Commonwealth Energy Biogas/PV Mini-Grid Renewable Resources Program

Making Renewables Part of an Affordable and Diverse Electric System in California

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Sixth Quarterly Data Report

Data for the Period October 2005 – January 2006

Project 2.2 Enhanced Energy Recovery through Optimization
of Anaerobic Digestion and Microturbines

Task 2.2.5 Collect and Analyze Data for Optimized Anaerobic Digestion System

Prepared For:
California Energy Commission
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Contents

Section **Page**

Appendixes

Tables

Figures

Acronyms and Abbreviations

AFT	Air Filter Technology
Btu/cf	British thermal units per cubic foot
cf/lb	cubic feet per pound
CO_2	carbon dioxide
DAFT	dissolved air flotation thickener
dtpd	dry ton per day
FID	flame ionization detector
g/cm^3	gram per centimeter cubed
gpd	gallon per day
gpm	gallon per minute
H_2S	hydrogen sulfide
HRT	hydraulic retention time
Hz	hertz
IEUA	Inland Empire Utilities Agency
lb/d	pound per day
lb/gal	pound per gallon
kHz	kilohertz
μg/L	micrograms per liter
MG	million gallon
mgd	million gallon per day
mg/L	milligram per liter
PIER	Public Interest Energy Research
ppbv	part per billion by volume, dry
ppmv	part per million by volume, dry
ppm	part per million
psig	pound per square inch gauge
PS	primary sludge
RP	Regional Plant
SiO_2	silicone dioxide
SLR	solids loading rate
SWD	side water depth

TDS	total dissolved solid
TSS	total suspended solid
TWAS	thickened waste-activated sludge
TS	total solid
VA	volatile acid
VS	volatile solid
VSR	volatile solids reduction

Executive Summary

Background

The *Process Selection Report for Wastewater Treatment Plants*, delivered under Task 2.2.1 (Project 2.2) of the Public Interest Energy Research Renewables (PIER) program, evaluated several different processes, and recommended focusing on ultrasound testing for enhanced anaerobic digestion and a custom treatment package for microturbine biogas cleaning.

The *Site Selection and Test Plan Report*, delivered under Task 2.2.2 (Project 2.2) of the PIER program, carried forward the conclusions from the above-mentioned reports and provided specific site recommendations, further definition of the processes and their integration into the host facility at the recommended site, and the test plan for the recommended processes.

Ultrasound Testing

The ultrasound process selected in Task 2.2.1 was recommended for testing at the City of Riverside Water Quality Control Plant. A specific location on the south side of digesters 1 and 2 at that plant was recommended and depicted on a plant layout. Two vendors of ultrasound systems, IWE.tec and Sonico, were selected to provide equipment. The recommended test plan was broken down into four phases: a pretest phase (preparing for the test), a baseline phase (with no ultrasound system installation), an ultrasound phase (with ultrasound system installation), and a continuation phase (after the shutdown of the ultrasound systems).

Microturbine Gas Cleaning

The microturbine gas cleaning test was recommended for testing at the Inland Empire Utilities Agency's Regional Plant 1 (IEUA RP-1). The recommended microturbine gas cleaning pilot system consists of a refrigerated dryer system for moisture removal, a packaged system for siloxane removal in the biogas, and a biological hydrogen sulfide (H_2S) removal scrubber. The recommended test plan was broken down into three phases: a pretest phase, a baseline phase, and an actual testing phase. During the pretest phase, the size of the different equipment for the pilot test program was optimized. The baseline for H_2S removal in Digester 4 is the existing method of ferric chloride injection. Once the equipment is installed, the biological H_2S removal testing phase will start. For the gas drying and packaged siloxane removal system, the baseline testing was conducted during two sample rounds in October and November 2004 and continuing weekly siloxane sampling on the combined gas. A continuation test phase is not required for the microturbine gas cleaning pilot program.

Quarterly Reports

The first quarterly data report submitted in December 2004 summarized the baseline test results obtained from June 1 to August 31, 2004, for the enhanced anaerobic digestion using ultrasound. The second and third quarterly reports presented the test results of the ultrasound test phase for the periods from September 1 to November 30, 2004, and December 1, 2004 through February 28, 2005, respectively. In addition, the baseline data were included for the microturbine gas cleaning test at RP-1. The ultrasound performance provided site-specific digester performance for gas production, biosolids production, and various other parameters based on the known amount of primary sludge (PS) and thickened waste-activated sludge (TWAS) fed to digesters. The data were used for comparing digester improvements with the ultrasound systems installed. The gas cleaning test baseline data mainly included baseline H_2S level in the biogas with ferric chloride addition, H_2S removal by the existing iron sponge system, and moisture and siloxane levels in digester gas. The data from the baseline test phase will be used for comparing moisture, H_2S, and siloxane removal by each recommended pilot testing system.

