich Burn |
| 50-500 hp | 413 | 380 | 950 |
| >500 hp | 266 | 185 | 460 |
| Total | 679 | 565 | 1,410 |

## 6.3 Commercial Deployment

### 6.3.1 Commercial Deployment Challenges

A number of regulatory, institutional and market barriers encumber this game changing technology from realizing its full potential. These barriers are noted below:

- Perception among State/local governments and Air Districts that engines have inherently higher emissions than other DG technologies
- Cost of emission permitting and maintaining emission compliance for small engines in California and in particular SCAQMD
- No CARB certification opportunity (even if only voluntary) for Tecogen existing and planned engine products (CHP, heat pump, chillers)
- Technology uncertainty and lack of sales, distribution and implementation wherewithal for non-Tecogen engine products
- Traditional CHP barriers confronting small CHP
  - Complicated grid interconnection requirements and approval process
  - Utility rate treatment harsher than that for renewables, fuel cells and efficiency
  - Absence of State incentives and Portfolio Standard for CHP in comparison with renewables, fuel cells, energy efficiency and demand response measures
  - Perceptions that engines are not reliable and lack high overall efficiencies in practice

### 6.3.2 Commercial Deployment Solutions

A patent has been applied for to safeguard technology rights and know-how of the two stage catalyst technology. The patent application is expected to be published in November 2011, at which time public disclosure would commence. Technology Transfer Activities include:

- Technology verification
    - Continued monitoring of the CM-75 unit operating at San Fernando Pools
    - Close monitoring of the INV-100 products shipped to SMUD and other INV-100 retrofits in California
    - Select and engage partner(s) to develop and test retrofit technology for non-Tecogen engine applications
- Selective outreach on technology and field results until patent application goes public
    - California Energy Commission
    - SCAQMD
    - Southern California Gas Company
    - Sacramento Municipal Utility District
- Once the patent application is published, an extensive outreach program will commence. Target audiences include:
    - State Government – CEC, CARB, CPUC, Governor's Office, Legislature
    - Local Government – Air Districts, Cities and Counties
    - U.S. EPA and DOE
    - Utilities
    - Prospective End Users
    - Prospective partners
    - Technology sector investors
- Outreach media tools
    - Power Point Presentations
    - White Paper(s)
    - Exhibits
    - Press Releases
    - Videos
    - Demonstration sites
- Outreach Forums
    - One-on-one meetings
    - AEE Energy Management Congress and Exhibit
    - SCG Energy Resource Center Workshops
    - PG&E Energy Center Workshops
    - California Center for Sustainable Energy (CCSE) Workshops

- DOE Pacific Region Clean Energy Application Center (PCEAC) Workshops
- American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Conference and Exhibit
- Power Generation Conference and Exhibit
- Gas Machinery Conference and Exhibit
- CHP Advocacy to improve the climate for CHP
- California Clean DG Coalition (CCDC)

### 6.3.3 Tecogen Product Launch

The InVerdẽUltra[100] product with the advanced emission feature will be commercially introduced in the fall of 2011. The InVerdẽUltra[100] unit will first be made available in California with select Northeast States (Massachusetts, New York & New Jersey) to follow.

Tecogen's existing CHP and engine chiller sites in California will be retrofitted with the second stage catalyst. Even though CARB 07 is not applicable to existing systems permitted under BACT regulations, the second stage catalyst adds assurance that the units are staying in compliance with the BACT requirements. There are over 100 such units currently operating in California.

New Tecochill products (engine driven chillers) and the engine driven heat pump under development will be outfitted with the two stage catalyst technology.

### 6.3.4 Non-Tecogen Products

The primary target for non-Tecogen products will be retrofits for the existing engine population in California. A strategic partner(s) will be sought with existing connections to California's engine market. Prospective partners include aftermarket engine control companies such as Woodward and Continental Controls Corporation. Specialty catalyst suppliers such as Miratech and DCL are other possibilities. Cost effective application of the ultra-low emission technology for retrofit to operating non-Tecogen engines will be assessed, and if deemed feasible, will be developed and tested in the field.

The engine OEMs, such as Waukesha and Caterpillar, will be approached about adding an ultra emission control option to their rich burn product lines and/or making the technology available to their regional dealers for new CHP systems and field retrofits.

