



Orange County Sanitation District

10844 Ellis Avenue • Fountain Valley CA 92708-7018

Retrofit Digester Gas Engine with Fuel Gas Clean-up and Exhaust Emission Control Technology

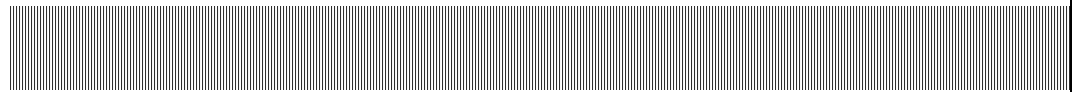
South Coast Air Quality Management District Contract #10114

Pilot Testing of Emission Control System Plant 1 Engine 1

Orange County Sanitation District Project No. J-79

FINAL REPORT

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Glossary of Terms

<u>Acronym</u>	<u>Definition</u>
ARB	Air Resources Board
AQMD	Air Quality Management District
BACT	Best Available Control Technology
bhp	Brake horse power
CEMS	Continuous emissions monitoring systems
CI	Compression Ignition
CO	Carbon monoxide
CO ₂	Carbon dioxide
Cpsi	Cells per square inch
°C	Degrees Centigrade
°F	Degrees Fahrenheit
DG	Digester Gas
DGCS	Digester Gas Cleaning System
EPA	Environmental Protection Agency
FTIR	Fourier Transform Infrared
GC/MS	Gas chromatography-mass spectrometry
H ₂ S	Hydrogen sulfide
HHV	Higher Heating Value
HI	Hazard Index
hp	Horse power
HRU	Heat Recovery Unit
IC	Internal Combustion
in. w.c.	Inches water column
KW	Kilowatt
MDL	Method Detection Limit
MMscf	Million standard cubic feet
MW	Megawatts
N ₂	Nitrogen
NG	Natural Gas
NMHC	Non-methane hydrocarbons
NMNEOC	Non-methane non-ethane organic compounds
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides
O ₂	Oxygen
OCSD	Orange County Sanitation District
PEMS	Parametric Emission Monitoring System
PM	Particulate matter
ppbv	Parts per billion by volume
ppm	Parts per million
ppmv	Parts per million by volume
psig	Pounds per square inch gage
RPM, rpm	Revolutions per minute
SCAQMD	South Coast Air Quality Management District
SCAT	Synthetic gas matrix catalyst activity test
scfm	Standard cubic feet per minute

<u>Acronym</u>	<u>Definition</u>
SI	Spark-ignited
VOCs	Volatile organic compounds
XRF	X-ray fluorescence



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Executive Summary

The Orange County Sanitation District (OCSD) owns and operates two wastewater treatment plants in Orange County, California, Reclamation Plant No. 1 (Plant 1) in Fountain Valley and Treatment Plant No. 2 (Plant 2) in Huntington Beach. Each plant operates a Central Power Generation System (CGS) to produce electrical power for the plant operations using large digester gas-fired internal combustion (IC) engines. Plant 1 has three (3) 2.5-megawatt (MW) internal combustion (IC) engines and Plant 2 has five (5) 3-MW IC engines, fueled primarily by digester gas (a biogas) and supplemented by small amounts of natural gas.

Plants 1 and 2 are within the jurisdiction of the South Coast Air Quality Management District (SCAQMD). SCAQMD has established regulations aimed at reducing and controlling air emissions from combustion sources, such as the engines at the plant CGS, including Rule 1110.2 *Emissions from Gaseous and Liquid-fueled Internal Combustion Engines*. In February 2008, SCAQMD amended Rule 1110.2, lowering the emission limits for nitrogen oxides (NO_x), volatile organic compounds (VOCs), and carbon monoxide (CO) for IC engines. The amended rule also requires biogas-fueled engines to meet new lower NO_x, CO, and VOC emission limits effective July 2012.

In April 2008, OCSD engaged Malcolm Pirnie to conduct an emission reduction technology evaluation of the CGS engines in order to identify technologies for reducing NO_x, CO, and VOC emissions to meet the new Rule 1110.2 emission limits, including combustion modification and post-combustion control. After a detailed review of different technologies, the post-combustion technology of catalytic oxidizer/selective catalytic reduction (Cat Ox/SCR) system with digester gas cleaning system (DGCS) using carbon adsorption was recommended as the technology with the most potential for meeting the future Rule 1110.2 emission limits. OCSD then embarked on a full-scale pilot study of the recommended technology on Engine 1 at Plant 1 to evaluate if the future amended Rule 1110.2 limits can be met for their digester gas-fired IC engines. Because SCAQMD recognized that the future emission limits in amended Rule 1110.2 were “technology-forcing,” the Governing Board directed staff to conduct a technology assessment to determine if cost-effective and commercially available technologies exist that can achieve these new lower emission limits. SCAQMD issued a grant to OCSD in 2009 (*SCAQMD Contract #10114*) to support the pilot test study at Plant 1 Engine 1, and the operation of the pilot study was granted a Permit to Construct/Operate for an Experimental Research Project by SCAQMD (Application Number 497717) in November 2009. The construction and installation of the pilot study equipment commenced in October 2009; the pilot study testing officially began on April 1, 2010 and officially ended on March 31, 2011.

Under the pilot study, Engine 1 at Plant 1 was equipped with a catalytic oxidizer to remove CO and VOCs, followed by an SCR system with urea injection to remove NOx (both systems supplied by Johnson Matthey). Due to space limitations at Plant 1, the catalytic oxidizer and SCR systems were mounted on a platform 14 feet above an onsite access road. Engine 1 is fueled primarily by digester gas, supplemented by natural gas. Digester gas contains low concentrations of siloxanes and other compounds which convert to sand-like particulate during combustion (silica) that contribute to rapid degradation of engines, gas turbines, and boilers, along with increased maintenance requirements. In addition, the silica also adheres to the catalyst media of the post-combustion control equipment. Therefore, a digester gas cleaning system (DGCS) was installed (supplied by Applied Filter Technology) to remove these contaminants from the digester gas before it was combusted in Engine 1. The potential for carbon media breakthrough was routinely monitored for using Draeger® tubes to measure hydrogen sulfide (H₂S) concentrations. Samples of the digester gas before and after the DGCS were also sent for laboratory analysis to measure for siloxane, H₂S, and VOCs that could indicate media breakthrough. During the study, inlet and outlet concentrations of CO, NOx, and VOCs were measured to determine the potential reductions in emissions due to the Cat Ox/SCR system. Sampling methods included:

- CO: Portable analyzer, SCAQMD Method 100.1
- VOCs: SCAQMD Methods 25.1/25.3
- NOx: Portable analyzer, SCAQMD Method 100.1
- Aldehydes: Modified CARB Method 430, SCAQMD Method 323 (formaldehyde)
- Ammonia slip (free ammonia): Modified SCAQMD Method 207.1 and Draeger® tubes

In addition, data from the OCSD's continuous emissions monitoring system (CEMS) was collected at the engine exhaust (inlet to the Cat Ox system) for NOx and at the stack exhaust for NOx, CO, and O₂. All CEMS data is based on 15-minute averages. Sampling was also performed for formaldehyde, acetaldehyde, and acrolein as required by the Experimental Research Project permit. In addition, ammonia levels in the stack exhaust were also measured to quantify potential ammonia slip, a result of the urea injection used in the SCR system. The overall conclusions of the pilot study are as follows:

1. The average NOx concentration at the stack exhaust after the pilot study controls was approximately 7 ppmv, below the 11 ppmv required under amended Rule 1110.2. The lowest NOx stack exhaust concentration met consistently under all valid conditions was 16 ppmv. While there were some periods (i.e., 15-minute block averages) where the NOx stack exhaust concentration was above 11 ppmv, after screening these periods, 181 periods out of 21,285 total operating periods (approximately 5,321 hours) remained as valid NOx excursions above the new Rule

1110.2 limit. These periods occurred during 61 separate events and accounted for less than 0.9% of the total measurement periods during the pilot study. Excursions were considered valid when they occurred during periods/events when the percentage of natural gas increased to above 5% of the fuel blend, when engine loads exceeded the loads mapped during the SCR system commissioning, or during periods/events not attributable to engine start-up or operational /system adjustments. An implication of these remaining periods are that the 11 ppmv limit is too conservative an emission limit, and may warrant further evaluation and potential increase and/or a specified percentage of allowable excursions.

2. SCR systems similar to the Johnson Matthey® system used in the present pilot study are commercially available for combustion units fueled by single component fuels, such as natural gas. Although the SCR system did not consistently meet the 11 ppmv limit with the digester gas/natural gas fuel blend in the pilot study, it did demonstrate a significant reduction in NOx emissions.
3. The free ammonia concentration was below 0.5 ppmv during all testing events using either SCAQMD compliance method 207.1, and below the Method Detection Limit (MDL) using Draeger® tubes.
4. The maximum CO concentration at the stack exhaust using the CEMS data was 42.2 ppmv, well below the amended Rule 1110.2 emission limit of 250 ppmv.
5. The maximum VOC concentration at the stack exhaust was found to be 4.95 ppmv, and was consistently well below the 30 ppmv limit in amended Rule 1110.2.
6. The use of the combined Cat Ox/SCR system in the pilot study resulted in significant reductions in CO, VOC, and NOx.
7. The DGCS system, in general, removed siloxanes from the digester gas to below Method Detection Limit (MDL) levels and significantly reduced sulfur compounds and VOCs successfully reducing catalyst masking which should lead to extended catalyst life. Additional benefits of the contaminant removal were significant improvements in engine maintenance requirements and lower O&M costs.
8. The total capitals cost to design, procure, and install a digester gas cleaning vessel to clean all the digester gas to the three Plant 1 engines, and a Cat Ox/SCR system with auxiliary equipment for Engine 1 is estimated to be \$2,300,000. The annual operations and maintenance (O&M) cost for these systems at Plant 1 is approximately \$59,000. Assuming a 20-year lifespan, the total annualized cost (capital cost plus O&M) for the DGCS and Cat Ox/SCR systems for Plant 1 Engine 1 is \$227,000.
9. The cost effectiveness analysis (based on dollars per ton of NOx, VOC, and CO emissions reduced) was developed for two scenarios: Scenario 1 assumed that the uncontrolled emissions were developed based on current permit limits (i.e., 45 ppmv, 209 ppmv, and 2,000 ppmv, respectively), and Scenario 2 assumed that the uncontrolled emissions were developed based on the results from the 2011 Annual Compliance Test for Engines 2 and 3. Both scenarios assumed that the controlled emissions were based on the Rule 1110.2 limits of 11 ppmv for NOx and 30 ppmv

for VOCs, and the pilot testing results of 15 ppmv for CO. Under these assumptions, the cost effectiveness for Scenarios 1 and 2 is \$7,987 and \$17,585, respectively, per ton of NOx plus VOCs reduced. The cost effectiveness for Scenarios 1 and 2 is \$636 and \$3,546, respectively, per ton of CO reduced. Note that the cost effectiveness for CO is conservative since the annualized cost is based on the entire system including the SCR and urea injection system. The annualized cost and emissions reduced calculations were based on operating each engine for a maximum of 6,000 hours per year.

1. Project Background and Objectives

1.1. Background

The Orange County Sanitation District (OCSD) owns and operates two (2) wastewater treatment plants that serve 21 cities and three special districts in the central and northwest Orange County, California, Reclamation Plant No. 1 (Plant 1) in Fountain Valley and Treatment Plant No. 2 (Plant 2) in Huntington Beach. In addition to the wastewater treatment processes, each plant operates a Central Power Generation System (CGS) to produce electrical power for the plant operations using large digester gas-fired internal combustion (IC) engines. Plant 1 has three (3) 2.5 megawatt (MW) internal combustion (IC) engines and Plant 2 has five (5) 3 MW IC engines, fueled primarily by digester gas (a biogas) and supplemented by small amounts of natural gas. Biogas, a by-product of the anaerobic digestion of wastewater solids, is classified as a renewable fuel, and the combustion of the biogas in the IC engines provides a beneficial reuse of a waste product.

Plants 1 and 2 are within the jurisdiction of the South Coast Air Quality Management District (SCAQMD). SCAQMD has established regulations aimed at reducing and controlling air toxic emissions from combustion sources, such as the engines at the plant CGS, including Rules 1110.2, 1401 and 1402. Under Contract J-79 Air Toxics Emission Reduction Strategic Plan (2003), Malcolm Pirnie was retained by the OCSD to perform an evaluation of regulations addressing air toxic requirements under the rules. Malcolm Pirnie prepared an emission reduction study/air toxics strategic plan for the OCSD to comply with the NO_x emission limit under Rule 1110.2 for IC engines. The study also addressed acceptable risk levels from Plant 1 and Plant 2 to comply with Rules 1401 and Rule 1402 (*Air Toxic Emission Reduction Strategic Plan* (Malcolm Pirnie, 2004) and *2012 Air Toxic Emission Reduction Strategic Plan* (Malcolm Pirnie, 2006)). The study identified the formaldehyde emissions from the CGS engines as a significant contributor to the overall risk levels, and also identified a catalytic oxidizer system with a digester gas cleaning system (DGCS) as a viable control technology to reduce the formaldehyde emissions from the digester gas-fired IC engines. This system was evaluated in a full-scale pilot study of a catalytic oxidizer system on Engine 3 at Plant 2 (*Catalytic Oxidizer Pilot Study* (Malcolm Pirnie, 2007)).

A catalytic oxidizer system is one of the most promising technologies for controlling carbon monoxide (CO) and volatile organic compounds (VOC) emissions from combustion units burning natural gas. However, fouling or rapid performance degradation of the catalytic oxidizers has been an issue for engines burning digester gas due to contaminants in the digester gas, such as volatile methyl-siloxanes and sulfurous compounds that tend to foul the catalytic oxidizers. Therefore, the use of a digester gas

cleaning system to prevent the contaminants in the digester gas from fouling and/or masking the catalyst was also evaluated.

In February 2008, SCAQMD further amended Rule 1110.2 to reduce emission limits for nitrogen oxides (NO_x), VOCs, and CO, and also to improve/enhance monitoring, recordkeeping and reporting requirements for IC engines. Biogas engines were given until July 2012 to meet new lower emission limits. Malcolm Pirnie conducted an emission reduction technology evaluation of the CGS engines and identified several technologies for reducing NO_x, CO, and VOC emissions, including combustion modification and post-combustion control (*Feasibility Study for a Technology Evaluation for Compliance with Amendments to SCAQMD Rule 1110.2 – Emissions from Gaseous and Liquid-fueled Internal Combustion Engines* (Malcolm Pirnie, 2008)). After a detailed review of the different technologies, the post-combustion technology of catalytic oxidizer/selective catalytic reduction (Cat Ox/SCR) system with DGCS using carbon adsorption was recommended as the technology with the most potential for meeting the future Rule 1110.2 emission limits.

In 2009, OCSD embarked on a pilot study of this recommended technology on Engine 1 at Plant 1 to evaluate if the future Rule 1110.2 limit can be met for their biogas-fired IC engines. Design of the pilot system included an SCR system for NO_x emission reduction, an oxidation catalyst unit for CO and VOC reduction (including formaldehyde), and a DGCS upstream from the IC engines for removal of siloxanes to prevent fouling of the catalysts. Additional benefits of the DGCS include the removal of total reduced sulfur and total volatile organic compounds. To supplement and support this study, SCAQMD issued a grant to OCSD (SCAQMD Contract #10114, 2009) for this pilot test study, and will be evaluating the data collected as part of their technology assessment of the feasibility of biogas engines achieving the future Rule 1110.2 emission limits for biogas-fired engines. The operation of the pilot study was granted a Permit to Construct/Operate for an Experimental Research Project by SCAQMD (Application Number 497717) (Appendix A-1).

1.2. SCAQMD Rule 1110.2

The IC engines at OCSD are subject to Rules 1110.2. Rule 1110.2 provides emission limits and monitoring requirements for all stationary and portable engines over 50 brake-horsepower (bhp). Rule 1110.2 (*Emissions from Gaseous- and Liquid- Fueled Engines*) was promulgated to reduce the NO_x, CO and VOC emissions from engines over 50 bhp. On February 1, 2008, Rule 1110.2 was amended in order to achieve further emissions reductions from stationary engines based on the cleanest available technologies. Under the February 2008 amendments to Rule 1110.2 shown below, more stringent NO_x, CO, and VOC limits were adopted, to become effective for biogas-fueled engines in July 2012 provided a technology assessment confirms that the limits below are achievable.

- NOx limit was lowered from 36 ppm (or ~ 45 ppm*) to 11 ppm at 15% O₂.
- VOC limit was lowered from 250 ppm* to 30 ppm at 15% O₂.
- CO limit was lowered from 2,000 ppm to 250 ppm at 15% O₂.

* Existing limits allow for an alternative emission limit for OCSD engines based on the engine efficiency correction factor.

The rule allows for some exemptions, including an exemption during engine start-up, to allow for sufficient operating temperatures to be reached for proper operation of the emission control equipment. The start-up period is limited to 30 minutes unless a longer period is approved for a specific engine by the Executive Officer and is made a condition of the engine permit.