The fourth quarterly report presented the test results of the continuation phase of the ultrasound testing project that covered the period from March 1 to May 31, 2005. The continuation phase was conducted to continue monitoring digester performance after the shut down of the ultrasound equipment. Since the 1-year enhanced anaerobic digestion ultrasound testing at Riverside Plant was completed by the end of the continuation phase, this quarterly report also summarized the findings from the complete test. The other component in this fourth quarterly report was the microturbine gas cleaning project at RP-1. Additional baseline siloxane data obtained during the same time period of March to May 2005 were included in this report.

The fifth quarterly report presented continuing baseline data for siloxane concentrations in the combined gas and digesters 1 and 2 gas streams at RP-1. Digester 4 H_2S production and control with ferric chloride baseline data was also presented for comparison with performance of the biological scrubber during the test phase.

This sixth quarterly report presents the pilot test phase data for the microturbine gas cleaning tests at IEUA RP-1 for both sewage sludge and manure digestion, for the period October 1, 2005, through January 31, 2006. The gas cleaning test focuses on removing H_2S, moisture, and siloxane for microturbines.

Microturbine Gas Cleaning

To establish baseline performance, the operation and performance of the digesters and gas treatment systems at RP-1 were monitored for key performance parameters such as ferric chloride addition, feed flow and total solids (TS) fed to the digester, digester gas production, H_2S concentration in the digester gas, and siloxanes in the combined gas before the iron sponge system.

In addition to the regular digester monitoring, two rounds of gas sampling were conducted to determine the reduced sulfur compounds, moisture content, siloxane, and volatile organic compounds (VOCs), as outlined in the pretest plan. The samples were taken on October 12 and November 16, 2004, and the results were presented in the second quarterly report.

Baseline for Digester Gas Siloxane Levels

Siloxanes are chemicals used extensively in industrial, personal care, and food products. They can therefore enter wastewater from a number of different sources, usually in a stable emulsion form. However, under digester conditions, they volatilize into the digester gas and form silicone dioxide (SiO_2) deposits during combustion that can cause severe damage in generator engines, boilers, and microturbines. Siloxanes were tested in the samples taken from the two rounds collected in October and November of 2004. Additional samples have been collected by plant staff since July 2004. Gas samples were taken from individual digesters and the combined gas line in various locations, such as combined gas at the flare, before and after the iron sponge system, and after the gas compressor. Two methods were used for measuring the siloxanes content of digester gas—the canister method and the impinger method. Eight selected siloxane compounds most commonly found in biogas were analyzed and the total siloxane calculated.

Over the entire baseline period the siloxane results for the combined gas have varied from 3 to 4,243 micrograms per liter (µg/L). The siloxane levels are usually significantly higher than the levels for microturbine operation requirement. For comparison, siloxanes were also analyzed in biogas samples collected from the Riverside plant digesters on November 16, 2004, and showed levels less than 5 ppmv.

The siloxane levels ranged from 25 to 3,124 µg/L for digesters 2, 3, 6, and 7 from two rounds of tests using canister method and additional impinger sampling conducted on Digester 2. Digester 1, the mesophilic acid digester, has had siloxane levels ranging from 2 to 1,357 µg/L using both Impinger and Canister methods. Digester 4, the manure digester, had nondetectable siloxanes from tests performed in July and October 2004

Baseline for H_2S Removal

The following methods of gas treatment are currently used:

- Ferric chloride addition to headworks for sludge digester gas H_2S control
- Ferric chloride addition directly to manure Digester 4 for digester gas H_2S control
- Iron sponges for H_2S removal from the combined digester gas stream

As the biological H_2S scrubber will be tested in the gas from Digester 4, this H_2S production from this digester have been monitored to provide the baseline operation parameters. Baseline data from routine digester gas H_2S monitoring for the period of January 2005 through September 2005 showed the monthly average H_2S in the digester gas ranged from 41 to 70 ppmv (average 56 ppmv), and the ferric chloride addition averaged 134 gpd, or 1,648 pounds per day (lb/d) at 40 percent active. The ferric dose and the digester gas H_2S concentration did appear to be affected by food waste addition to the digester.