### 6.3.5 Independent Verification of Technology

Tecogen felt a third-party verification of the technology was a critical step in supporting the patent's premise, as well as a necessary course in the commercialization process. The AVL California Technology Center was selected to perform the independent verification test. , AVL is the world's largest privately owned and independent company involved in the development of powertrain systems that employ internal combustion engines, as well as instrumentation and test systems. Their dynamometer test cell is equipped with a state-of-the-art Continuous Emissions Monitoring System (CEMS). AVL completed this testing in May 2011, successfully confirming Tecogen's results.

# CHAPTER 7: Conclusions and Recommendations

## 7.1 Conclusions

The project met its goals of developing, testing, and demonstrating an ultra clean emissions technology for rich-burn engine CHP systems that exceeds California Air Resources Board Distributed Generation limits. Furthermore, the after treatment strategy developed during this project has succeeded Tecogen's original commercial after treatment strategy, due to its demonstrated effectiveness, and has already been integrated into new CHP product shipments. The project team's conclusions are highlighted below. These findings address the two rich-burn after treatment strategies tested in the laboratory and evaluated during subsequent field tests. The first strategy relied upon robust single-stage TWC after treatment, with the catalyst volume sized by the manufacturer to achieve CARB limits. The second strategy, developed in the laboratory, involves a novel two-stage strategy that supplements the traditional TWC with an air-assisted oxidation catalyst operating at low temperature.

*Single-Stage Strategy:*

1. Adding 50 percent more TWC volume to a baseline system sized to achieve conventional BACT limits in California , yields very little additional emissions benefit. Yet with the DCL TWC, the incremental benefit of the additional 50 percent catalyst volume was just enough for Tecogen's 100 kW platform to achieve stable compliance with the CARB limits in the laboratory and justify subsequent field testing.
2. Although additional TWC volume produced CARB compliant results, laboratory AFR sweep testing showed the window of compliance, as a function of HEGO mV, was substantially smaller against the CARB limits than against the non-DG BACT limits. This is due to the mutually opposing natures of NOx and CO conversion efficiencies as a function of AFR, and the asymptotic nature of TWC conversion efficiencies as a function of the residence time of the exhaust in the catalyst (such as space velocity). This suggests that long-term CARB compliance with a single-stage strategy would not just be a case of providing sufficient catalyst, but of also operating the AFR control with even less control flexibility.
3. Regardless of AFR control and tuning, the single-stage after treatment field test could not produce CARB compliant emissions, assuming a maximum CHP thermal credit, for more than a few months of engine operation (~1838 hours). Degradation of the results was observed within three weeks of operation.

4. It is reasonable to suspect the DCL performance degradation was somewhat accelerated by exhaust gas operating temperatures that were always near, and frequently over, DCL's commercial operating limit of 1250°F (677°C). Tecogen's INV-100 post-catalyst exhaust temperatures were commonly 1260-1280°F (682-693°C) over the course of the monitoring period. Therefore, this report does not conclude that a traditional TWC approach cannot achieve the limits over a commercially viable term. Rather, such an approach did not produce long-term success applied to Tecogen's engine during the RSA field test. Despite this caveat, the laboratory findings in Conclusions #1-2 still stand, and highlight challenges for the traditional single-stage TWC approach at the CARB DG levels.

*Two-Stage After Treatment Strategy:*

5. Tecogen's two-stage after treatment strategy demonstrated significant widening of the CARB compliant AFR control band in comparison to an equal volume of TWC operated under the single-stage approach.
6. The widening of the AFR control window is achieved with the air-assisted second stage catalyst, which provides significant CO reduction in rich-biased regions that would otherwise be non-compliant for CO. The two-stage approach dates back to vehicle applications in the 1980's. However, the conventional two-stage strategy died out as it could not comply with more progressive automotive emissions limits. Furthermore, Tecogen's testing showed the conventional two-stage strategy could not achieve typical California non-DG BACT limits, and especially not CARB DG limits, without significant modification.
7. The San Fernando Pools field test of the two-stage strategy continues to produce CARB compliant results (without thermal credit) as of June 14, 2011, although the data in the various figures in this report and general performance discussions only cover the period ending May 13, 2011.
8. Performance conclusions are most appropriately described for the time period starting March 28, 2011, after which no corrective or investigative modifications have been made (the first stage TWC was replaced in February 2011).
9. Since March 28, 2011, over 3900 two-minute emissions samples have been recorded and 99.9 percent of the $NO_x$/CO samples have been compliant with CARB 2007 DG limits, even without the CHP thermal credit. This is a testament to both the two-stage catalyst approach, which widens the tight AFR compliance window, and Tecogen's AFR control algorithms, which must still maintain very tight and consistent AFR control.