1.3. Objectives

Because the future Rule 1110.2 emission limits shown above are “technology-forcing,” the SCAQMD Governing Board directed staff to conduct a technology assessment to determine if cost-effective and commercial technologies are available to achieve their limits. This pilot study will be used by SCAQMD as part of that technology assessment to evaluate the ability of the biogas-fueled engines at OCSD wastewater treatment plants to meet these future limits.

The objective of this study is to evaluate the effectiveness of a Cat Ox/SCR system with a DGCS as a post-combustion emissions control technology for an IC engine operating on biogas at a wastewater treatment plant. The data collected will be evaluated as part of the technology assessment study for the 2012 biogas engine emission limits under amended Rule 1110.2. Data were gathered on engine performance and emission reductions. Data were also gathered to obtain information for use in full-scale design (e.g., back pressure, impact on heat recovery unit (HRU)), to assess the performance of the DGCS (e.g., siloxane removal, media life), and to determine the economic feasibility of operating the Cat Ox/SCR system and the DGCS.

1.4. Report Organization

This report is organized into the following sections:

- Executive Summary
- Section 1. Project Background and Objectives
- Section 2. Pilot Study Work Plan
- Section 3. Results and Discussion
- Section 4. Cost Effectiveness Analysis
- Section 5. Conclusions and Recommendations

- Appendices



2. Pilot Study Work Plan

2.1. General Description

The engines at the CGS at both the Fountain Valley Reclamation Plant 1 and Huntington Beach Treatment Plant 2 are lean-burn, spark-ignited IC engines, and have been permitted to operate by SCAQMD. Plant 1 has three (3) 2,500 kilowatts (KW) units, while Plant 2 has five (5) 3,000 KW units. The engines are of conventional four-stroke cycle stationary Vee engine construction. They utilize spark-ignited pre-chamber technology to achieve extremely low NOx emissions. These electrical power generation stations utilize state-of-the-art low emission, spark-ignited, reciprocating engines fueled by digester gas and/or natural gas to drive generators. The engine generators normally operate in parallel with the grid, providing electrical loads at both plants. Excess power at Plant 2 is exported to the local utility. Waste heat energy in the cooling systems and exhaust are extracted and utilized for process heating through heat recovery units on each engine. Plant 2 has the capability to produce additional electrical energy with waste heat energy through use of a steam turbine-generator. Typically, at any given time one unit is down at Plant 1 and two units are down at Plant 2 for maintenance while the remaining units operate over a range of 60-120% load. Once placed on line, an engine will operate approximately 1,000-2,000 hours before being shut down for routine maintenance.

At Plant 1, each of the three IC engines are rated at 3,471 bhp, and each engine can produce up to 2.5 MW of electricity. This pilot study was conducted on Engine 1 at Plant 1 (see Figure 2-1). Details of the three Plant 1 engines, including Engine 1 are shown in Table 2-1.

Based upon a carefully designed series of studies performed for OCS D to meet existing and emerging regulatory standards, the full-scale pilot study of Engine 1 at Plant 1 included a DGCS using carbon media for removal of siloxanes and other harmful contaminants from the digester gas, and post-combustion control technology using a catalytic oxidizer system to reduce emissions of CO and VOCs, and SCR technology with urea injection for controlling of NOx emissions. The engine is equipped with continuous emissions monitoring system (CEMS) at the engine exhaust for measuring NOx concentration entering the Cat Ox/SCR system, and at the stack for measuring NOx, CO, and oxygen (O₂) concentrations after the Cat Ox/SCR system. Figure 2-2 and Appendix A-2 shows a schematic of the overall system.

Construction of the pilot study was initiated in October 2009. During the design and construction for the pilot study, two other projects were also in progress at Plant 1:

- J-79-1 Central Generation Automation. During this project, the engine control systems (ECS) for the CGS at both plants were replaced. The existing ECS at both

facilities were no longer being manufactured and parts replacement was not reliable. The new systems provide automatic load management capability, as well as an emissions monitoring feedback signal for exhaust emissions control.

- J-79-1A Continuous Emissions Monitoring Systems. Installation of a CEMS at the stack outlets of the CGS engines at both plants and NO_x inlet analyzers.

Prior to the start of the full-scale pilot study, both J-79-1 and J-79-1A projects were completed at Plant 1 Engine 1 before the pilot system commenced operation in April 2010 and initial performance testing was performed on both the DGCS and Cat Ox/SCR system.

2.2. Digester Gas Cleaning System

Digester gas is generated during the anaerobic digestion of the sewage sludge produced during the wastewater treatment process. This biogas contains contaminants such as hydrogen sulfides (H₂S), VOCs, and low concentrations of volatile siloxane compounds. Siloxane is a compound that is found in numerous consumer personal products and thus enters the wastewater treatment system. During combustion, the siloxanes convert to silica, sand-like particulate that deposit on the surfaces of combustion equipment contributing to a rapid degradation of engines, gas turbines, and boilers, along with increased maintenance requirements. In addition, the silica also adheres to the catalyst media of any post-combustion control equipment. These deposits can cause masking of the catalyst sites that significantly reduces the effectiveness of the catalyst. Based upon the pilot testing performed at Plant 2 (Malcolm Pirnie, 2008), the DGCS was shown to be successful in removing contaminants such as siloxanes, H₂S, and VOCs from the digester gas, and extending the catalyst performance life comparable to an IC engine combusting natural gas. In addition, the use of the DGCS resulted in a significant reduction in operations and maintenance (O&M) costs for the CGS engines.

2.2.1. DGCS Technology and Equipment

In order to minimize the masking effect from the siloxanes and sulfurous compounds, and prevent the deterioration of the post-combustion Cat Ox/SCR system installed for the pilot study, the digester gas was scrubbed to remove these contaminants prior to combustion. A DGCS (SAG™) supplied by Applied Filter Technology, Inc. (AFT) and consisting of a single carbon media vessel was installed at Plant 1. The SAG™ process was developed to remove siloxanes and other contaminants considered harmful to power generation equipment including engines, gas turbines, fuel cells and boilers. The media also treats VOCs, H₂S, and other sulfides. The vessel contains three layers of specialized graphite-based molecular sieves, which are small to large black pellets or spheres, capable of removing, through adsorption, the siloxanes from the biogas. The sieve types and layer depths (and the resulting vessel size) are determined by gas analysis to confirm system performance parameters. The biogas enters the SAG™ vessel at the top and proceeds down through the layers of sieves, exiting through flanged septa connected to a

manifold header. Each layer removes a specific type of contaminant and, in turn, protects the layer following it by removing contaminants that can foul it. The SAG™ siloxane media is a loose pellet form of polymorphous graphite carbon-based media specifically designed for removal of siloxanes in methane, and can be disposed of as a non-hazardous waste at a local approved site. Following system start-up, the vessel is allowed to process the biogas until there is breakthrough. In the present pilot study, the potential for media breakthrough was conservatively determined using H₂S as a marker. Once the potential for breakthrough is determined, the media is scheduled for change out. The vessel is then taken out of service, the media is replaced, and the vessel is returned to service.

The SAG™ unit used in the pilot study was a single stage, 7.5 ft diameter by 8 ft straight-sided dished downflow carbon steel filter unit. The unit contained 9,900 lbs of SAG™ three-stage media for siloxane removal. It includes interior high build epoxy coating and corrosion allowance vessel plate thickness. The DGCS system was sized and designed such that it could be used to clean all the digester gas produced at Plant 1. The DGCS was designed for the conditions presented in Table 2-2.

The DGCS was located along the south side of the Gas Compressor Building. Figure 2-3 shows a photograph of the DGCS at the Plant 1.

2.2.2. DGCS Measurement and Monitoring Methods

One objective of this pilot study was to assess the performance of the DGCS with respect to the removal of siloxanes and other contaminants, along with the life of the removal media. Based on the pilot testing performed at Plant 2 Engine 3, the DGCS proved successful in removing contaminants from the digester gas. The catalyst at Plant 2 Engine 3 fouled rapidly after combustion of uncleaned digester gas. Catalyst performance with the DGCS was comparable to that of a catalyst installed on the exhaust of an IC engine operating on natural gas.

Testing was performed to determine if the equipment met the design specifications. Two sampling methods are commonly used for measuring siloxanes: gas chromatography-mass spectrometry (GC/MS) and the wet chemistry method. Digester gas analyzed using GC/MS can be collected using either Tedlar® bags or canisters. The wet chemistry method requires samples to be collected using methanol impingers over a two to four hour sampling period, and then sent to a lab for analysis. After discussions with several certified laboratories, and review of several published papers, both methods were found to have merit; however, the collection of the samples using Tedlar® bags for measurement by GC/MS provided the most flexibility for minimum sampling time and equipment required. In the initial performance testing of the gas cleaning system, samples were collected using Tedlar® bags, canister, and methanol impinger methods at the digester gas inlet location at the same time, during the same day, and the analytical results were compared to determine the most appropriate method for analyzing

performance breakthrough. During the initial test, individual measurements of inlet total siloxane, consisting of, hexamethylcyclotrisiloxane (D3), octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5), hexamethyldisiloxane (L2), octamethyltrisiloxane (L3), and any other siloxane compounds identifiable according to the test method, were recorded.

For the sampling performed using Tedlar® bags at the DGCS inlet, the samples were collected and sent to a certified laboratory for the analysis of speciated siloxanes using TO-14/15, speciated VOCs using TO-15, total reduced sulfides using EPA 1023 Method 16B, or ASTM Procedure D-5504 GC/SCD, and the overall gas components and quality (% CH₄, % CO₂, % N₂, heating value using) using EPA Method 3C. One sample was also collected at the DGCS outlet to confirm that the DGCS met performance standards for all siloxanes to be measured as non-detect (i.e., below Method Detection Limit, MDL).

Samples were also collected in SUMMA® canisters at the DGCS inlet and sent to a certified laboratory for analysis of speciated siloxanes. In addition, speciated VOCs were analyzed using TO-15, total reduced sulfides were analyzed using ASTM D-5504, and overall gas components and quality (% CH₄, % CO₂, % N₂, heating value) was analyzed using ASTM D-1946.

The wet chemistry method was used at the DGCS inlet. During the test, the digester gas sample was collected using methanol impingers over a 4-hour period, and the samples were sent to the laboratory for individual measurements of inlet total siloxane.

Hydrogen sulfide testing was conducted weekly using Draeger® tubes. The H₂S concentration was used as an indicator that the media was nearing saturation. Breakthrough itself was determined to occur when the total siloxane concentration at the outlet of the carbon adsorber was above the MDL or when the H₂S concentration reached 15 ppm. Originally, the monitoring plan recommended by the vendor, AFT, was to use an H₂S concentration threshold of 5 ppm at the outlet to trigger siloxane and siloxane compound testing every week until breakthrough occurred. However, a more conservative approach for media saturation was used for the pilot study. Saturation and media replacement was triggered when measurable H₂S levels (generally around 1 ppm) were found using the Draeger® tube readings. The procedures used for taking the Draeger® tube measurements are shown in the Monitoring Test Procedure in the CD attached to this report. OCS staff also performed routine sampling of the digester gas for H₂S (Draeger® tubes), sampling for reduced sulfides (SCAQMD Method 307-91), and sampling for speciated VOCs (TO-15).

2.2.3. Selection of DGCS Sampling Method

Details of the DGCS performance test are presented in a Technical Memorandum (Malcolm Pirnie, May 5, 2010) found in Appendix A-3. Table 2-3 summarizes the results of the comparison of siloxane sampling methods.

As shown in the summary of the results shown in the table, the Tedlar® bag sampling method detected the highest level of total siloxane. In addition, the Tedlar® bag sampling method provided the most flexibility for minimum sampling time and equipment required. Based on these criteria, the Tedlar® bag method was chosen as the sampling method for the digester gas sampling for siloxanes.

2.3. Cat Ox/SCR System

Based on the results of the Catalytic Oxidizer Study on Plant 2 Engine 3 (Malcolm Pirnie, 2007) and the Feasibility Study (Malcolm Pirnie, 2008), the combination of a catalytic oxidizer followed by selective catalytic reduction equipment with urea injection provided by Johnson Matthey (JM) was selected for the pilot study.

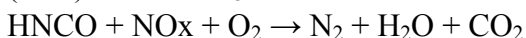
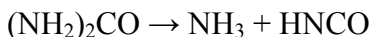
Catalytic oxidation is a post-combustion control technology which has been commercially proven to reduce CO, VOCs and air toxics, including formaldehyde and acrolein, from engines burning natural gas. There is, however, limited performance data for an engine fired with digester gas, either with or without a gas cleaning system. The digester gas, which is generated during the biological consumption of solids that are collected during the wastewater treatment process, contains low but detrimental concentrations of siloxane compounds, which convert to silica during combustions and deposit on the surfaces of post-combustion equipment, including catalyst media. This fouling of the catalyst, or catalyst masking, significantly reduces the effectiveness of the catalyst. In order to minimize this masking effect, the digester gas can be pre-cleaned to remove these siloxanes prior to combustion.

The Johnson Matthey catalyst elements are manufactured in a “block” form. The catalyst block substrate is made from stainless steel foil that is retained by a stainless steel frame. This structure undergoes a proprietary coating process in which the foil is chemically treated to increase surface area. Active platinum group metal catalysts are then applied. The coating, catalyst composition, and honeycomb pore size were designed by Johnson Matthey to provide optimum durability and pollutant removal efficiency for the specified operating environment.

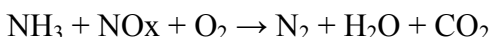
In the SCR system, the exhaust enters a mixing tube where a stream of atomized urea is introduced into the gas. The urea quantity is controlled by the urea injection control system. Mixing vanes distribute the atomized particles throughout the exhaust gas. Ammonia is formed from aqueous urea ((NH₂)₂CO) after the urea injection, which involves evaporation of water, thermal decomposition of urea, and finally hydrolysis of

iso-cyanic acid. Evaporation of water is initiated when the aqueous urea is injected into the exhaust gas pipe. This mixture then enters the SCR housing. A chemical reaction between the ammonia from the urea, the exhaust gas NO_x component, and SCR catalyst results in the reduction of the NO_x into nitrogen (N₂), carbon dioxide (CO₂), and water (H₂O). The basic equations are:

Urea Reaction



Ammonia Reaction



The percent reduction of NO_x is determined by the amount of urea introduced into the gas flow.

The Cat Ox/SCR system was installed in a horizontal position on a platform, elevated at a height of approximately 14 feet directly west of Engine 1 at Plant 1. This platform-mounted installation allowed for easy access to the equipment and access to the roadway underneath the platform. Figure 2-4 shows a photograph of the platform installation. The Cat Ox/SCR system was designed for the conditions and performance guarantees presented in Tables 2-1 and 2-4, respectively.

2.3.1. SCR/Catalytic Oxidizer System Technology and Equipment

Oxidation Catalyst Housing. The oxidation catalyst consisted of one Johnson Matthey Model 4040SS-4-30/36 housing for the catalyst at Engine 1. The housing has access doors on both sides of the housing, with four tracks for installing catalyst. One of the tracks houses the initial catalyst supplied, with three tracks available for later expansion if needed. There is a 30-inch flange on the inlet and a 36-inch flange on the outlet of the housing. When completely full of catalyst (4 layers), the total weight of the housing plus the catalyst is about 8,190 pounds. The housing has a number of two ³/₄ inch ports on the inlet and two ³/₄ inch ports on the outlet of the oxidation catalyst housing.

Oxidation Catalyst. A total of sixteen (16) whole oxidation catalyst blocks were part of this system. They were arranged 4 blocks wide x 4 blocks high x 1 block deep. [A whole block is approximately 2 feet wide x 2 feet tall x 3¹/₄ inches deep and constitutes approximately 1 ft³ of catalyst volume.] The cell density of this catalyst is 200 cells per square inch (cpsi). Figure 2-5 shows a photograph of the catalyst.

SCR Catalyst Housing. Johnson Matthey provided a JM Model 4040SS-4-36 housing for the catalyst. The housing was fabricated in 304 stainless steel. Two layers of catalyst were installed and there were two open tracks for addition of another layer if desired at a later date. The housing was equipped with access doors on both sides of the housing.

There are 36-inch inlet and outlet flanges (150# ANSI) provided on the housing. When completely full of catalyst (4 layers), the total weight of the housing plus the catalyst is approximately 8,190 pounds. The housing has a number of two $\frac{3}{4}$ inch ports on the inlet and two $\frac{3}{4}$ inch ports on the outlet of the SCR housing for sampling.

SCR Catalyst. The catalyst consists of thirty-two (32) whole SCR catalyst blocks on 200 cpsi metal substrate. They are arranged 4 blocks wide x 4 blocks high x 2 blocks deep. [A whole block is approximately 2 feet wide x 2 feet tall x $3\frac{1}{4}$ inches deep, and constitutes approximately 1 ft³ of catalyst volume.]

Urea Injection Control System. This system was designed to control the injection rate of urea into the SCR based on engine load for one fuel blend. During the initial commissioning of the system, the engine load, the urea injection rate, and the NOx and ammonia outlet concentrations were measured and mapped. Mapping refers to the process in which the urea injection rate is correlated to the engine load in order to meet the desired NOx exhaust concentration. The system allowed for up to 25 combinations of engine load versus urea injection rate (set points).