The cost for purchasing ferric chloride is $318/ton (includes 7.75 percent tax), according to the plant staff. The average daily cost for ferric chloride was $251, which corresponds to 0.8 cent per gallon of digester feed, 0.7 cent per pound of TS feed, or 0.2 cent per cubic feet biogas generated; and $14 per pound of H_2S removed from the biogas through addition of ferric chloride, assuming that the H_2S concentration would be 2,000 ppm without treatment.

Gas Cleaning Pilot Test Phase

Of the systems tested, the biological scrubber offered the most significant advantages from operational and economic standpoints. With the shutdown of the H_2S control with FeCl3 addition, the H_2S concentration in the Digester 4 gas increased significantly, reaching concentrations over 8,000 ppmv, while maintaining a scrubber outlet concentration <5 ppmv at that time. The chiller did not provide significant moisture removal as it was located downstream of the gas compressors. In a full-scale installation, the chiller would be more cost effective installed upstream of the compressors. However, the chiller did provide approximately 15 percent removal in siloxanes, despite the low moisture removal volume. Both the HOX and carbon media in the SagPack vessels proved to be effective at reducing siloxane concentrations to 2 ug/L or less. Longer-term operation would be required to determine the life-cycle costs of the two media. However, the carbon media removed a greater amount of organic compounds from the gas stream indicating that it was less selective for siloxanes. This would reduce the life of the carbon media, but may have advantages if greater removal of organic and reduced sulfur compounds was required.

SECTION 1

Introduction

In June 2001, the Commonwealth Energy Team was awarded a programmatic contract under the California Energy Commission's (Energy Commission's) Public Interest Energy Research (PIER) Program to conduct research on strategies for making renewable energy more affordable in California. The Commonwealth Energy approach involves assessing the combined potential of biogas and photovoltaic (PV) resources in a defined study area and identifying how these resources could be developed in a complementary and cost-effective manner. The Commonwealth Energy Team conducted this research in a real world setting so that the findings could be applied elsewhere in California and thereby benefit more California ratepayers. The local area Commonwealth Energy selected for its renewable energy research activities is the Chino Basin, referred to in this report as the study area.

1.1 Background

The Chino Basin is rich in PV and biogas resources. Moreover, it is a rapidly growing area with substantial and increasing electrical loads. The underlying goal of the Commonwealth Energy PIER Renewables Mini-Grid Program is to identify potential Building Integrated PV (BIPV) and biogas energy projects, bring innovative technologies and business practices to these projects, assess the benefit to the local electricity distribution system (the mini-grid), and then use the findings to develop a business model for siting cost-effective, renewable energy projects. A description of the Commonwealth Energy PIER Program, including the results of some of the work undertaken to date, is presented on the project Web site, http://www.pierminigrid.org.

An important element of the Commonwealth PIER Renewables Mini-Grid Program is a project devoted to research on improving energy recovery from biogas derived from anaerobic digestion. This project is identified as Project 2.2, "Enhanced Energy Recovery Through Optimization of Anaerobic Digestion and Microturbines." The work summarized in this report, Task 2.2.5 "Collect and Analyze Data for Optimized Anaerobic Digestion System," is the fifth activity of Project 2.2. This task requires providing quarterly data reports on data collection and analysis activities.

1.2 Overview of Project 2.2

Project 2.2 is entitled "Enhanced Energy Recovery through Optimization of Anaerobic Digestion and Microturbines." The objectives of Project 2.2 are to:

- Increase and optimize digester gas production through thermal hydrolysis and ultrasound processes
- Develop and optimize cost-effective gas cleanup systems

- Evaluate and quantify environmental benefits that result from using microturbines at sewage treatment plants
- Evaluate performance and cost during operation so sewage treatment plants have greater certainty on cost and reliability of using microturbines

The first task, 2.2.1, evaluated several different processes and selected an ultrasound process for enhanced anaerobic digestion and a custom treatment package for gas cleaning of microturbines, to be carried further to site selection and testing.