10. Testing at SFP has demonstrated that VOC emissions from the two-stage after treatment are also CARB 2007 compliant and are less of a challenge than CO emissions.
11. For these ultra-low levels of emission control, a low cost on-board diagnostics method for discerning between compliant and non-compliant catalyst performance was not found. This is not to say Tecogen's use of pre-catalyst and post-catalyst (first stage) oxygen sensors and thermocouples cannot offer diagnostic clues to abnormal operation, but no self-diagnostic compliance monitoring algorithms were developed during this project.
12. Tecogen's integration of a Testo 350XL portable emissions analyzer into the CHP system's automatic data retrieval process and implementation of semi-continuous emissions monitoring provided exceptional insight into day-to-day performance of both field test units.

## 7.2 Recommendations

1. Continue semi-continuous monitoring of the San Fernando Pools field test unit. The SFP unit continues to demonstrate CARB compliant results as of June 14, 2011, but the second-stage configuration that has produced the most exceptional results has only been in place since March 28, 2011, less than three months. Although Tecogen has already sold new 100 kW CHP products configured with the two-stage strategy, none have been commissioned yet. Clearly, the on-going tracking of the SFP performance is of critical value to Tecogen to determine the effective lifetime of the catalysts before substrate cleaning or replacement is required. Tecogen's implementation of semi-continuous monitoring produces far superior data to that of periodic emissions monitoring due to its ability to show when changes in system performance occur, and at what rate.
2. Eventually reinstall the first stage TWC that was removed from SFP February 10, 2011. The original first stage TWC was removed in February, after eight months of operation, in response to decreasing CARB compliance consistency. Although original first stage was thought to be demonstrating signs of general catalyst degradation, the installation of a replacement first stage TWC did not immediately demonstrate tangibly improved results. Later, the emissions results suddenly improved when the second stage was reconfigured, but the results were far superior to what had been achieved earlier in the program under similar conditions with the original first stage catalysts. In other words, the cause and effect does not appear to have been the replacement catalyst itself, but perhaps the sealing of the catalysts. If the original catalysts were reinstalled with particular attention to sealing within the housing, and these catalysts were to

demonstrate performance similar to what is currently being achieved, then Tecogen would instantly jump forward in its understanding of the potential operating lifetime of the two-stage concept.

3. Demonstrate the two-stage concept with the second stage configured with a true oxidation catalyst. To date, Tecogen's efforts have demonstrated the two-stage after treatment concept using identical TWC products in both stages. Tecogen can expect to realize cost savings by installing only palladium and/or platinum load catalysts, instead of TWC, which contain rhodium as well. No performance differences are expected, but this should be verified.
4. Develop and deploy retrofits for non-CHP Tecogen products. This process would demonstrate the performance versus cost implications of the two-stage strategy over a broader array of Tecogen engine products, ones that would be less cost effective than CHP. The operating cost information would be critical for regulators and end-users to understand.
5. Demonstrate the efficacy of this technology to non-Tecogen stationary engine products, both CHP and mechanical drive systems.
6. Evaluate the long term performance of the traditional TWC strategy on an engine that does not operate so close to, or over, the TWC manufacturer's maximum temperature specifications. Short-term laboratory testing clearly demonstrated the two-stage after treatment advantage of widening the AFR compliance window, but it would be inappropriate to declare single-stage performance as incapable of being a CARB compliance option on all engines based on Tecogen's field test. Although Tecogen's impression is that a distinct advantage will remain with the two-stage strategy, a test that operates a single-stage TWC farther away from the product's maximum temperature limits would provide better support for this conclusion.
7. Research alternative platinum group metal formulations in the overall two-stage after treatment design. Regarding the first-stage assembly, research the effects of loading the first-stage catalyst with rhodium as the only precious metal. TWC are loaded with rhodium for best NOx reduction and platinum, palladium, or both for best oxidation reactions. The two-stage catalyst approach reduces the oxidation burden on the first stage. It is possible that the two-stage approach could become more cost effective by loading the first stage with rhodium only, leaving the second-stage to perform the bulk of oxidation reactions rather than just second-order CO and VOC oxidation. It is also possible this approach may exceed the capabilities of the low-temperature second-stage. Regarding the second stage, research the performance of different oxidation promoter loading configuration options such as platinum-only, palladium-only, and combinations of the two.