In addition to the load map control, the injection system also uses a system of bias set points to trim the urea injection. The NOx curve bias is a percentage that can be input by the operator to increase or decrease the urea injection rate. This bias is typically set to 0%, but can be modified if engine operation is expected to change the NOx produced in the exhaust emissions. The NOx add bias increases the urea injection rate by an input gallon per hour setting based on the NOx outlet concentration from the stack exhaust CEMS analyzer. When the NOx outlet concentration reaches the level set in the control system, the urea injection rate will increase by the bias set point. The NOx subtract bias decreases the urea injection rate in the same manner. For the pilot test, no NOx subtract bias was set.

The SCR process requires precise control of the urea injection rate. An insufficient injection may result in unacceptably low NOx conversions. An injection rate that is too high can result in release of excessive ammonia emissions. These excess gaseous ammonia emissions are known as “ammonia slip”. Under the research permit for this study, the maximum allowable ammonia slip is 10 ppm. Excess ammonia can lead to clogging and equipment problems in downstream equipment. In addition, emissions of ammonia slip to the atmosphere can result in odors and a visible plume. The ammonia slip increases at higher NH₃/NOx ratios. The stoichiometric NH₃/NOx ratio is approximately 1.

2.3.2. Cat Ox/SCR Measurement and Monitoring Methods

Preliminary Testing/SCR Urea Injection Mapping. The objective of the preliminary testing was to measure the performance of the system at varying loads and fuel blends

(i.e., digester gas and natural gas), and to map the urea injection system. The CO, NO_x, and O₂ concentrations at varying engine loads and fuel distributions at the inlet of the oxidation catalyst and the outlet of the SCR catalyst were monitored for a period of six (6) hours at ten (10)-minute intervals using the TESTO® 350 XL Portable Monitor during startup as part of the preliminary testing. In addition, ammonia measurements were taken at the outlet of the SCR catalyst at ten (10)-minute intervals using Draeger® tubes. A data logger was used to monitor temperature and pressure differential on a real-time basis over the six (6)-hour testing period. Carbon monoxide was also monitored with the TESTO® 350 XL Portable Monitor. Load and fuel distribution of the engine were varied according to the schedule shown in Table 2-5. The recorded data is provided in Appendix C-1.

A secondary objective of the preliminary testing was to provide varying load and fuel scenarios for Johnson Matthey to map the urea injection system. A description of the SCR urea injection mapping during the pilot test is provided in a technical memorandum in Appendix A-4. Figure 2-6 presents a mapping diagram of the urea injection rate designed for a 95% digester gas to natural gas fuel blend during the pilot testing period after system adjustments were made on June 8, 2010.

Source Testing Using Compliance Methods. Source testing using SCAQMD compliance methods was performed after preliminary testing of the Cat Ox/SCR system and equipment startup and commissioning in order to measure the emissions of the system. The following summarizes the source testing using compliance methods performed on April 7-8, 2010:

- The initial testing using compliance methods was performed for one fuel blend (95% digester gas and 5% natural gas)
- Source testing was performed to sample for CO, NO_x, VOCs, ammonia, and aldehydes (formaldehyde).
- SCAQMD Method 100.1 was used to measure NO_x, CO, CO₂, and O₂ concentrations, modified CARB Method 430 was used to measure aldehydes (i.e., formaldehyde), Method 25.3 was used to measure total non-methane non-ethane organic compounds (NMNEOC), and modified SCAQMD Method 207.1 was used for measuring ammonia.

Table 2-6 describes details of the April 2010 initial test program using compliance methods.

2.4. Pilot Study Test Program Timeline

Table 2-7 presents the pilot study project timeline. The full equipment commissioning took place between March 23 and April 1, 2010. The pilot testing was conducted from April 1, 2010 through March 31, 2011. Since Engine 1 is used to provide power to the

plant, it continued operation throughout the construction and commissioning of the system, with occasional stoppages as needed by the present study as well as the J-79-1 and J-79-1A projects.

**Table 2-1:
Engine 1 Design Parameters**

Manufacturer:	Cooper-Bessemer
Model:	LSVB-12-SGC
Cycle:	4-stroke
Bore:	15½ in
Stroke:	22 in.
Configuration:	Vee-12
Rated Speed:	400 RPM
Rated Output:	2,500 KW
BMEP:	138 psi
Horsepower	3,471 bhp
Load	100%
Operating Hours per Year	Up to 8,760
Type of Fuel	Cleaned Digester Gas / Natural Gas
Design Exhaust Flow Rate	27,555 acfm
Design Exhaust Temperature	800°F

**Table 2-2:
DGCS Design Specifications**

Gas Description	Anaerobic digester gas
Flow	1440 scfm
Pressure drop per foot of media	0.5 in. w.c.
Pressure drop total with piping	7.5 in. w.c
Pressure - actual	58 psig inlet (actual)
Pressure - design	150 psig
Maximum gas inlet Temperature	70°F
Maximum Ambient Temperature	100°F
Minimum Ambient Temperature	40°F
Humidity	Saturated at 70°F
Siloxane – design	5 ppm
Siloxane – current	5 ppm
Total Reduced Sulfur (H ₂ S) - design	50 ppm
Total VOC – design	50 ppm
Siloxane removal	Below best available detection limit at time of testing (i.e. 100 ppbv per species using methanol impinger; or 500 ppbv per species in Tedlar® bag by GC/MS)

**Table 2-3:
Comparison of DGCS Sampling Methods**

Comparison of DGCS Sampling Methods	
DGCS Inlet	Total Siloxane (ppbv)
Tedlar® – Inlet	3,584
SUMMA Canister – Inlet	554
Methanol Impinger – Inlet	1,457

**Table 2-4:
Cat Ox/SCR Performance Guarantees**

Exhaust Component	Maximum Catalyst System Inlet (ppmv)	Maximum Catalyst System Outlet (ppmv)	Reduction Guarantee
NOx	50	9	82.0%
VOC	120	25	79.2%
CO	800	100	87.5%
Free Ammonia Slip	N/A	10	N/A

- Notes: 1) Provided by Johnson Matthey price quotation, dated May 8, 2009.
2) N/A indicates not applicable. Ammonia was not measured before the catalyst.

**Table 2-5:
Preliminary Testing Schedule**

Test Run	Engine Load %	Natural Gas/Digester Gas Fuel Ratio (% NG / % DG)	Time Period (min)
1	60	50 / 50	30
2	80	50 / 50	30
3	100	50 / 50	30
4	110	50 / 50	30
5	60	100 / 0	30
6	80	100 / 0	30
7	100	100 / 0	30
8	110	100 / 0	30
9	60	5 / 95	30
10	80	5 / 95	30
11	100	5 / 95	30
12	110	5 / 95	30

**Table 2-6:
Initial Pilot Study Test Program (95% Digester Gas and 5% Natural Gas)**

Parameter	Reference Method	Load	No. of Tests	Sample Location
Aldehydes ⁽¹⁾	Modified CARB Method 430	Max.	2 2	Catalytic Oxidizer Inlet Stack Exhaust
Volume Flow	SCAQMD 1.1-4.1 EPA 19	Max. Normal Min.	1	Stack Exhaust
NO _x , CO, O ₂ and CO ₂	SCAQMD 100.1	Max. Normal Min.	1	Stack Exhaust
Ammonia	Modified SCAQMD 207.1	Max. Normal Min.	2	Stack Exhaust
VOCs (as NMNEOC)	SCAQMD 25.3	Max.	1	Catalytic Oxidizer Inlet SCR Outlet Stack Exhaust
NO _x , CO, O ₂	CEMS	N/A	N/A	Stack Exhaust
NO _x , O ₂	CEMS	N/A	N/A	Catalytic Oxidizer Inlet

Note: 1) Aldehydes analysis included formaldehyde, acetaldehyde, and acrolein.
2) N/A indicates not applicable.

**Table 2-7:
Pilot Study Project Timeline**

Action	Date
Project Construction Period	10/2009 – 3/2010
Commissioning	
■ Digester Gas Cleaning System Commissioning (AFT)	3/9/10
■ Cat Ox/SCR System Commissioning (Johnson Matthey)	3/22/10-3/31/10
Preliminary Testing/SCR Urea Injection Mapping (Johnson Matthey)	3/31/10 – 4/1/10
Pilot Study – Commence Testing	4/1/10
Source Testing using Compliance Methods (SCEC)	4/7/10 – 4/8/10
Urea Injection Mapping Adjustment #1 (Johnson Matthey)	5/13/10
Urea Injection Mapping Adjustment #2 (Johnson Matthey)	6/8/10
Completed Pilot Testing	3/31/11
Post-Pilot Study Testing	4/1/11 – present
Urea Injection Mapping Adjustment #3 (Johnson Matthey)	4/11/11 – 4/12/11

Figure 2-1: Plant 1 Engines 1, 2, and 3 (pictured left to right)



Figure 2-2: Schematic of the Pilot Testing System

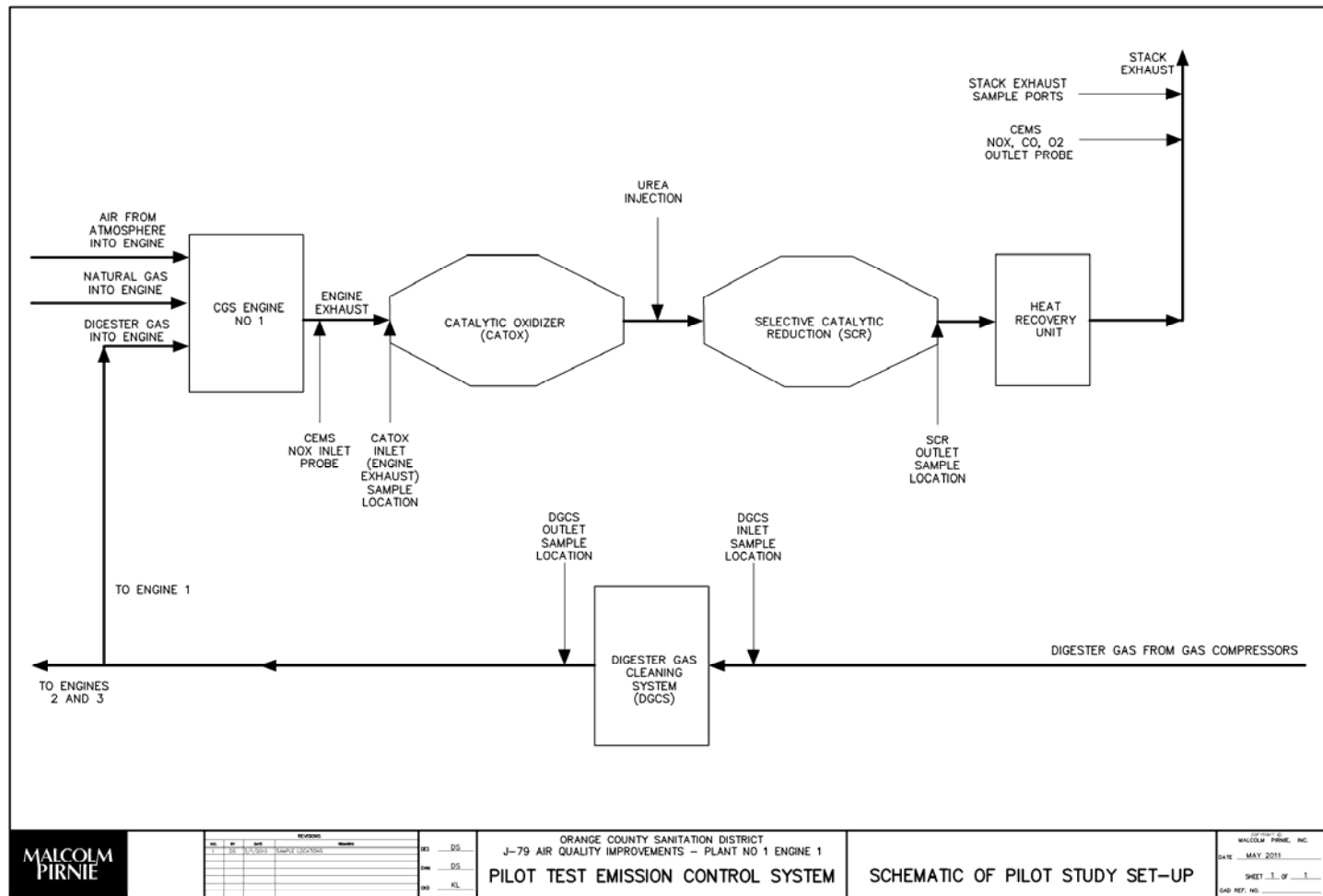


Figure 2-3: Digester Gas Cleaning System



Figure 2-4: Cat Ox/SCR Platform Installation



Figure 2-5: Catalyst and Housing

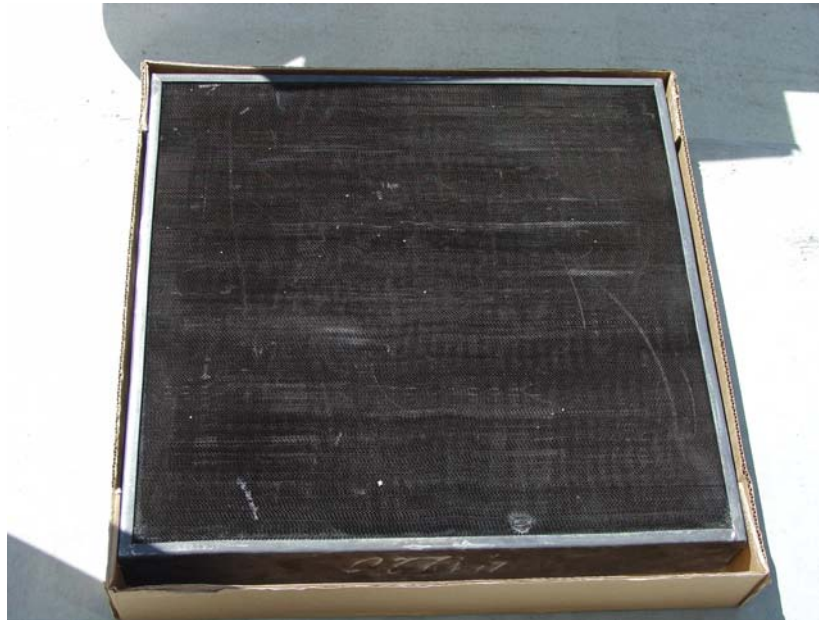
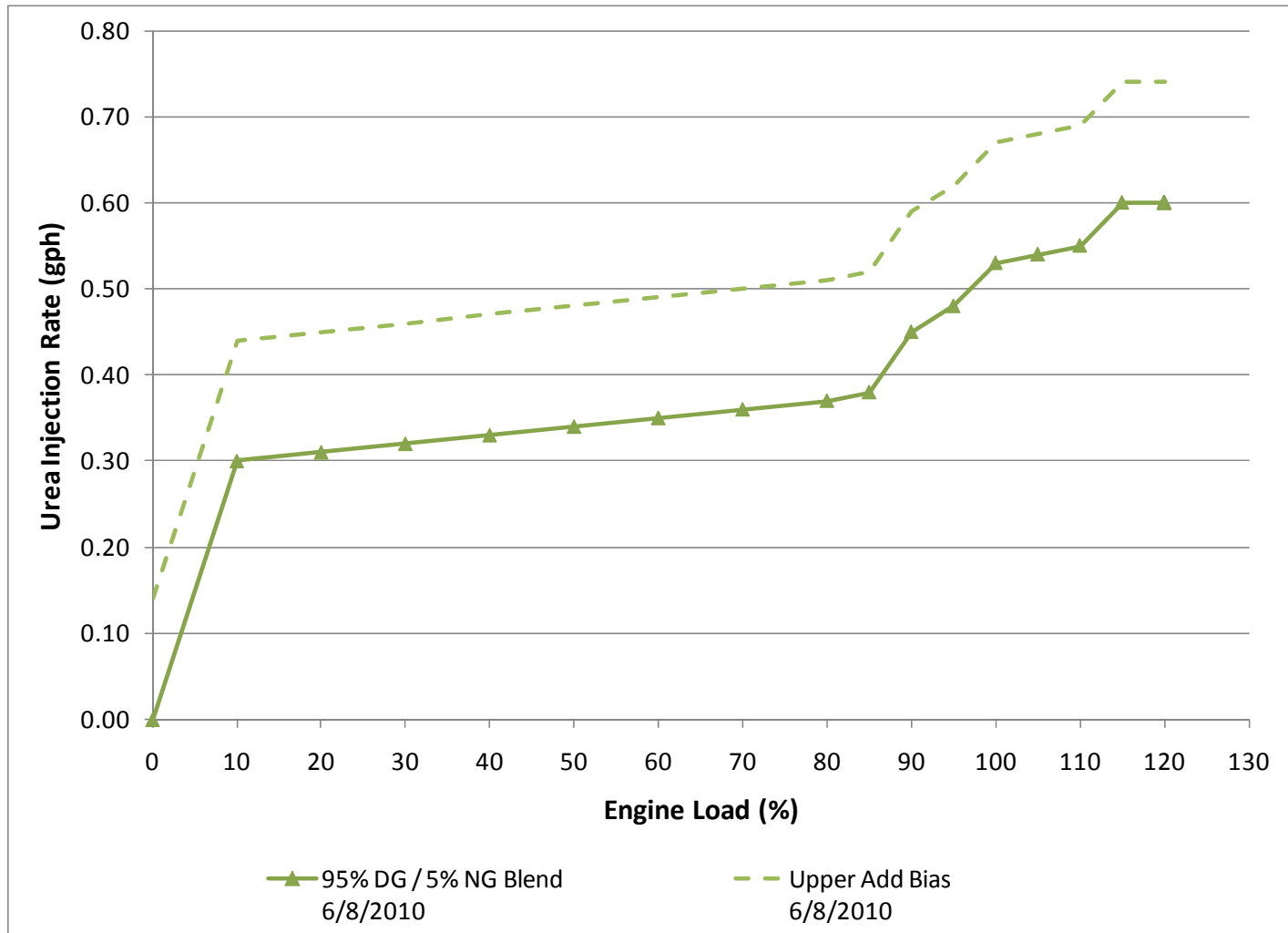


Figure 2-6: SCR Urea Injection Curve for Pilot Testing
(June 8, 2010 through March 31, 2011)



3. Results and Discussion

3.1. Digester Gas Cleaning System

The digester gas cleaning system installed at Plant 1 was designed to remove siloxanes and other impurities from the digester gas prior to being used to fuel the three IC engines. Throughout the pilot study, the performance of the DGCS system was evaluated by monitoring for carbon media performance and change out frequency. Samples for the family of siloxanes, H₂S, and speciated VOCs in the digester gas were taken at the inlet and outlet to the DGCS carbon vessel, and sent to the laboratory for testing. When the testing indicated that the DGCS media needed replacement, flow to Engine 1 was curtailed until the media was replaced. Digester gas continued to be used by Engines 2 and 3 since they were not equipped with post-combustion catalyst controls that could be fouled by the siloxanes and other contaminants in the digester gas. Once the DGCS media was replaced, the testing was resumed on Engine 1.