The *Site Selection and Test Plan Report*, delivered under Task 2.2.2 (Project 2.2) of this PIER program, carried forward the conclusions from the above-mentioned report and provided specific site recommendations, further definition of the processes and integration into the host facility at the recommended site, and the test plan for the recommended processes. The second Task 2.2.2 included a report on selection of the best sites at which to deploy the technologies and processes for enhanced anaerobic digestion that were selected in Task 2.2.1. It also provided (1) expanded process flow diagrams that further define the selected processes and show integration into the selected host facility, and (2) the test plan for the new systems.

Five quarterly data reports have been prepared prior to this report. These included the baseline, test, and continuation phases of the ultrasound enhanced digestion test conducted at the City of Riverside Regional Water Quality Control Plant, and continued baseline data for the gas cleaning test.

1.3 Aim of this Report

This report provides the pilot test phase data for the microturbine gas cleaning tests at IEUA RP-1. The fifth quarterly report provided the baseline gas cleaning project data through the end of September 2006. The test gas cleaning data for both sewage sludge and manure digestion, for the period October 1, 2005 through January 31, 2006, are summarized in this report. The gas cleaning test focuses on removing H_2S, moisture, and siloxane for microturbines.

1.4 Report Content and Organization

This report is organized as follows:

- **Section 1** introduces the Commonwealth Energy program, provides background information on the Chino Basin, presents an overview of the Commonwealth PIER project for Enhanced Energy Recovery through Optimization of Anaerobic Digestion and Microturbines, and describes the objectives and content of this report.
- **Section 2** provides an overview of the microturbine gas cleaning project summary and evaluation of the Chiller and SagPack unit performance (October 1, 2005 to January 31, 2006).
- **Section 3** provides a summary of the pilot test data for the Chiller/SagPack system at the RP-1 plant (October 1, 2005 to January 31, 2006).

- **Section 4** provides a summary of the pilot test data for the biological H_2S scrubber installed on Digester 4 at the RP-1 plant (October 1, 2005 to December 31, 2006).
- **Section 5** provides a summary of economic considerations for the gas cleaning systems.
- **Section 6** describes the conclusions and recommendations from the pilot test results.
- **Section 7** describes quality assurance and data analysis procedures followed for the data collected through the sixth quarter.

1.5 Task 2.2.5 Scope and Deliverables

The scope for task 2.2.5 is to submit quarterly data reports on data collection and analysis activities. Gas quantity and quality information is to be collected before and after installation.

The work statement for Task 2.2.5 lists data to be collected as follows:

- The data to be collected after installation to analyze the performance of the microturbine and associated gas cleaning systems include power generation, heat recovery, air emissions, construction costs, and operating costs. The equipment's performance will be measured in terms of heat rate, reliability, and emissions. Analyses will be conducted and compared to predicted values for these data.
- The data will also be collected to analyze the effectiveness of the systems installed for anaerobic digestion gas production optimization. Information collected prior to installation on flow rates, solids quality and quantity, digester loading rates, process recycles, and gas production will be compared to similar data collected after installation. Installation, operation, and maintenance cost information will be collected. The analysis process will focus on determining the impact on process operation.

The deliverables for Task 2.2.5 are:

- Quarterly Data Report No. 1
- Quarterly Data Report No. 2
- Quarterly Data Report No. 3
- Quarterly Data Report No. 4
- Quarterly Data Report No. 5
- Quarterly Data Report No. 6

The microturbine and gas cleaning systems pilot equipment was installed at IEUA's RP-1 facility. The pilot equipment for anaerobic digestion gas production optimization was installed at the City of Riverside Regional Water Quality Control Plant. As a result of the timing of these two separate installations, the test for anaerobic digestion gas production optimization was completed before the microturbine and gas cleaning systems pilot equipment was in operation. Therefore, the sixth quarterly report, for the period October 1, 2005 to January 31, 2006, includes only the pilot test data for the microturbine gas cleaning systems at RP-1.

Test data points for the parameters listed above for microturbine and gas cleaning systems pilot testing are included in this report, as follows:

- **Power Generation**—Section 5
- **Heat Recovery**—Section 5
- **Air Emissions**—Section 3 (siloxanes and organic compounds) and Section 4 (H_2S)
- **Construction and Operating Costs**—Section 5

SECTION 2

Microturbine Gas Cleaning Overview

This section provides an overview of microturbine gas cleaning test technologies and describes the gas cleaning pilot program. The pilot test data obtained during the period of October 1, 2005, through January 31, 2006, are summarized in this section. During this phase, the chiller and SagPack system was started up and the biological H_2S scrubber was brought on line. A complete set of baseline gas cleaning data is provided in Appendix A.