8. Continue dithering and UEGO investigations as a method to improve the consistency of AFR control as a function of age. The two-stage catalyst approach widens the air/fuel ratio window that will still achieve a specified NOx and CO regulation in comparison to a single-stage approach. However, any technique that decrease the margin of error in operating air/fuel ratio, can lead to further improvements in the flexibility of the two-stage approach. As mentioned above, ammonia production in the first-stage decreases the operating flexibility of the second-stage. Dithering has been observed to reduce ammonia production in three-way catalysts. Ammonia production is also a function of air/fuel ratio, regardless of whether the AFR strategy uses dithering or steady-state control. Therefore, tighter control of air/fuel ratio, perhaps via the use of UEGO sensors, can reduce the tendency for ammonia production and increase the allowable operating temperature of the oxidation catalyst.

## 7.3 Public Benefits

CHP provides numerous benefits to California ratepayers:

- Provides ultra high natural gas use efficiencies, conserving natural gas resources and enhancing utilization of California's gas distribution system
- Achieves combined electric and thermal efficiencies of 80 percent or more.
- Reduces Greenhouse Gas (GHG) emissions from conventional fossil energy sources
- Eliminates transmission and distribution losses, Reduces or eliminates grid congestion
- Provides commercial, institutional, industrial and multi-family residential energy users with an option to curb energy costs
- Boosts power reliability for business adopters

Engines are the most cost effective CHP technology less than 5 MW in size. With a cost effective emission control solution for engines and proactive state policies toward CHP, engines are expected to account for approximately 1,500 MW of new CHP in California over the next twenty years[14]. This equates to avoided $CO_2$ emissions of about 1.6 million metric tons (MMT) and avoided natural gas consumption of 23 trillion BTU in 2029.

[14] Estimate based on the 2009 California Energy Commission report *Combined Heat and Power Market Assessment*

# GLOSSARY

| | |
|---|---|
| AFR | Air-to-Fuel Ratio |
| AFRC | Air Fuel Ratio Controller |
| CARB | California Air Resources Board |
| CARB 2007 | CARB emission guidelines for Distributed Generation |
| CEC | California Energy Commission |
| CHP | Combined Heat and Power |
| CO | Carbon Monoxide |
| EGO sensor | Exhaust Gas Oxygen sensor |
| EHRU | Exhaust Heat Recovery Unit |
| EPA | US Environmental Protection Agency |
| Equivalence | (Stoichiometric AFR)/(Actual AFR), symbolized by the Greek symbol, phi ($\phi$) |
| HEGO sensor | Heated Exhaust Gas Oxygen sensor, also known as a narrow-band oxygen sensor |
| HHV | Higher Heating Value |
| ICE | Internal Combustion Engine |
| kW | kilowatt |
| Lambda | (Actual AFR)/(Stoichiometric AFR), symbolized by the Greek symbol, Lambda ($\lambda$) |
| MAP | Manifold Absolute Pressure |
| NOx | Nitrogen Oxide (NO) and Nitrogen Dioxide ($NO_2$) |
| OEM | Original Equipment Manufacturer |

| | |
|---|---|
| OSC | Oxygen Storage Capacity |
| PCS | Power Conditioning System |
| PID | Proportional, Integral, and Derivative mathematical functions used in process control |
| PIER | California Energy Commission’s Public Interest Energy Research (PIER) Program |
| PMG | Permanent Magnetic Generator |
| RMCS | Remote Monitoring and Control System |
| SCAQMD | South Coast Air Quality Management District |
| THC | Total Hydrocarbons |
| TWC | Three-Way Catalyst |
| UEGO sensor | Universal Exhaust Gas Oxygen sensor, also known as a wide-band oxygen sensor |
| VOC | Volatile Organic Compounds |
| WC | Water Column |

# REFERENCES


Alexio, Joe, Ming Chen, Thierry Leprince, Shazam Williams. *A Predictive Model For Catalytic Converters on Stationary Power Internal-Combustion Engines, Paper no. 226*, presented at the International Council on Combustion Engines. Kyoto, Japan, 2004.

Cornellius, Stephen J. *Modeling and Control of Automotive Catalysts*, PhD. Dissertation, Sidney Sussex College, University of Cambridge. 2001.

Heywood, John B. *Internal Combustion Engine Fundamentals*. Chapter 11. McGraw-Hill, 1988.

Kojima, Mike. *Air-Fuel Meter Shootout*. FordMuscle magazine. June 2007

Toema, Mohamed A. *Physics-Based Characterization of Lambda Sensor Output To Control Emissions From Natural Gas Fueled Engines*, PhD. Dissertation, Kansas State University. 2010.