3.1.1. DGCS Sample Integrity

The composition of the digester gas at the inlet to the DGCS was tested for a number of compounds, including H₂S, as an indicator compound for media breakthrough, reduced sulfides, siloxanes, and a number of speciated VOCs. Since the sampling was performed using Tedlar® bags, and occasionally SUMMA canisters, the potential exists for ambient air to be captured along with the digester gas, thus diluting the sample. In order to assure that the samples were not diluted, the fixed gas composition of the gas was also measured. Fixed gases are gases for which no liquid or solid can form at the temperature of the gas, such as air at typical ambient temperatures. In the present study, N₂, O₂, CO₂, and CH₄ were the fixed gases sampled. The digester gas typically consisted of 36% carbon dioxide, 61% methane, 2% nitrogen, and less than 1% oxygen. In the event that ambient air is pulled into the digester gas sample bag, the percentage of nitrogen will be significantly greater than 2%, and the concentrations of the digester gas contaminants would be diluted.

A summary of the fixed gas composition sampling data from March 2010 through February 2011 is shown in Table 3-1. The full fixed gas composition data set is found in Appendix B-1. Over the course of this fixed gas composition sampling, three samples were eliminated due to errors in sample collection that led to a nitrogen percentage greater than 5%; one sample set (Tedlar® and Summa canister) was also eliminated due to extremely high nitrogen concentrations indicating that ambient air had leaked into the sample. However, a comparison of the inlet and outlet fixed gas composition demonstrated that the integrity of the overall digester gas samples taken was maintained with inlet and outlet concentrations of CO, CH₄, N₂, and O₂ staying within the range

expected, indicating that the carbon media did not adsorb methane or the other fixed gases.

3.1.2. Digester Gas Quality

Table 3-2 presents the results of the reduced sulfides component of the digester gas. The data indicate that H₂S is the biggest constituent of the reduced sulfides sampled. The average H₂S concentration was approximately 26 ppmv. The high H₂S input concentration makes it a good indicator compound for detecting catalyst media breakthrough at the outlet of the system. Table 3-3 presents the results of the speciated siloxane sampling. Typical of digester gases in general, D5 and D4 are the largest siloxane components of the Plant 1 digester gas. Table 3-4 presents the results of the VOC sampling. The reduced sulfide, speciated siloxane, and VOC data sets are found in Appendices B-2, B-3, and B-4, respectively.

3.1.3. DGCS Performance

The DGCS was monitored for carbon media performance and change out frequency throughout the study. Digester gas samples were taken at the inlet and outlet of the DGCS carbon vessel for total siloxane concentration and H₂S, and at the inlet for speciated siloxanes, reduced sulfides, and VOCs. Samples below the method detection level (MDL) were not used in the summary analysis.

Siloxane samples were collected using Tedlar® bags and analyzed using GC/MS at both inlet and outlet of the system. Due to the length of time required to analyze the siloxane samples (approximately several days to two weeks), H₂S sampling at the DGCS outlet using Draeger tubes was used as a real-time indicator of the DGCS carbon media performance. When H₂S was detected in the DGCS outlet above approximately 1 ppmv, Engine 1 was shut-down to prevent fouling of the catalyst material until the carbon media was replaced in the DGCS. The use of 1 ppmv H₂S as an indicator for potential media saturation is a conservative threshold selected to ensure that media breakthrough would not occur during the study. Table 3-5 presents the results of the siloxane and H₂S sampling. The table indicates that the siloxane concentrations at the inlet varied over the course of the study. As shown in Table 3-3, the average inlet concentration of total siloxanes at was approximately 5.0 ppmv. The DGCS generally removed siloxanes to below the MDL.

The carbon media was replaced three times during the pilot study: in June 2010, in September 2010, and in February 2011 after treatment of approximately 147, 174, and 157 million cubic feet of digester gas, respectively. Appendix B-5 provides a summary of reduced sulfide and speciated siloxane sampling events with DGCS carbon media use and change out frequencies. This media change-out information will be used in the cost evaluation for the overall system presented in Section 4. The effectiveness of DGCS media life may be longer than experienced during the current pilot testing because the

media change-outs were conservatively scheduled to protect the catalyst. For longer term operations, a design change to optimize media life could include the installation of two vessels in series. The second vessel would act as a polisher to provide catalyst protection from siloxane breakthrough while allowing the media in the primary vessel to be completely exhausted.

3.2. Cat Ox/SCR System

The purpose of the demonstration project testing program was to evaluate the effectiveness of the Cat Ox/SCR system for removal of CO, VOC, and NO_x to comply with amended Rule 1110.2, to monitor for ammonia slip, and to evaluate the performance of the engine with the emissions control equipment installed. The pilot testing of the Cat Ox/SCR system began on April 1, 2010, immediately after completion of the SCR urea injection mapping by Johnson Matthey. The pilot study continued until March 31, 2011.

The concentrations of CO, NO_x, and O₂ in the engine exhaust gas before and after the Cat Ox/SCR system were determined by an independent source testing firm using SCAQMD Method 100.1, a chemiluminescent compliance testing method, during source testing on April 7 and 8, 2010. Routine monitoring of CO, NO_x, and O₂ concentrations using OCSD's TESTO 350 XL portable handheld analyzer was also performed. The use of the portable analyzer measuring CO and NO_x allowed for numerous data sets to be collected at regular intervals throughout the pilot study. The detailed portable analyzer test report can be found in Appendix C-1. In addition, a CEMS monitored and recorded the 15-minute block average NO_x concentrations at the catalytic oxidizer inlet (engine exhaust) and the NO_x, CO and O₂ concentrations at the stack exhaust. VOC concentrations were measured periodically at the engine exhaust and stack exhaust using SCAQMD Method 25.3.

The results of the source testing at Plant 1 using SCAQMD compliance methods on April 7-8, 2010 and SCAQMD Rule 1110.2 compliance testing in January 2011 are shown in Tables 3-6 and 3-7, respectively. Results for the January 2011 source testing at Plant 1 in Table 3-7 are also shown for Engines 2 and 3 for comparison. As shown in the January 2011 annual compliance test results (Table 3-7), the average NO_x and CO concentrations in Plant 1 Engine 1 over three loads are 6.2 and 7.9 ppmv, respectively. This is lower than the average Engines 2 and 3 NO_x and CO concentrations over three loads of 30.2 and 390.5, respectively. Results of the routine pilot test sampling events are provided in Section 3.3.

3.3. Compliance with Future Rule 1110.2 Emission Limits

The results of the pilot study were evaluated for compliance with the future Rule 1110.2 emission limits. The CO and VOC results represent data collected after the initial startup of the equipment from April 1, 2010 through March 31, 2011. The NO_x results represent

data collected after the urea injection system was optimized on June 8, 2010 through March 31, 2011.

3.3.1. Carbon Monoxide Concentration

CO concentration data were collected during source testing at the engine exhaust and stack exhaust routinely throughout the pilot testing period using the hand-held portable analyzer at the engine exhaust and SCR outlet and also continuously at the stack exhaust by the CEMS. The data collected during these events is summarized in Table 3-8. All CO data collected by the portable analyzer and the CEMS are presented in Appendices C-1 and C-3, respectively.

The CO concentration data at the engine exhaust (CO inlet) and the stack exhaust (CO outlet) are presented graphically in Figure 3-1. The CO inlet concentration was measured with the portable analyzer. The CO outlet concentration, measured by the CEMS, is shown as the maximum daily 15-minute average CO outlet concentration. The percent reduction in CO concentration measured across the Cat Ox/SCR system by the portable analyzer consistently exceeded 96% reduction. This performance was consistent when firing either digester or natural gas. This CO concentration removal rate exceeds the expected performance based upon the catalytic oxidizer vendor guarantee of 87.5% CO removal, provided in Table 2-4.

3.3.2. Volatile Organic Compounds Concentration

The VOC concentration data in terms of NMNEOC was collected during source testing at the engine exhaust, the stack exhaust, and routinely throughout the pilot testing period using SCAQMD Method 25.3. All data collected is presented in Appendix C-2. As shown in Table 3-9, the average VOC concentration at the stack exhaust was 3.58 ppmv, below the emission limit of 30 ppmv in the future Rule 1110.2.

Data measured during the pilot testing period were compared to VOC concentrations measured for the OCSD Rule 1110.2 Annual Permit Compliance Test Report for Year 2011. Table 3-7 summarizes the annual permit compliance VOC test results for OCSD Plant No. 1.

The average uncontrolled VOC concentration for Engines 2 and 3 during the compliance testing was 97 ppmv, while the controlled VOC concentration from Engine 1 stack exhaust was 3.24 ppmv. This is in the same range of the VOC concentrations measured during the pilot testing period (i.e., 3.58 ppmv), confirming the effectiveness of the catalytic oxidizer (at approximately 96%) in removing VOCs from the engine exhaust.

It should be noted that the stack exhaust VOC concentrations for Engines 2 and 3 of 97.2 and 96.9 ppmv, respectively, are much higher than the VOC concentrations measured at the Engine 1 engine exhaust during the pilot testing period, which averaged 21.84 ppmv

(refer to Appendix C-2). One possible explanation to this is the arrangement of the Engine 1 sampling port before the catalytic oxidizer. Typically, when sampling using SCAQMD Method 25.3, two samples are gathered from two separate probes and the results of the analyses are averaged. In the case of this pilot study, the valve at the engine exhaust sampling port was not large enough to locate two adjacent probes, and it was not possible to expand the sampling port. Therefore, the sample and duplicate sample were not taken at the same time, but one after the other. The VOC data collected at the engine exhaust represents the higher of the two sample data results, in line with SCAQMD's general mandate that the higher value be reported when the results differ by more than 20%. Despite the lower accuracy in the engine exhaust sample due to the sizing of the sampling port, the sample taken at the stack exhaust location met the SCAQMD accuracy criteria.

3.3.3. Nitrogen Oxides Concentration

NOx concentration data were collected during source testing at the engine exhaust and stack exhaust, routinely throughout the pilot testing period using the portable hand-held analyzer at the engine exhaust, after the catalytic oxidizer and stack exhaust; and continuously at the engine exhaust and stack exhaust by the CEMS.

Based on the results of previous source testing, it is observed that the concentration of NOx produced in the engine exhaust for a given load is higher when firing natural gas than when firing digester gas at any given load. Therefore, the efficiency of the SCR system is reduced as the percentage of natural gas increases. The original urea injection set points, set on April 1, 2010 during commissioning, were set for a blend of digester gas and natural gas. The set points, which are a function of engine load, were adjusted on June 8, 2010 to decrease urea flow because a higher ratio of digester gas to natural gas was fired in Engine 1 than was originally anticipated. Therefore, the urea injection rates were reduced to control a lesser concentration of NOx in the exhaust gas. The data presented in this section represents the pilot testing period from June 8, 2010 through March 31, 2011. The data collected during this period are summarized in Table 3-10. The entire dataset collected is presented in Appendix C-3.

The NOx concentration data at the engine exhaust and the stack exhaust measured by the CEMS are presented graphically in Figure 3-2. The NOx inlet and outlet concentration is shown as the daily maximum 15-minute average NOx concentration. The percentage reduction in NOx concentration measured across the Cat Ox/SCR system by the portable analyzer ranged from 76 to 98%. This NOx concentration removal rate is close to the expected performance based upon the Cat Ox/SCR vendor guarantee of 82% NOx removal. A review of the NOx concentration data over the period of the pilot study indicates that the performance of the SCR is affected both by the ratio of digester to natural gas used as fuel in the engine, and by the system's responsiveness to engine operating parameters, such as start-up and differing load conditions. The inability of the

SCR system to meet the vendor guarantee may be due to periods of increased natural gas flow in the fuel gas. This was to be expected because the urea injection system was mapped for a primarily digester gas (greater than 95 percent) fuel blend. The control system can only be set with one set of engine load to urea injection set points and is not designed to change urea injection rates depending on the fuel blend. Johnson Matthey has not designed a control system that can accommodate varying loads and fuel blends. Therefore, during periods when the fuel is supplemented by natural gas, the NOx removal efficiency is expected to be reduced. If the set points were adjusted for a natural gas fuel usage, which is atypical, the system may over-inject urea potentially causing an ammonia slip as discussed below.

3.3.3.1. NOx Concentrations Above Rule 1110.2 Limit

During the pilot testing period, the NOx outlet concentration occasionally spiked above the future Rule 1110.2 limit of 11 ppmv. NOx concentrations are measured continuously by the CEMS system and averaged in 15-minute blocks for compliance purposes. For the purposes of this Report, each 15-minute block is defined as a “period”. A “high NOx outlet event” is defined as one period or multiple periods in a short time span where the NOx outlet concentration exceeds 11 ppmv. The NOx outlet concentration exceeded 11 ppmv for a total of 97 high NOx outlet events (940 periods out of 21,285 periods of engine operating time) during the pilot test.

Many of the high NOx outlet events were removed from the data set when evaluating performance of the SCR system. A majority of the spikes in NOx outlet concentration correlated with high NOx outlet events when: 1) the engine had just come online, 2) there was an increase in the percentage of natural gas in the engine fuel blend, 3) engine loads exceeded the loads mapped during the initial urea injection rate programming, and 4) operational adjustments of the Cat Ox/SCR system took place. Once excursions over 11 ppmv were screened for exempt or non-valid conditions such as engine start-up and non-control system error, 181 15-minute periods out of 21,285 periods of operating time (less than 0.9% of the total measurement periods during the pilot study) remained above 11 ppmv. The lowest NOx stack exhaust concentration met consistently under all valid conditions was 16 ppmv. Table 3-11 presents a break-down of the number of high NOx outlet events and periods when the NOx outlet concentration at the stack exhaust exceeded 11 ppmv.

Exempt or Non-Valid Periods. A total of 7 high NOx outlet events (703 periods or 3.3% of the total engine operating period) were during times when operational issues and system adjustments caused the NOx to exceed 11 ppmv. These events included urea injection system adjustments by the system vendor, operation of the SCR system without urea in the storage tank, modifications to the engine automation system, improper operation of the SCR system, and clogging in the urea injection lance. These periods

were removed from the stack exhaust NO_x data set because they do not represent proper operating conditions of the SCR system.

During the pilot testing period, 29 high NO_x outlet events (56 periods or 0.3% of the total engine operating time) were classified as occurring during engine start-up. Rule 1110.2(h)(10) allows for an exemption during engine start-up to allow for sufficient operating temperatures to be reached for proper operation of the emission control equipment. The start-up period is limited to 30 minutes unless a longer period is approved for a specific engine by the Executive Officer and is made a condition of the engine permit. Periods where NO_x outlet concentrations exceeded 11 ppmv within 30 minutes of engine start-up were removed from the data set for evaluation of the SCR system performance.

Validated Periods. A number of the remaining high NO_x outlet events could be attributed to periods during which the engine was operating with natural gas fuel or at a load that exceeded the range that was originally mapped into the urea injection system. The urea injection system was programmed assuming a fuel blend of 95% digester gas to 5% natural gas. An event was attributed to a rise in natural gas usage if the fuel blend decreased to below 95% digester gas during the same period or during the period immediately preceding the event. A total of 17 high NO_x outlet events (43 periods or 0.2% of total engine operating time) occurred when the fuel blend decreased to below 95% digester gas. It was observed that the production of NO_x at the engine exhaust increased as the percentage of natural gas in the engine fuel increased. Therefore, as the digester gas to natural gas fuel ratio decreased to below 95% digester gas (i.e., using more natural gas in the fuel blend), the urea injection system would not inject a sufficient quantity of urea to compensate for the additional NO_x being produced and NO_x outlet concentration would increase.