2.1 Overview of Gas Cleaning Tests

The biogas used for operating microturbines must meet stringent quality requirements (maximum of 150 parts per million [ppm] moisture, 25 ppm H_2S, and 0.0141 µg/L or 10 parts per billion by volume [ppbv] siloxanes) to prevent early deterioration of the microturbines. The biogas produced in the digesters at a wastewater treatment plant is typically saturated and contains approximately 500 to 2,000 ppm H_2S, and 2 to 5 ppm siloxane. Biogas from manure digestion is also saturated and contains approximately 500 to 2,000 ppm H_2S with no siloxanes. The content of each of these contaminants needs to be decreased to meet the biogas quality stated above.

This section provides an overview of the gas cleaning test, including the test purpose, pilot test site location, technologies to be tested, a process flow diagram, and the test plan.

2.1.1 Gas Cleaning Test Purpose

The purpose of the microturbine gas cleaning pilot test is to collect and analyze data for different technologies to determine their efficacy in removing hydrogen sulfide, moisture, and siloxanes.

2.1.2 Gas Cleaning Test Location

The RP-1 facility has been selected to conduct the biogas cleaning pilot test program because it has microturbines and biogas is generated using both municipal waste and manure.

2.2 Existing Gas Quality Control at RP-1

RP-1 has seven anaerobic digesters (Nos. 1 through 7). The biogas system consists of an iron sponge system to remove H_2S, biogas compressors and storage, an energy recovery building, a waste gas burner, and eight microturbines. Six of the seven digesters (digesters 1 through 3 and 5 through 7) at RP-1 process the solids from sewage wastewater treatment. Digester 4 is used to process dairy manure.

To control H_2S in the biogas from digestion of municipal waste, iron salts are added at the headworks to bind the sulfur as iron sulfide. To reduce H_2S levels in the manure digester biogas, iron salt is added directly to this digester. After the biogas is collected from all the digesters, it is treated through iron sponges, further reducing the H_2S concentration from around 60 ppm to 20 ppm on average. Under normal operation, the gas from Digester 1 (the acid digester) is directed to the waste gas burner as the low methane content of the gas from Digester 1 reduces the performance of the co-generation engines. The biogas compressors are located downstream of the iron sponges and increase the biogas pressure to around 60 pounds per square inch gauge (psig) before it is stored in the biogas storage system. From the storage system, the biogas is distributed to the engine generators, boilers, and microturbines. There is no siloxane removal for the internal combustion engines, but carbon filters were installed to reduce siloxane levels in the biogas used in microturbines.

2.3 Gas Cleaning Test Technologies

The proposed gas cleaning pilot systems consist of testing technologies that have the potential to:

- Remove moisture through gas drying through a refrigerated dryer system that consists of a refrigeration unit, and two heat exchangers. The gas drying system may also bring the benefit of some siloxane removal through the condensate.
- Remove H_2S in biogas through a biological process. The bacteria in this process oxidize the sulfide to produce both elementary sulfur and sulfuric acid.
- Remove siloxanes through packaged systems. SAGPack series manufactured by Applied Filter Technology (AFT) was selected for pilot testing. A new media will be tested in parallel with AFT's standard media.

None of the test technologies have been used in the U.S. or been applied at the scale needed for microturbine gas treatment.

2.4 Gas Cleaning Test Plan at RP-1

The process flowchart for the proposed pilot test, equipment needed to conduct this test, sampling locations, parameters to be tested, and testing frequencies were discussed in detail in the Task 2.2.2 *Site Selection and Test Plan Report*.

2.4.1 Gas Cleaning Test Recommendations and Schedule

The test recommendation was to proceed with pretesting of the biogas to optimize the size of the different equipment for the pilot test program (gas drying chiller, biological H_2S removal scrubber, and SagPack siloxane removal media) and provide baseline data and costs.

The existing method for removal of H_2S in Digester 4 (ferric chloride injection) needs to be monitored to establish the removal efficiency baseline for this H_2S removal technology. Additional baseline testing was conducted during two sample rounds in October and November 2004 to test for reduced sulfur compounds in the digester gas, and sulfur concentrations in the digester feed and effluent.