A total of 22 high NO_x outlet events (63 periods or 0.3% of the total engine operating time) occurred when the engine load exceeded 100%. During the pilot testing period, the urea injection rate setpoints were set for an engine load range of 0% to 100%. An event was considered to be due to an increase in engine load if the engine load increased to above 100% during the same period or during the period immediately preceding the event. When the engine load exceeded 100% of design load for an extended period of time, the urea injection rate was not able to adjust properly because the engine operation surpassed the programming of the system.

There are 22 high NO_x outlet events (75 periods or 0.4% of the total engine operating time) that could not be attributed to operational issues/system adjustments, engine start-up, increased natural gas fuel usage, or high engine load. The NO_x outlet concentrations during the majority of these periods typically ranged between 11 and 12 ppmv, with a maximum of 16 ppmv.

The maximum NO_x concentration at the outlet was 16 ppmv after removing the non-control system related exceedances, including operational issues/system adjustments and engine start-up. The validated average, minimum, and maximum NO_x outlet concentrations recorded by the CEMS are presented in Table 3-12. The validated data set includes the NO_x outlet concentration data during increased natural gas fuel usage, high engine load, and other high NO_x outlet events not attributed to operational issues/system adjustments, engine start-up, increased natural gas fuel usage, or high engine load. Following the pilot test, the urea injection setpoints and biases may be increased to account for increased NO_x production due to increased natural gas in the fuel blend and higher engine loads. Increasing the urea injection setpoints may also reduce the number of other high NO_x outlet events that fall just above the 11 ppmv NO_x limit.

In April 2011, after the official pilot testing period concluded, a Johnson Matthey technician adjusted the urea injection rate curve to 1) expand the curve to a maximum of 125% engine load and 2) to increase the urea injection rate at high engine loads. The increase in urea injection rate should accommodate for the increased NO_x production when the engine incorporates more natural gas into the fuel blend. Further observation will be required to confirm if these adjustments will lead to a reduction in the number of periods where stack exhaust NO_x outlet concentration exceeds 11 ppmv.

3.3.4. Ammonia Concentration

The SCR system reduces NO_x through a chemical reaction between ammonia and NO_x, facilitated by a catalyst to form nitrogen and water vapor. Once urea is injected into the engine exhaust stream, it breaks down into ammonia and other constituents. Hydrolysis of the urea on the face of the catalyst generates more ammonia. While NO_x reduction is the goal of the SCR system through the consumption of the ammonia, injection of too much urea can result in excess ammonia (total ammonia) at the SCR outlet in the form of free ammonia (NH₃), and/or other ammonia-formed compounds. Parts of the total ammonia can then participate in secondary reactions with other compounds in the exhaust gas forming by-products, such as ammonium sulfates (combined ammonia). These secondary ammonia by-products may have the undesirable potential to increase maintenance requirements on the equipment downstream from the SCR, due to clogging and particulate buildup. The remaining gaseous ammonia (free ammonia) that is emitted at the stack exhaust is referred to as ammonia slip. SCAQMD regulated the amount of ammonia slip in the Pilot Study Research Permit not to exceed 10 ppmv of free ammonia at the stack exhaust.

Three methods were used for determining ammonia concentration:

- On-site field measurement of free ammonia using Draeger® or Sensidyne® tubes,
- Modified SCAQMD Method 207.1 to measure free ammonia, and

- Estimated total ammonia concentration (free plus combined ammonia) calculation method using inlet and outlet NOx CEMS concentrations and the urea injection rate.

Free ammonia concentration data was collected during source testing at the stack exhaust using modified SCAQMD Method 207.1, and also routinely monitored throughout the pilot testing period using Draeger® tubes or Sensidyne® tubes at the SCR outlet. Both tests provide concentration data for free ammonia. Total ammonia was also calculated from the CEMS data based on the NOx inlet and outlet concentrations and the urea injection rate. The limitations of this total ammonia calculation are discussed in detail in a technical memorandum *OCSO Cat Ox/SCR Pilot Study: Ammonia Sampling and Calculation Methods* (Malcolm Pirnie, May 2011) found in Appendix C-2. As with the NOx data, the ammonia data presented in this section represents data collected during the pilot testing in the period from June 8, 2010 through March 31, 2011, after the urea injection rate set points were adjusted on June 8, 2010. Figure 3-3 presents the maximum total ammonia estimate for each day of the pilot test between these dates using the calculation method.

Over the course of the pilot testing period, the Draeger® tubes consistently measured free ammonia concentrations at the stack exhaust below MDL. During the same time period when the ammonia field measurements were taken, the calculated total ammonia concentration using the 15-minute block averages reported by the CEMS had a value ranging from 0 to 5 ppm of ammonia.

Estimated Total Ammonia Calculation. The calculation method for total ammonia is dependent on the NOx inlet and NOx outlet concentrations and the urea injection rate, which is continuously adjusting based on the engine load and the NOx outlet concentration. The ammonia calculation equation is shown below, where CF can be used as a correction factor to account for factors such as secondary reactions and limitations of the urea injection system, and as a tool to adjust the calculation of total ammonia to estimate free ammonia.

$$\text{NH}_3 = [\text{Urea Fed} - (\text{NOx in} - \text{NOx out}) / 2] \times \text{CF}$$

The CF was assumed to be equal to 1 in the present study. Throughout the pilot testing, differences were observed between the free ammonia measured in the field and total ammonia estimated using the calculation method. The calculation method assumes that the ammonia/NOx reaction is the only reaction consuming the urea. There is the potential for ammonia molecules to be consumed in other secondary reactions in the exhaust stream, such as those with sulfur compounds. Sulfur dioxide (SO₂) and sulfur trioxide (SO₃) can react with ammonia to produce ammonium sulfate (NH₄HSO₄) and ammonia bisulfate (ammonia hydrogen sulfate) ((NH₄)₂SO₄) which can precipitate out of the exhaust gas at low temperatures (300-450°F) as ammonium salts (combined ammonia). Ammonium salts have the potential to deposit on equipment downstream from

the SCR catalyst, such as the heat recovery boiler, reducing their efficiency and increasing maintenance requirements. Field measurements during the pilot test were only performed for free ammonia which did not include ammonia compounds, such as the ammonium salts. Low ammonia concentration Draeger® tube measurements combined with the and high exhaust gas temperatures (~ 800°F) taken directly after the SCR catalyst indicate that the potential for these secondary reactions is low.

Engine load fluctuates with time. When the IC engines are set to a base load, it was observed that the actual engine load fluctuated rapidly by as much as ten percent below the set point. This was found to be typical for the OCS D IC engines. However, since urea injection rate is mapped to engine load, the rapid fluctuations in load can result in rapid changes in urea injection rates. Rapidly changing urea injection rates, instead of steady rates with smooth transitions, can cause inaccuracies in the ammonia calculation.

SCAQMD Sampling Using Compliance Methods. Free ammonia was measured at the stack exhaust once during the initial source testing event from April 7-8, 2010, and once after the pilot testing period on May 10, 2011. On both occasions, ammonia slip concentrations at three engine loads measured by Modified SCAQMD Method 207.1 were found to be less than 0.5 ppmv. Neither the Draeger® tube nor Sensidyne® tube free ammonia measurements at the SCR exhaust were above the MDL. However, the total ammonia estimate based on the theoretical calculation using the CEMS data was three to ten times higher than the measured value using the compliance method. Results of these sampling events are compared in Table 3-13.

Further sampling of the exhaust emissions can be performed to establish a value for the correction factor, CF, in the estimated total ammonia calculation method for the calculation of free ammonia. If found, the presence of sulfur dioxide and sulfur trioxide in the exhaust gas before the SCR, and ammonium sulfate and ammonia bisulfate, in the exhaust gas after the SCR, can indicate secondary reactions taking place due to the injection of urea. In addition, inspection of the heat recovery boiler during the next scheduled maintenance may also indicate the presence of ammonium salts in the exhaust gas. A correction factor can be applied to the estimated total ammonia calculation to account for these secondary reactions, thus allowing for the estimation of free ammonia. If ammonium salts are identified in the heat recovery boiler, adjustments to the urea injection rates or additional maintenance of the heat recovery boiler may be required.

Compliance monitoring for free ammonia is more accurate when reflective of gaseous ammonia emitted from the stack, while the estimated total ammonia calculation method may reflect both free ammonia and ammonia by-products produced in the exhaust gas. Although the pilot study data indicates that there is minimal, if any, free ammonia (ammonia slip) due to the SCR system, it is recommended that the OCS D perform

additional and routine testing for ammonia slip during varying loads and fuel blends over a period of time.

3.4. Engine Performance

A significant amount of operational data was collected throughout the pilot test. The data logger installed within the urea injection control cabinet collected additional data beyond that collected by the CEMS. These data included the temperature at the catalytic oxidizer inlet and outlet, and the SCR inlet and outlet and the differential pressure across the catalytic oxidizer and SCR catalysts. The system urea injection and back pressure performance proposed by Johnson Matthey is provided in Table 3-14. The data collected by the data logger are summarized in Table 3-15 and were validated to remove periods when the engine was offline. Periods when the engine was offline were identified as those periods when the urea injection is offline, when the temperatures in the catalyst housings cool and the NOx inlet concentration decreases to zero.

During the pilot test, there were no notable back pressure effects on engine performance due to the installation of the Cat Ox/SCR system with a digester gas cleaning system. The engine manufacturer's allowable back pressure is 20 inches of water column (in. wc.). The engineering design estimate of the maximum engine exhaust system back pressure without the Cat Ox/SCR system was 11 in. wc. Therefore, the available system design back pressure for the Cat Ox/SCR system and additional exhaust ductwork was 9 in. wc. Based on the data provided by the data logger in during the pilot test, the average differential pressure through the catalytic oxidizer and SCR are approximately 0.3 and 1.0 in. wc., respectively. Therefore, it is concluded that the system does not negatively affect engine performance.

The exhaust gas temperature reported through the catalytic oxidizer and SCR and the urea injection rate indicate proper system performance. The average inlet and outlet temperature through both catalysts is between 750°F and 800°F, which is in the proper temperature range for ammonia to react in the SCR catalyst. The actual urea injection rate of approximately 0.6 gallons per hour (gph) is also below the urea usage estimate of 1.1 gph proposed by Johnson Matthey.

The DGCS has had a positive effect on engine performance. The use of cleaned digester gas at Plant 2 Engine 3 resulted in much less frequent maintenance requirements for the engine, including longer time intervals between spark plug changes and major maintenance events. OCSO Operations continues to use the DGCS from the 2007 pilot study at Plant 2 Engine 3 after improvements in performance of the engine and maintenance cost savings resulted from use of the DGCS. These savings are discussed further in Section 4.

3.5. Summary of System Results

The overall results of the pilot study are:

- The maximum NO_x concentration at the stack exhaust after the pilot study controls was approximated 16 ppmv, and the average NO_x concentration was approximately 7.2 ppmv, below the 11 ppmv required under amended Rule 1110.2. Further adjustment of the urea injection rate was performed after the end of the pilot study, and these new data will be evaluated further to determine if this urea injection rate modification will eliminate excursions above 11 ppmv.
- While there were some excursions above 11 ppmv, once these excursions were screened for exempt conditions like start-up, and non-control system error, less than 0.9% of the total measurement periods during the pilot study, or 181 15-minute periods out of 21,285 periods in total remained above 11 ppmv.
- Using monitoring data for gaseous free ammonia collected using the SCAQMD method and Draeger® tube method, the free ammonia concentration was below 0.5 ppmv and MDL over the pilot study, respectively.
- Based on the calculation method for total ammonia, the maximum total ammonia concentration during ammonia concentration sampling events was estimated to be 4.65 ppmv. It is believed that this is an overestimate due to limitations of the calculation, such as not accounting for potential secondary ammonia reactions. Despite this, the estimated total ammonia calculation method can be used as a tool to prompt a field measurement to determine free ammonia (ammonia slip) with the application of an appropriate correction factor, CF. Further evaluation needs to be performed to develop a correction factor that will correlate the calculation method and the measured values of free ammonia.
- The percentage reduction in CO concentration measured across the Cat Ox/SCR system by the portable analyzer ranges consistently exceeded a 96% reduction in CO concentration from the engine exhaust.
- The maximum CO concentration at the stack exhaust using the CEMS data was 42.2 ppmv, well below the amended Rule 1110.2 emission limit of 250 ppmv.
- The catalytic oxidizer was found to result in removing approximately 96 % VOCs from the engine exhaust.
- The maximum VOC concentration at the stack exhaust was found to be 5.42 ppmv using Method 25.3, and consistently well below the 30 ppmv in amended Rule 1110.2.

- The DGCS system, in general, removed siloxanes from the digester gas to below MDL levels and significantly reduced sulfur compounds and VOCs successfully reducing catalyst masking which should lead to extended catalyst life.
- The DGCS system resulted in overall improvements in engine maintenance requirements.
- No back pressure concerns for the engine due to the additional equipment were identified.

**Table 3-1:
Summary of Fixed Gases in Plant 1 Digester Gas**

Fixed Gas	DGCS Inlet			DGCS Outlet		
	Min.	Max.	Avg.	Min.	Max.	Avg.
	(%)	(%)	(%)	(%)	(%)	(%)
Carbon Dioxide (CO ₂)	25.5	40.1	33.9	23.1	37.2	32.8
Methane (CH ₄)	53.7	62.6	58.7	45.0	62.5	58.0
Nitrogen (N ₂)	0.9	5.1	2.2	1.1	1.9	1.5
Oxygen (O ₂)	0.1	1.4	0.6	0.1	0.8	0.4

**Table 3-2:
Summary of Reduced Sulfides in Plant 1 Digester Gas**

Compound	DGCS Inlet		
	Min.	Max.	Avg.
	(ppmv)	(ppmv)	(ppmv)
Hydrogen Sulfide	14.7	31.9	26.4
Carbonyl Sulfide	0.01	0.03	0.02
Methyl Mercaptan	0.05	0.08	0.06
Ethyl Mercaptan	0.2	0.3	0.3
Dimethyl Sulfide	0.006	0.02	0.01
Carbon Disulfide	0.004	0.009	0.006
n-Propyl Thiol	0.5	0.8	0.6
iso-Propyl Thiol	0.2	0.4	0.3
Dimethyl Disulfide	ND	ND	ND
Isopropyl Mercaptan	0.3	0.3	0.3
n-Propyl Mercaptan	0.3	0.3	0.3

Note: 1) ND indicates non-detect.

**Table 3-3:
Summary of Speciated Siloxanes in Plant 1 Digester Gas**

Compound	DGCS Inlet		
	Min.	Max.	Avg.
	(ppbv)	(ppbv)	(ppbv)
Hexamethyldisiloxane (L2)	<MDL	<MDL	<MDL
Hexamethylcyclotrisiloxane (D3)	10	17	12
Octamethyltrisiloxane (L3)	10	19	14
Octamethylcyclotetrasiloxane (D4)	369	1,600	704
Decamethyltetrasiloxane (L4)	73	170	121
Decamethylcyclopentasiloxane (D5)	1,300	14,000	5,371
Total Siloxanes	919	15,700	5,452

Note: MDL is mean detection level.

**Table 3-4:
Summary of Speciated VOCs in Plant 1 Digester Gas**

Analyte	DGCS Inlet		
	Min.	Max.	Avg.
	(ppbv)	(ppbv)	(ppbv)
Acetone	7.0	88.0	26.0
Benzene	7.3	15.7	10.7
Chlorobenzene	4.5	6.4	5.4
Cyclohexane	4.9	22.0	13.6
1,4-Dichlorobenzene	5.0	28.0	16.4
cis-1,2-Dichloroethene	17.2	103.0	41.4
trans-1,2-Dichloroethene	4.6	4.6	4.6
Ethyl Acetate	22.2	22.2	22.2
Ethylbenzene	37.0	141.0	74.2
4-Ethyltoluene	12.7	68.6	33.7
Freon 11	5.2	6.3	5.8
n-Heptane	57.8	122.0	84.2
Hexane	27.0	210.0	76.5
Methylene Chloride	5.2	14.0	8.9
Methyl Isobutyl Ketone (MIBK)	4.4	4.5	4.4
Propene	2,410	3,730	3,226
Styrene	4.2	24.7	10.7
Tetrachloroethene (PCE)	11.0	11.0	11.0
Tetrachloroethylene	6.0	26.3	13.5
Toluene	1,090	7,300	2,296
1,2,4-Trichlorobenzene	9.2	9.2	9.2
Trichloroethene (TCE)	9.6	28.0	15.8
Trichloroethylene	6.2	22.9	11.7
1,2,4-Trimethylbenzene	67.1	240.0	123.1
1,3,5-Trimethylbenzene	30.0	88.0	45.8
2,2,4-Trimethylpentane	27.0	66.0	52.0
m & p-Xylene	47.0	180.0	96.1
o-Xylene	20.0	64.0	36.3
Total VOCs	1,594	11,133	4,927

**Table 3-5:
Summary of Siloxane and H₂S Sampling**

Date of Sampling	Approximate Volume of Gas Treated (million cubic feet)	Total Siloxane		H ₂ S			
				SCAQMD 307-91		Draeger Tube	
		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
		(ppmv)	(ppmv)	(ppmv)	(ppmv)	(ppmv)	(ppmv)
3/16/2010	0.00	3.58	<MDL	N/A	N/A	N/A	N/A
4/7/2010	27.26	8.51	<MDL	N/A	N/A	N/A	N/A
4/21/2010	53.41	N/A	N/A	25.70	ND	26	ND
4/29/2010	68.93	15.70	ND	N/A	N/A	N/A	N/A
5/11/2010	91.86	N/A	N/A	31.70	0.263	31	ND
5/27/2010	122.58	2.67	0.015	N/A	N/A	N/A	N/A
6/8/2010	144.70	N/A	N/A	27.97	2.162	30	2
6/11/2010	146.46	8.49	0.248	N/A	N/A	N/A	N/A
6/12/2010	Carbon media changed.						
6/22/2010	18.44	N/A	N/A	21.62	ND	27	N/A
6/29/2010	32.70	8.69	N/A	N/A	N/A	N/A	N/A
7/7/2010	46.34	N/A	N/A	28.57	ND	25	N/A
7/21/2010	68.89	N/A	N/A	24.87	ND	25	N/A
8/3/2010	90.04	N/A	N/A	27.45	ND	25	N/A
8/12/2010	106.00	N/A	N/A	28.19	ND	26	N/A
8/12/2010	106.00	3.73	ND	N/A	N/A	N/A	N/A
9/1/2010	137.15	4.57	<MDL	N/A	N/A	N/A	N/A
9/1/2010	137.15	N/A	N/A	14.69	ND	14	N/A
9/14/2010	162.45	N/A	N/A	23.01	0.545	23	N/A
9/15/2010	164.63	4.35	<MDL	N/A	N/A	N/A	N/A
9/17/2010	168.63	N/A	N/A	N/A	N/A	N/A	2.5
9/20/2010	173.62	5.73	<MDL	N/A	N/A	N/A	N/A
9/21/2010	Carbon media changed.						
11/4/2010	43.40	5.23	N/A	N/A	N/A	N/A	N/A
1/12/2011	114.53	6.55	N/A	N/A	N/A	N/A	N/A
1/25/2011	137.78	N/A	N/A	28.54	ND	27	N/A
2/9/2011	156.47	N/A	N/A	31.87	1.755	30	N/A
2/9/2011	156.47	4.58	<MDL	N/A	N/A	N/A	N/A
2/14/2011	Carbon media changed.						
2/23/2011	17.72	N/A	N/A	24.46	ND	25	N/A
2/24/2011	20.09	6.64	N/A	N/A	N/A	N/A	N/A

- Notes: 1) All samples are taken using Tedlar® bags, except where otherwise noted as using Draeger® tubes for H₂S.
2) Inlet and outlet sample results from 5/19/10 are not accurate due to an error in collection, indicated by high nitrogen composition (>5%), and are not included in the minimum, maximum and average.



- 3) Outlet sample results from 6/29/10 are not accurate due to an error in collection, indicated by high nitrogen composition (>5%), and are not included in the minimum, maximum and average.
- 4) Inlet and outlet sample results from AccuLabs on 8/12/10 are not accurate due to an error in collection, indicated by high nitrogen composition (>5%), and are not included in the minimum, maximum and average.
- 5) Sample results from 8/19/10 are not consistent with sample results from other laboratories and are concluded to be erroneous and not included in the minimum, maximum and average.
- 6) N/A indicates that the compound was not analyzed.
- 7) ND indicates non-detect.
- 8) <MDL indicates less than the Method Detection Limit.

**Table 3-6:
Plant 1 Engine 1 April 7-8, 2010 Testing using SCAQMD Compliance
Methods**

Parameter	Units	Low Load	Normal Load	High Load	Average Load
Load	KW	1,598	2,303.5	2,515.8	2,139.1
	%	65	90	105	86.7
Volume Flow	dscfm	5,662	8,423	9,244	7,776.3
Fuel Flow	NG scfm	14.2	19.7	20.8	18.2
	DG scfm	470.7	635.3	688.8	598.3
Stack Exhaust					
NOx	ppm	6.5	4.7	8.5	6.6
CO	ppm	7.3	4.9	4.9	5.7
TGMNNEO	ppm	N/A	N/A	2.6	2.6
Formaldehyde	ppm	N/A	N/A	0.434	N/A
Acetaldehyde	ppm	N/A	N/A	0.023	N/A
Acrolein	ppm	N/A	N/A	< MDL	N/A
Ammonia	ppm	0.12	0.18	0.43	0.2
O ₂	%	10.59	11.97	12.03	11.5
CO ₂	%	8.56	7.55	7.69	7.9
Engine Exhaust					
TGMNNEO	ppm	N/A	N/A	25.86	N/A
Formaldehyde	ppm	N/A	N/A	21.44	N/A
Acetaldehyde	ppm	N/A	N/A	0.419	N/A
Acrolein	ppm	0.18	0.18	< MDL	N/A

Notes: 1) N/A indicates not applicable.
2) <MDL indicates less than the Method Detection Limit.

**Table 3-7:
SCAQMD Rule 1110.2 Year 2011 Permit Compliance Test Report**

Parameter	Units	Low Load	Normal Load	High Load	Average Load
Engine 1					
Load	KW	1,655	1,929	2,438	2,183.5
	%	66	77	98	87.3
Volume Flow	dscfm	6,194	7,406	9,124	8,265.0
NOx	ppm	4.6	5.4	6.9	6.2
CO	ppm	6.2	7.6	8.2	7.9
TGMNNEO	ppm	N/A	3.2	N/A	N/A
PM	gr/dscf	N/A	0.0	N/A	N/A
O ₂	%	10.90	11.84	12.16	12.00
CO ₂	%	8.59	7.83	7.52	7.68
Engine 2					
Load	KW	1,618	1,852	2,455	2,153.7
	%	65	74	98	86.2
Volume Flow	dscfm	6,513	7,598	9,867	8,732.5
NOx	ppm	27.8	27.6	31.6	29.6
CO	ppm	348.7	390.4	432.3	411.4
TGMNNEO	ppm	N/A	97.2	N/A	N/A
PM	gr/dscf	N/A	0.0010	N/A	N/A
O ₂	%	11.79	12.04	12.53	12.29
CO ₂	%	7.80	7.60	7.16	7.38
Engine 3					
Load	KW	1,748	1,981	2,488	2,234.6
	%	70	79	100	89.4
Volume Flow	dscfm	6,703	7,746	9,652	8,699.0
NOx	ppm	29.1	30.1	31.2	30.7
CO	ppm	317.3	343.8	394.7	369.3
TGMNNEO	ppm	N/A	96.9	N/A	N/A
PM	gr/dscf	N/A	0.0049	N/A	N/A
O ₂	%	11.68	12.01	12.49	12.25
CO ₂	%	7.87	7.57	7.18	

Notes: 1) N/A indicates not applicable

**Table 3-8:
Summary of CO Concentrations from Inlet and Outlet of Cat Ox/SCR
System**

Sampling Method	Catalytic Oxidizer Inlet Concentration (ppmvd) ¹			SCR Outlet/Stack Exhaust Concentration (ppmvd) ¹		
	Min.	Max.	Avg.	Min.	Max.	Avg.
Portable Analyzer ²	367.5	598.7	451.6	<MDL	17.2	5.8
CEMS ³	N/A ⁴	N/A ⁴	N/A ⁴	4.0	42.2	7.5

- Notes:
- 1) Concentrations are presented in parts per million by volume dry (ppmvd) at 15% O₂
 - 2) CO concentrations by portable analyzer are measured routinely starting on April 7, 2010, after initial mapping of the SCR system.
 - 3) NOx and CO CEMS data is based on an average of the 15-minute average NOx and CO concentrations for each calendar day.
 - 4) N/A: CEMS measures CO at the stack exhaust only; therefore, there is no CEMS data at the Cat Ox inlet.

**Table 3-9:
VOC Concentrations at Stack Exhaust**

Date	Stack Exhaust (ppmv)
4/7/2010	2.60
5/11/2010	0.73
8/12/2010	5.42
11/4/2010	4.21
2/24/2011	4.95
Average	3.58

Notes: All concentrations are adjusted to 15% O₂.

**Table 3-10:
Summary of NOx Concentrations¹ at Inlet and Outlet of Cat Ox/SCR System**

Sampling Method	Catalytic Oxidizer Inlet Concentration (ppmvd)			Catalytic Oxidizer Outlet Concentration (ppmvd)			SCR Outlet/Stack Exhaust Concentration (ppmvd)			NOx Reduction (%)
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Avg.
SCAQMD Method 100.1 ²	---	---	---	---	---	---	N/A	N/A	6.6	N/A
Portable Analyzer ³	37.9	43.5	40.9	36.4	44.0	40.1	6.9	10.2	8.4	79.5
CEMS ⁴	19.3	64.7	30.7	---	---	---	0.8	15.9	7.2	77

- Notes:
- 1) Concentrations are presented in parts per million by volume dry (ppmvd) at 15% O₂.
 - 2) Method 100.1 measurements by SCEC were performed at the stack exhaust only.
 - 3) NOx concentrations by portable analyzer are measured routinely starting on April 7, 2010, after initial mapping of the SCR system.
 - 4) NOx and CO CEMS data is based on an average of the 15-minute average NOx and CO concentrations for each calendar day. CEMS data was not collected at the Cat Ox outlet.
 - 5) N/A indicates not applicable.

**Table 3-11:
Count of Periods and Events with NOx Concentration Above 11 ppmvd**

Number of 15-minute periods when NOx stack exhaust concentration exceeded 11 ppmvd	Total High NOx Outlet Events ⁴	% of Total Operating Time ⁵	
Operational Issues and System Adjustments ^{1, 2}	703	7	3.3
Engine start-up (30 minutes) ³	56	29	0.3
Total Non-Valid	759	36	3.6
Increase in NG Fuel Composition	43	17	0.2
High Load (>100%)	63	22	0.3
Other	75	22	0.4
Total Valid	181	61	0.9
Total	940	97	4.5

- Notes:
- 1) Operational issues occurred 7/1/10-7/4/10, 12/29/10-1/4/11, 3/14/11, 3/17/11, and 3/22/11.
 - 2) NOx at the stack exhaust exceeded 11 due to system adjustments to the urea injection system.
 - 3) The first 30 minutes after start-up of the engine are exempt from amended Rule 1110.2. Data was excluded where NOx at the stack exhaust exceeded 11 ppmvd during engine start-up.
 - 4) An "event" is defined as one or more consecutive 15-minute periods or periods in close succession where the NOx outlet concentration exceeded 11 ppmvd.
 - 5) The total engine operating time is 21,285 15-minute periods (approximately 5,321 hours).

**Table 3-12:
Summary of All vs. Validated NOx Inlet and Outlet Concentrations**

Parameter	NOx Engine Exhaust (ppmvd)	All NOx Stack Exhaust (ppmvd)	Validated NOx Stack Exhaust (ppmvd)
Average	30.68	7.53	7.16
Minimum	10.72	0.80	0.80
Maximum	64.70	45.23	15.88
Number NOx Stack Exhaust Periods > 11 ppmvd	N/A	940	181
Percentage of 15-minute periods > 11 ppmvd	N/A	4.4%	0.9%

- Notes:
- 1) Concentrations are presented in parts per million by volume dry (ppmvd) at 15% O₂.
 - 2) NOx CEMS data is based on the 15-minute average NOx concentrations from June 8, 2010 through March 31, 2011.
 - 3) N/A indicates not applicable

**Table 3-13:
Ammonia Concentration Sampling Event Summary**

Date	Engine Load (%)	Free NH ₃ Field Measurement ¹ (ppmv)	Total NH ₃ Calculated Value ² (ppmv)	Free NH ₃ SCAQMD Method 207.1 (ppmv)
4/7/2010 & 4/8/2010	65	<MDL	1.66	0.12
	90			0.18
	105			0.43
4/21/2010	110	<MDL	0.09	N/A
4/29/2010	90	<MDL	0.00	N/A
5/6/2010	94	<MDL	2.18	N/A
5/19/2010	100	<MDL	2.54	N/A
6/29/2010	100	<MDL	0.97	N/A
7/28/2010	100	<MDL	0.63	N/A
8/12/2010	95	<MDL	2.50	N/A
11/4/2010	100	<MDL	4.95	N/A
1/12/2011	100	<MDL	0.32	N/A
2/24/2011	100	<MDL	0.09	N/A
5/10/2011	70	<MDL	1.12	0.37
	90		1.60	0.31
	110		3.12	0.38

- Notes:
- 1) Free ammonia field measurements are taken using MDL to 2.5-3 ppm range and 2 to 30 ppm range Draeger® tubes.
 - 2) Total ammonia was determined based on the theoretical calculation which uses NOx inlet and NOx outlet of the catalytic oxidizer/ SCR system and the urea injection rate. The calculated value reported is based on the 15-minute block averages from the CEMS for the time period when the exhaust gas sample was taken for the field measurement. No correction factor was applied.
 - 3) <MDL: below Method Detection Limit.
 - 4) N/A indicates not applicable. No data was taken using Method 207.1 during these field measurement events.

**Table 3-14:
Catalytic Oxidizer /SCR System Performance Proposal**

Urea usage estimate (32.5% urea solution) @ 80% NOx reduction	1.1 gallons/hour
Estimated pressure drop across catalytic oxidizer using a 4040 arrangement with one layer of standard depth (~ 3.5") catalyst elements @ 200 CPSI = A	0.7 in. wc.
Estimated pressure drop across SCR converter using a 4040 arrangement with two layers of standard depth (~ 3.5") catalyst elements @ 200 CPSI = B	1.4 in. wc.
Estimated pressure drop across 12 foot long mixing duct with one static mixer installed = C	1.9 in. wc.
Total system pressure loss estimate (includes loss through oxidation converter, SCR converter, expansion joint, and mixing duct) using 4040 oxidation catalyst and two layers of 4040 SCR catalyst (A + B + C)	4.0 in. wc.
Estimated pressure drop across one additional layer (~ 3.5") of either catalytic oxidizer or SCR elements that are 200 CPSI	0.7 in. wc.
Additional system pressure drop loss estimate if an additional layer (~ 3.5") of 100 CPSI catalyst in the 4040 housing is employed	0.4 in. wc.
Additional system pressure drop loss estimate if an additional layer (~ 2") of 200 CPSI catalyst in the 4040 housing is employed	0.3 in. wc.

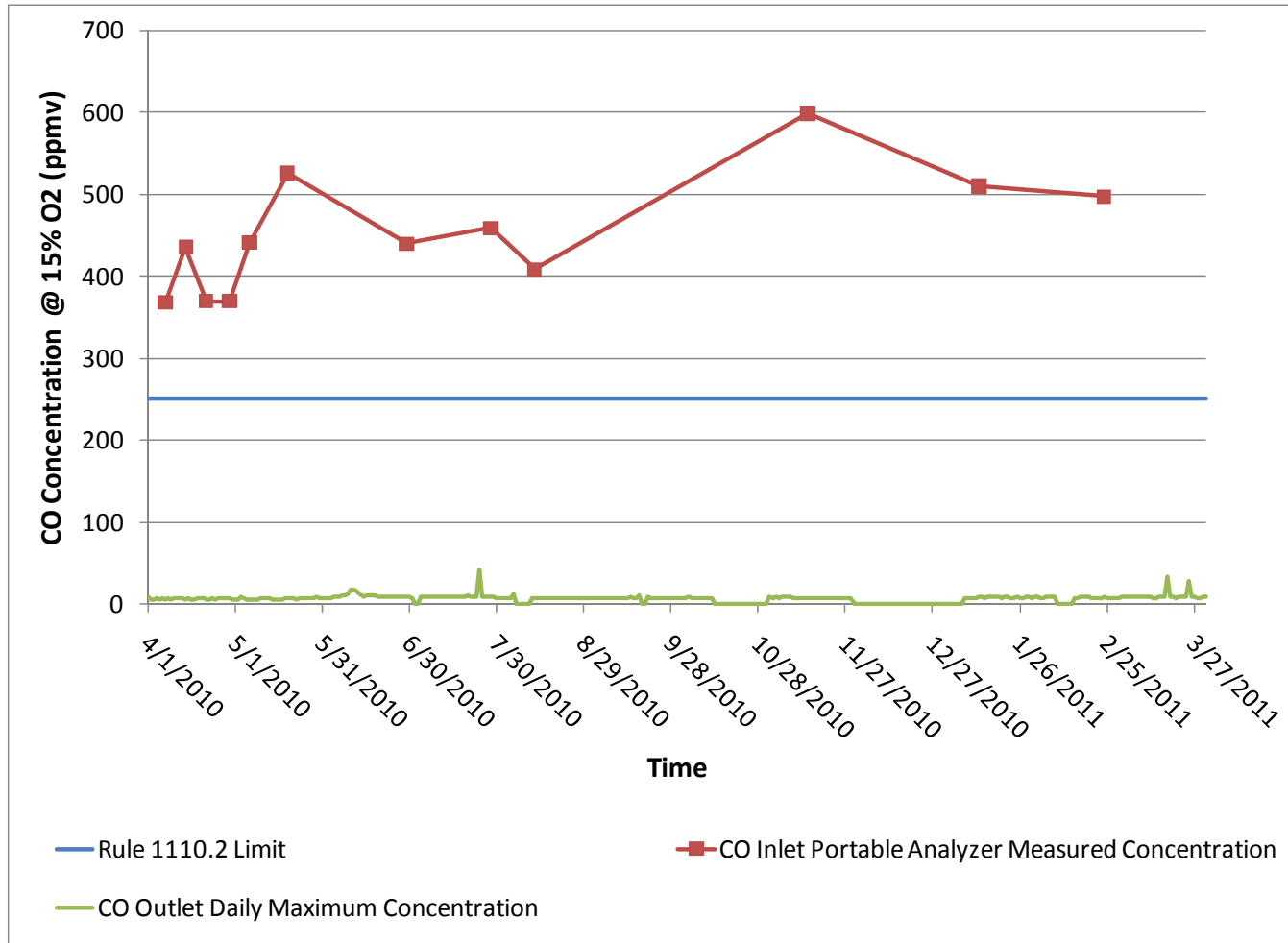
Notes: Estimates provided by Johnson Matthey in their system proposal, dated May 8, 2009.

**Table 3-15:
Catalytic Oxidizer /SCR System Performance Data**

	Unit	Average Value
Urea Injection Rate	gallon per hour	0.62
Catalytic Oxidizer Inlet Temperature	°F	781
Catalytic Oxidizer Outlet Temperature	°F	779
Catalytic Oxidizer Differential Pressure	in. wc.	0.3
SCR Inlet Temperature	°F	796
SCR Outlet Temperature	°F	756
SCR Differential Pressure	in. wc.	1.0

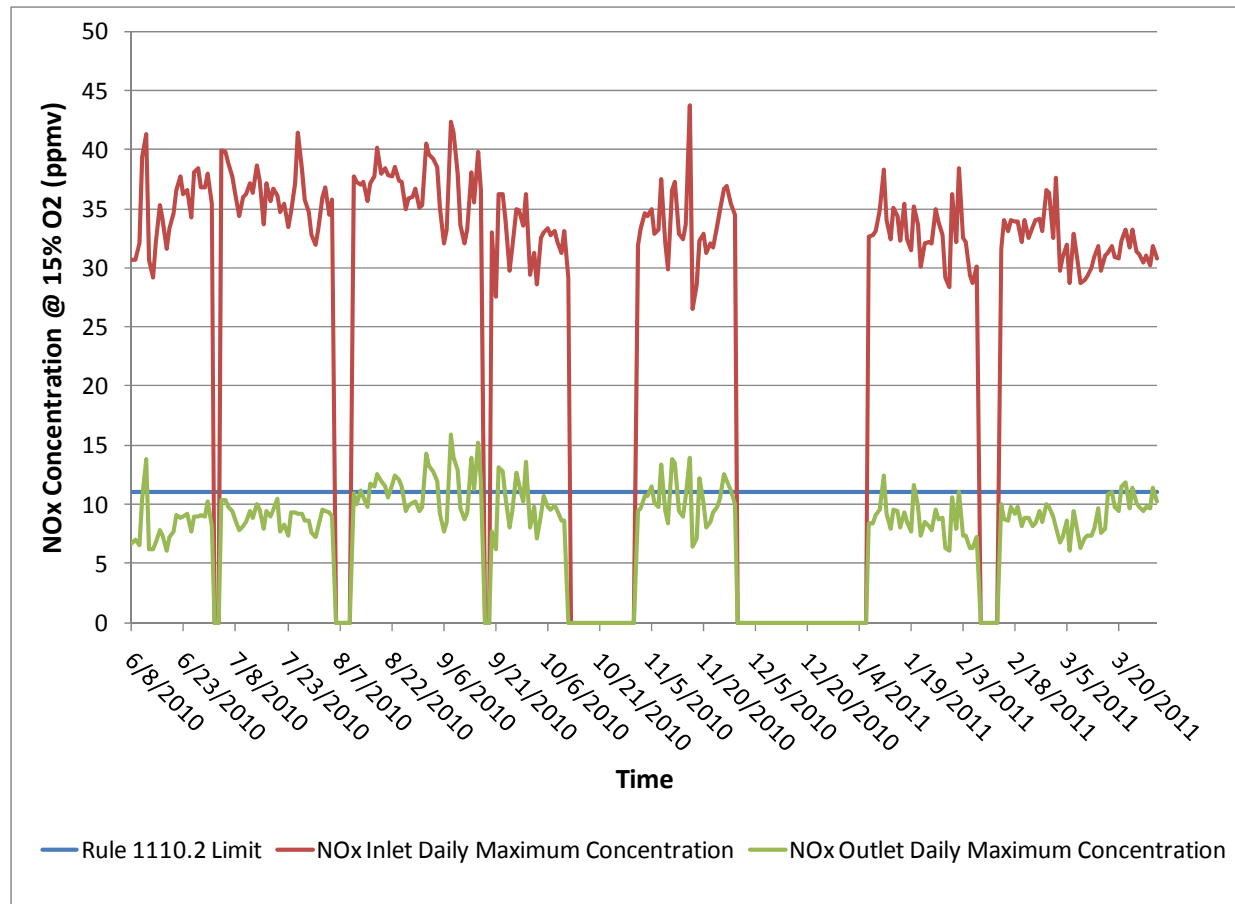
- Notes:
- 1) Estimates are provided by the data logger located inside of the urea injection cabinet for the period of April 1, 2010 through November 4, 2010 and January 1, 2011 through February 24, 2011.
 - 2) The data have been validated to remove periods where the engine was offline, as indicated when urea injection is offline, temperatures in the catalysts cool and NOx inlet value drop.

Figure 3-1: Catalytic Oxidizer Inlet and Outlet CO Concentration



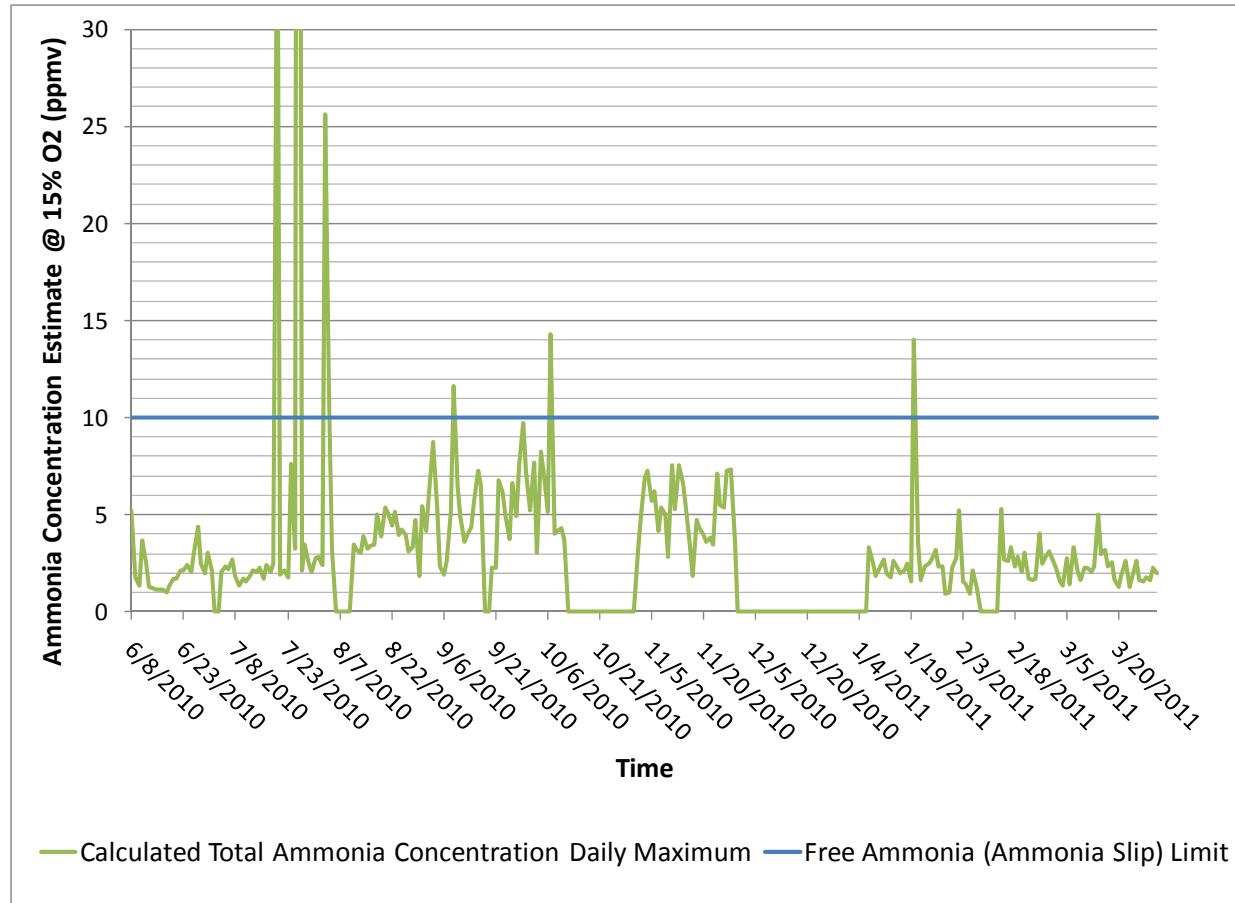
- Notes:
- 1) The first 30 minutes after start-up of the engine are exempt from amended Rule 1110.2. Data was excluded where NOx at the stack exhaust exceeded 11 ppmvd during engine start-up.
 - 2) CEMS values shown are maximum values for each calendar day and may not all occur at the same time as the portable analyzer measurement.
 - 3) Spikes where inlet and outlet NOx concentrations drop to 0 ppmv occur when the engine is offline.

Figure 3-2: Selective Catalytic Reduction Inlet and Outlet NOx Concentration



- Notes:
- 1) The first 30 minutes after start-up of the engine are exempt from amended Rule 1110.2. Data was excluded where NOx at the stack exhaust exceeded 11 ppmvd during engine start-up.
 - 2) Data was excluded where NOx at the stack exhaust exceeded 11 due to system adjustments to the urea injection system.
 - 3) Data was excluded where operational issues occurred from 7/1/10-7/4/10, 12/29/10-1/4/11, 3/14/11, 3/17/11, and 3/22/11.
 - 4) Values shown are maximum values for each calendar day and may not all occur at the same time within the day.
 - 5) Spikes where inlet and outlet NOx concentrations drop to 0 ppmv occur when the engine is offline.

Figure 3-3: Selective Catalytic Reduction Estimated Total Ammonia Concentration



- Notes:
- 1) The first 30 minutes after start-up of the engine are exempt from amended Rule 1110.2. Data were excluded where NO_x at the stack exhaust exceeded 11 ppmvd during engine start-up.
 - 2) Data were excluded where the SCR system was offline due to system adjustments to the urea injection system.
 - 3) Data were excluded where operational issues occurred from 7/1/10-7/4/10, 12/29/10-1/4/11, 3/14/11, 3/17/11, and 3/22/11.
 - 4) Values shown are maximum 15-minute values for each calendar day.
 - 5) Spikes where inlet and outlet ammonia concentrations drop to 0 ppmv occur when the engine is offline.
 - 6) Ammonia concentration values reported on July 20, 2010 and July 26, 2010 occurred within one hour of an engine shutdown or startup and were not part of the 30-minute exemption from amended Rule 1110.2.

4. Cost Effectiveness Analysis

A cost analysis for the implementation of the DGCS and Cat Ox/SCR systems at Plant 1 Engine 1 was performed. The cost analysis was developed for one digester gas cleaning vessel, with an approximate capacity of 9,900 lbs of carbon media and associated piping, and one Cat Ox/SCR system with platform installation.

4.1. Capital and Operation & Maintenance Costs

The capital project budget includes the following construction costs: equipment; installation; mechanical; structural; electrical; site/architectural; instrumentation; and material sales tax; as well as the construction contractor's expenses, such as contractor overhead, profit, mobilization, bonding, and insurance. For capital cost the following assumptions apply:

- The construction cost subtotal is time dated for June 2009 and based on the pilot test construction contract price, including change orders.
- The equipment cost is time dated for June 2009 and based on the pilot test costs of the following equipment: one Cat Ox/SCR system with urea injection control cabinet for Plant 1 Engine 1; one digester gas cleaning vessel with inlet, outlet, and bypass piping sized to treat 100 percent of the digester gas for the Plant 1 cogeneration facility; one NOx probe and umbilical sample line from the Engine 1 exhaust to the CEMS panel in the control room; and seven expansion joints for the engine exhaust ductwork.
- Project design and engineering is assumed to be 15% of the total construction and equipment cost.
- The annualized total capital project budget is based on a 20-year evaluation period and 4.0 percent annualized rate, as set forth in the SCAQMD July 9, 2010 Board Meeting Minutes, Attachment B: Assessment of Available Technology for Control of NOx, CO and VOC Emissions from Biogas-Fueled Engines – Interim Report.

Annual O&M costs associated with operating the digester gas cleaning system and Cat Ox/SCR system includes the following components:

- Annual additional electrical cost;
- Annual carbon media replacement costs;
- Oxidation and SCR catalyst replacement costs;
- Annual urea usage costs;
- Annual equipment maintenance costs;
- Periodic siloxane, VOC, and H₂S testing;

- The reduction in O&M costs due to the use of clean digester gas was considered. Such reduction in O&M costs includes a reduction in frequency of major maintenance interval service and maintenance shutdowns related to siloxane compounds present in the digester gas.
- The reduction in annual emissions fees for NO_x, VOC, CO, and formaldehyde based on the estimated emissions reductions realized from the engine exhaust control system was considered.

The assumptions related to the O&M costs are the following:

- Annual operating hours of a single engine at Plant 1 is estimated to be 6,000 hours.
- The change-out of the carbon media for the digester gas cleaning system is estimated to be approximately \$40,000 per change-out. The change-out frequency with three engines operating at Plant 1 at 6,000 annual operating hours is approximately three (3) times per year. The total annual cost of carbon media for three engines at 6,000 annual operating hours is \$120,000 per year. Therefore, the cost for carbon media for a single engine is approximately \$40,000 per year.
- The replacement of the sixteen catalytic oxidizer media blocks and thirty-two SCR catalyst media blocks is estimated to take place once every three years for each engine. Although the Cat Ox/SCR system demonstrated performance for one year during the pilot testing period, it is assumed that the media will perform for three years based on the vendor warranty of 16,000 operating hours. Assuming that each engine operates for 6,000 hour per year, the engine should reach 16,000 operating hours in 2 years and 8 months. The costs of each catalytic oxidizer media block and SCR catalyst media block are \$3,450 and \$1,850, respectively.
- Urea cost is assumed to equal \$4.50 per gallon, including tax, at an average rate of 0.7 gallons per hour for 6,000 annual operating hours.
- Equipment maintenance and testing is assumed to equal \$5,000 per year for annual maintenance of the SCR urea injection system, \$5,400 per year for siloxane testing (\$600 per sample, 3 samples per change out, and 3 change outs per year), and \$3,000 per year for VOC and H₂S sampling.
- Annual reduced engine maintenance cost using cleaned digester gas, assumed to equal \$130,641 for three engines operating at 6,000 hours annually. Therefore, the approximate savings per engine is approximately \$43,547 per year as estimated by OCSD. Currently, the three engines at Plant 1 are consuming all of the digester gas produced by the facility. Therefore, although the annual cost of maintenance is decreased, the total operating time of each engine will remain the same.
- Calculation of emissions reductions for NO_x, VOC, and CO is provided in Scenario 2 in Section 4.2 below. Scenario 2 assumed that the uncontrolled NO_x, VOC, and CO emissions were based on the results from the 2011 Annual Compliance Test for Engines 2 and 3. The controlled emissions were based on the Rule 1110.2 limits of 11 ppmv for NO_x and 30 ppmv for VOCs, and the pilot testing results of 15 ppmv for CO. Fees per ton of NO_x, VOC, and CO are assumed to be \$270.26, \$576.75, and

\$3.57, respectively, based on the Annual Emission Report provided by the OCSD dated February 23, 2011.

- The uncontrolled emissions of formaldehyde were based on the results of the 2009 Annual Compliance Test for Engine 3 of 1.4 lb/hr. The controlled emissions of formaldehyde were based on the results of the 2011 Annual Compliance Test for Engine 1 of 0.069 lb/hr. It is assumed that the annual operating hours of a single engine at Plant 1 is 6,000 hours. Therefore, formaldehyde emissions reduction is 4.13 tons per year. The fee per ton of formaldehyde is assumed to be \$800.00 based on the Annual Emission Report provided by the OCSD dated February 23, 2011.
- Annual O&M costs do not include the cost of ammonia sampling because it is assumed that ammonia sampling is part of the annual compliance test. The estimated ammonia sampling cost is \$2,500 for one sampling event per year using SCAQMD Method 207.1. The annual cost of weekly ammonia testing using Draeger® tubes or similar colorimetric tubes is assumed to equal \$300.

The capital cost and annual O&M costs for a single engine is presented in Table 4-1.

4.2. Unitized Cost of Carbon Media and Emissions Reduction

The cost of implementation of the DGCS and Cat Ox/SCR systems can be unitized as a cost per cubic foot of digester gas treated or as a cost per ton of NO_x and VOC reduced in the emissions. The following summarizes these metrics for evaluating costs.

4.2.1. Cost for Volume of Digester Gas Treated

A metric for evaluating the cost of the DGCS is the cost per cubic foot of digester gas treated. This metric is based on the frequency of the carbon media change-out as well as the cost per change-out. The digester gas volume that passed through the catalyst during the pilot test ranged from 146 MMcf to 169 MMcf. The cost of each carbon media change-out is assumed to be approximately \$40,000. Therefore, the cost per treated digester gas ranges between \$237/MMcf and \$274/MMcf. The capacity of the digester gas cleaning vessel is 9,900 pounds of carbon media. Therefore the media per volume of treated digester gas ranges between 59 lbs/MMcf and 68 lbs/MMcf. Note that these are conservative estimates. The pilot test only utilized a single digester gas cleaning vessel as opposed to a lead/lag configuration in which two vessels, a lead vessel followed by a second lag vessel, are used. Therefore, the carbon media was replaced more frequently than necessary to prevent potential breakthrough of siloxane compounds that may foul the catalyst. In a lead/lag configuration, the volume of gas treated between change-outs can be extended since breakthrough can be allowed to occur in the lead vessel because any siloxane compounds would be removed in the lag vessel.

4.2.2. Cost for Reductions in NO_x and VOCs, and CO Emissions

A metric for evaluating the cost effectiveness of the Cat Ox/SCR system is cost per ton of NO_x, VOC, and CO removed by the system. Based on the total annualized cost per

engine, two scenarios for estimating NO_x, VOC, and CO emissions reduced were developed. The following are the assumed uncontrolled and controlled concentrations for the two scenarios:

Scenario 1

- Uncontrolled concentrations are based on the current permit limits of 45 ppmv of NO_x, 209 ppmv of VOCs, and 2,000 ppmv of CO, each at 15% O₂.
- Controlled emissions are based on the future Rule 1110.2 limits of 11 ppmv of NO_x and 30 ppmv of VOCs, each at 15% O₂. Controlled emissions for CO are based on 15 ppmv because the Cat Ox/SCR system consistently reduced CO emissions well below the Rule 1110.2 limit of 250 ppmv. The concentration of 15 ppmv provides a factor of safety of 2 over the average CO concentration of 7.5 ppmv. The factor of safety gives credit for projected emissions reduction, but allows for reduced efficiency as the catalyst approaches the end of its lifecycle, prior to replacement.

Scenario 2

- Uncontrolled concentrations from the 2011 Annual Source Test Report are 31 ppmv of NO_x, 97 ppmv of VOCs, and 371 ppmv of CO at 15% O₂ for Plant 1 (Engines 2 and 3).
- Controlled emissions are based on the future Rule 1110.2 limits of 11 ppmv of NO_x and 30 ppmv of VOCs, each at 15% O₂. Controlled emissions for CO are based on 15 ppmv because the Cat Ox/SCR system consistently reduced CO emissions well below the Rule 1110.2 limit of 250 ppmv. The concentration of 15 ppmv provides a factor of safety of 2 over the average CO concentration of 7.5 ppmv. The factor of safety gives credit for projected emissions reduction, but allows for reduced efficiency as the catalyst approaches the end of its lifecycle, prior to replacement.

The assumptions used for each scenario were:

- Annual operating hours of a single engine at Plant 1 is estimated to be 6,000 hours;
- Exhaust flowrates are based on high load; and
- VOCs emissions are calculated as methane.

Table 4-2 provides a summary of the cost effectiveness for the two scenarios for one engine at Plant 1. The cost effectiveness in terms of dollars per ton of NO_x and VOCs reduced for Scenarios 1 and 2 was \$7,987 and \$17,585, respectively. The cost effectiveness in terms of dollars per ton of CO reduced for Scenarios 1 and 2 was \$363 and \$3,546, respectively. Note that the cost effectiveness for CO is conservative since the annualized cost is based on the entire system including the SCR and urea injection system.

**Table 4-1:
Estimated Capital and O&M Costs for Plant 1 Engine 1**

Capital Cost	Plant 1 Engine 1¹
Equipment (Cat Ox/SCR, DGCV, CEMS, Expansion Joints)	\$708,000
Labor and Contractor Cost²	
Bonding/Insurance	\$21,272
Mobilization	\$56,748
Prime Contractor Labor and Construction (i.e. concrete & rebar, piping, fittings, valves, installation & start-up, management, etc.)	\$765,723
Steel Subcontractor (i.e. structural steel, miscellaneous metal, handrail, grating)	\$249,941
Insulation Subcontractor	\$82,879
Electrical Subcontractor (i.e. wiring, conduit, grounding, etc.)	\$76,311
Painting Subcontractor	\$28,655
Labor and Contractor Cost Subtotal (including contractor markups for overhead, profit, mobilization, bonding, insurance)	\$1,281,529
Construction Subtotal (June 2009 dollars)	\$1,989,529
Project Design and Engineering (15% of construction subtotal)	\$298,429
Total Capital Cost	\$2,287,958
Annualized Capital Cost (4 % annual rate, 20 years)	\$168,352
Annual O&M Cost for 1 Engine (operating 6,000 hrs/yr)³	Plant 1 Engine 1
Carbon Media Replacement	\$40,000
Catalyst Replacement	\$38,133
Urea Cost	\$18,900
Electrical Cost	\$1,200
Equipment Maintenance and Testing	\$13,400
Reduced Engine Maintenance	\$(43,547)
Reduced Emission Fees	\$(9,136)
Annual O&M Cost per Engine	\$58,950
Total Annual Capital and O&M Cost for 1 Engine	Plant 1 Engine 1
Total Annualized Cost per Engine	\$227,302

- Notes: 1) Engine Size: 2,500 kW/3,471 bhp
 2) Subcontractor costs include a 10% prime contractor markup.
 3) Assumptions for the basis of O&M costs is provided in Section 4.1.



**Table 4-2:
Cost per Ton NOx and VOC Emissions Reduced at Plant 1 Engine 1**

Capital Cost	Plant 1 Engine 1
Annualized Capital Cost (4 % annual rate, 20 years)	\$168,352
Annual O&M Cost per Engine ^{1,2}	\$58,950
Total Annualized Cost per Engine	\$227,302
Scenario 1	Plant 1 Engine 1
Uncontrolled NOx – Current Permit Limit (ppmv)	45
Controlled NOx – Future Rule 1110.2 Limit (ppmv)	11
Uncontrolled VOC – Current Permit Limit (ppmv)	209
Controlled VOC – Future Rule 1110.2 Limit (ppmv)	30
Uncontrolled CO – Current Permit Limit (ppmv)	2,000
Controlled CO (ppmv) ³	15
NOx Reduction (ton/yr)	10.05
VOC Reduction (ton/yr)	18.41
CO Reduction (ton/yr)	357.21
Cost Effectiveness (\$/ton of NOx and VOC reduced)	\$7,987
Cost Effectiveness (\$/ton of CO reduced)	\$636
Scenario 2	Plant 1 Engine 1
Uncontrolled NOx – 2011 Source Testing Data (ppmv)	31
Controlled NOx – Future Rule 1110.2 Limit (ppmv)	11
Uncontrolled VOC (ppmv)	97
Controlled VOC – Future Rule 1110.2 Limit (ppmv)	30
Uncontrolled CO – 2011 Source Testing Data (ppmv)	371
Controlled CO (ppmv) ³	15
NOx Reduction (ton/yr)	6.03
VOC Reduction (ton/yr)	6.89
CO Reduction (ton/yr)	64.10
Cost Effectiveness (\$/ton of NOx and VOC reduced)⁴	\$17,585
Cost Effectiveness (\$/ton of CO reduced)⁴	\$3,546

- Notes:
- 1) Engine Size: 2,500 kW/3,471 bhp
 - 2) Annual Operating Hours: 6,000 hours/year
 - 3) Controlled emissions for CO are based on 15 ppmv because the Cat Ox/SCR system consistently reduced CO emissions well below the Rule 1110.2 limit of 250 ppmv. The concentration of 15 ppmv provides a factor of safety of 2 over the average CO concentration of 7.5 ppmv.
 - 4) Cost effectiveness of NOx and VOC reduced and CO reduced are calculated separately. The cost effectiveness of NOx and VOC is equal to the annualized cost per engine divided by the sum of NOx and VOC tons per year reduced. The cost effectiveness of CO is equal to the annualized cost per engine divided by the CO tons per year reduced and does not take NOx or VOC reduction into consideration.

5. Conclusions and Recommendations

In order to evaluate if the amended Rule 1110.2 limits could be met for their digester gas-fired IC engines, OCS D proposed to perform a pilot study on Engine 1 at Plant 1. In previous studies, OCS D had identified a catalytic oxidizer and SCR system along with a DGCS as the most feasible technology to lower air toxic emissions and to meet the new lower emissions limits. Because SCAQMD recognized that the emission limits in the new Rule 1110.2 were “technology-forcing,” they provided a grant to OCS D to support the pilot study at Plant 1 Engine 1 as part of a Rule 1110.2 technology assessment study to determine if cost-effective and commercial technologies are available to comply with the new lower emission limits. The 12-month pilot study at Plant 1 evaluated the effectiveness of the control systems to meet Rule 1110.2 limits.

5.1. System Performance

The DGCS system, in general, removed siloxanes from the digester gas to below MDL levels and significantly reduced sulfur compounds and VOCs successfully reducing catalyst masking which should lead to extended catalyst life. Additional benefits of the contaminant removal were significant improvements in engine maintenance requirements, and lower O&M costs. The use of cleaned digester gas resulted in much less frequent maintenance requirements for the engine, including longer time intervals between spark plug changes and major maintenance events.

There were no notable back pressure effects on engine performance due to the installation of the Cat Ox/SCR system with a DGCS during the pilot test. The system design back pressure for the Cat Ox/SCR system and additional exhaust ductwork was estimated to not exceed 9 in. wc. per the engine manufacturer’s recommendations. Based on the data monitored during the pilot test, the average differential pressure through the catalytic oxidizer and SCR systems are approximately 0.3 and 1.0 in. wc, respectively.

The combined Cat Ox/SCR system with digester gas cleaning evaluated in the pilot study resulted in significant reductions in CO, VOC, and NOx emissions from the digester gas fired IC engine at Plant 1 providing substantial air quality benefits from this system. In addition, NOx and CO, along with VOCs (as NMNEOCs) are considered indirect greenhouse gases, affecting tropospheric ozone and methane levels.

5.2. Comparison to Rule 1110.2 Limits and Other Criteria

- The average NOx concentration at the stack exhaust after the pilot study Cat Ox/SCR system was approximately 7 ppmv, below the 11 ppmv under amended Rule 1110.2. The lowest NOx stack exhaust concentration met consistently under all valid conditions was 16 ppmv. While there were some periods when the NOx stack exhaust

concentration was above 11 ppmv; after screening these periods to eliminate unusual operational events or start-up conditions, 181 periods out of 21,285 total operating periods (approximately 5,321 hours) remained as valid periods where the NOx stack exhaust concentration was above the new Rule 1110.2 limit. These periods occurred during 61 separate events and accounted for less than 0.9% of the total measurement periods during the pilot study.

- Free ammonia (ammonia slip), the result of excess urea injection in the SCR system, was below 0.5 ppmv using SCAQMD compliance sampling methods and below the MDL using Draeger® tubes over the course of the pilot study. The total ammonia calculation method, unlike the measurement methods for free ammonia, did predict low levels of total ammonia. It was noted that the total ammonia calculation method estimates did not include the use of a project-specific correction factor, CF, which could be used to account for secondary reactions that would consume ammonia, thus bringing the total ammonia calculation method estimates more in line with the measurements of free ammonia.
- The maximum CO concentration at the stack exhaust (42.2 ppmv) was well below the amended Rule 1110.2 emission limit of 250 ppmv.
- The maximum VOC concentration at the stack exhaust (4.95 ppmv) was consistently well below the 30 ppmv in amended Rule 1110.2.

Therefore, with the exception of a relatively limited number of periods when the NOx stack exhaust concentration was above the new amended Rule 1110.2 limit, the combined Cat Ox/SCR system equipped with a DGCS was able to meet the new emission limits.

5.3. Cost Effectiveness

The total capital costs to design, procure, and install a digester gas cleaning vessel to clean all the digester gas to the Plant 1 engines, and a Cat Ox/SCR system with auxiliary equipment for Engine 1 is estimated to be \$2,300,000. The annual O&M cost for these systems at Plant 1 is approximately \$59,000. Assuming a 20-year lifespan, the total annualized cost (capital cost plus O&M) for the DGCS and Cat Ox/SCR systems for Plant 1 Engine 1 is \$227,000.

The cost effectiveness analysis (based on dollars per ton of NOx, VOC and CO emissions reduced) was developed for two scenarios: Scenario 1 assumed that the uncontrolled emissions were based on permit limits (i.e., 45 ppmv, 209 ppmv, and 2,000 ppmv, respectively), and Scenario 2 assumed that the uncontrolled emissions were based on the results from the 2011 Annual Compliance Test for Engines 2 and 3. Both scenarios assumed that the controlled emissions were based on the Rule 1110.2 limits of 11 ppmv for NOx, 30 ppmv for VOCs, and the pilot testing results of 15 ppmv for CO. Under these assumptions, the cost effectiveness estimates for Scenarios 1 and 2 are \$7,987 and \$17,585, respectively, per ton of NOx plus VOCs reduced. The cost effectiveness estimates for Scenarios 1 and 2 are \$636 and \$3,546, respectively, per ton of CO reduced.

Note that the cost effectiveness for CO is conservative since the annualized cost is based on the entire system including the SCR and urea injection system. The annualized cost and emissions reduced calculations were based on operating each engine for a maximum of 6,000 hours per year.

5.4. Recommendations

SCR systems similar to the Johnson Matthey system used in the present pilot study are commercially available and have successfully demonstrated NO_x control for single fuels, such as natural gas. However, based on previous source testing data, the NO_x concentration is higher for natural gas than digester gas at a given load; therefore, there is a potential for variations in NO_x concentration at the inlet to the SCR system at a given load due to the varying fuel blend in biogas-fueled engines. Since the urea injection rate can only be established based on engine load and not inlet NO_x concentration, it is difficult to maintain a targeted NO_x limit at the stack exhaust using this type of SCR system.

NO_x concentrations in the stack exhaust were above the amended Rule 1110.2 NO_x limit of 11 ppmv for a small number of sampling periods during the pilot study. These periods where the NO_x stack exhaust concentration was over 11 ppmv may indicate that this limit is too conservative, especially for biogas-fueled and dual-fueled engines where a steady SCR control efficiency is difficult to maintain. Recommendations regarding the new amended Rule 1110.2 NO_x limit of 11 ppmv are as follows:

1. Given the variations in the engine load and urea injection rate mapping requirements for the digester gas-fired IC engine, using the 15-minute block average for compliance with the NO_x emission limit may also be too restrictive, and a longer averaging time may be more appropriate for biogas-fired engines. Alternatively, allowing a limited number of excursions above the 11 ppmv for biogas-fueled engines, for example, 5% of the total annual continuous (i.e., 15-minute averaging periods) NO_x data, to account for the difficulty in accurately mapping the urea injection rate to control NO_x outlet concentration, may also be warranted.
2. In April 2011, after the official pilot testing period concluded, a Johnson Matthey technician adjusted the urea injection rate curve to 1) expand the curve to a maximum of 125% engine load and 2) to increase the urea injection rate at high engine loads. The increase in urea injection rate should accommodate for the increased NO_x production when the engine combusts a fuel blend with a higher percentage of natural gas. Further observation will be required to confirm if these adjustments will lead to a reduction in the number of periods where stack exhaust NO_x outlet concentration is above 11 ppmv.

Further sampling of the exhaust emissions can be performed to establish a correction factor for the estimated total ammonia calculation method and to confirm that the SCR system does not produce measurable free ammonia. Recommendations regarding the estimated total ammonia calculation method are as follows:

3. The presence of sulfur dioxide and sulfur trioxide in the exhaust gas before the SCR, and ammonium sulfate and ammonia bisulfate in the exhaust gas after the SCR, can indicate secondary reactions between the ammonia and sulfur compounds in the exhaust gases taking place due to the injection of urea. The correction factor, CF, can be used in the estimated total ammonia calculation method to account for these reactions, thus improving this calculation for estimating free ammonia.
4. Although the pilot study data indicates that there is minimal, if any, free ammonia due to the SCR system, it is recommended that the OCSO perform additional and routine testing for free ammonia during varying loads and fuel blends over a period of time to accumulate data corroborating that the SCR system does not produce measurable free ammonia under all operating conditions for a given mapped urea injection versus engine load set point.