Baseline testing for the chiller and SagPack system was conducted during two detailed rounds of sampling on each digester in October and November 2004, and by weekly siloxane sampling of the Digester 1 and combined gas streams through the end of September 2005. During the two detailed sample rounds, gas from each digester and the combined gas were tested for siloxanes, moisture, and VOCs. For the Microturbine Gas Cleaning pilot program, a continuation test phase is not required. Table 2-1 summarizes the time requirement for the different technologies and corresponding phases.

TABLE 2-1
Microturbine Gas Cleaning Test Duration

Phase	Duration	Status
Pretest Phase (all pilot technologies)	1 month	Completed
Baseline Phase Additional Sampling	1 month	Completed
Biological H_2S Removal Phase	3 months	Completed
Gas Drying and Package System Phase	3 months	Completed

SECTION 3

Chiller and SagPack Performance

The baseline data collected for both the biological H_2S removal system and moisture/ siloxane removal by Chiller/SagPack were presented in the previous quarterly reports. This section presents the pilot test data for the Chiller and SagPack system for siloxane and moisture removal obtained during October 2005 through January 2006. Siloxanes are chemicals used extensively in industrial, personal care and food products. They can therefore enter wastewater from a number of different sources, usually in a stable emulsion form. However, in the conditions in a digester, they volatilize into the digester gas, and form silicon dioxide (SiO_2, also known as silica) deposits during combustion that can cause quite severe damage in generator engines and microturbines.

3.1 Siloxane Sampling Methods

Two sampling methods were used for collecting the digester gas samples for siloxanes measurement, the canister and the impinger methods. There is currently no EPA-approved methodology for gas siloxane sampling and analysis. For this study, digester gas canister sampling grabs samples using Summa® canisters were collected from the digester gas lines. Sample lines were 0.25-inch Teflon, and sampling location had positive pressure (greater than 5-inch water column positive pressure). EPA Method TO-15 was used for laboratory analysis of the samples. The sampling protocol provided by an independent sampling specialist is attached in Appendix B of this report. The advantages and disadvantages of the canister method are summarized below.

Advantages:

- Shorter sampling time
- Lower limits of detection
- May be more accurate

Disadvantages:

- Siloxanes can be adsorbed onto the surface of stainless steel canisters if not properly pretreated
- Siloxane standards are not readily available to laboratories
- Short-term sample

In the impinger method, siloxanes are absorbed into liquid methanol using impingers. Samples are drawn into the impinger with a vacuum pump at a known flow rate over a period of 3 to 4 hours. Samples are analyzed by injection of the methanol into a GC/MS or GC/flame ionization detector (FID). The siloxanes concentration in the gas is back calculated using the measured gas flow rate through the methanol and the duration of sample collection. The advantages and disadvantages of the impinger method are summarized below.

Advantages:

- Long-term composite sample
- Possibility of better limits of detection
- Widespread acceptance

Disadvantages:

- Time-consuming in the field
- May not capture 100 percent of siloxanes

Eight selected siloxane compounds that are most commonly found in biogas were analyzed and reported and the total siloxanes can be summed.

3.2 RP-1 Baseline Siloxane Data

Table 3-1 summarizes the siloxane results from both canister and impinger methods for individual digester and combined gas during the baseline period. Combined gas samples were taken from various locations in the gas system, such as combined gas at flare, before and after iron sponge system, and after compressor. Figure 3-1 is the graphic presentation of total siloxanes in the combined digester gas in µg/L.

During September and October, 2004, the RP-1 staff noticed a buildup of white material in the Waukesha IC engines at the plant. Analysis of the material by the plant laboratory showed that it was primarily composed of silicon. The baseline siloxane data support this, as concentrations in the October gas samples were significantly higher than in a sample collected in July 2004, which had a total siloxane concentration of 18 µg/L (2 ppmv). The concentration remained high in November, however, it was lower in the following months, with occasional high spikes. The total siloxane results for the combined gas varied from 3 to 309 mg/L, lower than the previous quarter. The cause of the initial prolonged increase in siloxane concentrations and the subsequent spikes has been difficult to determine as siloxanes in the influent wastewater are in a very stable emulsion form that is not amendable to laboratory analysis. Without any treatment, the siloxane levels are significantly higher than the microturbine operation requirement. Internal combustion engines have a less stringent requirement, with a maximum siloxane level of 25 µg/L (1.8 ppmv) for Waukesha engines.

FIGURE 3-1
Total Siloxane in RP-1 Combined Digester Gas (µg/L)

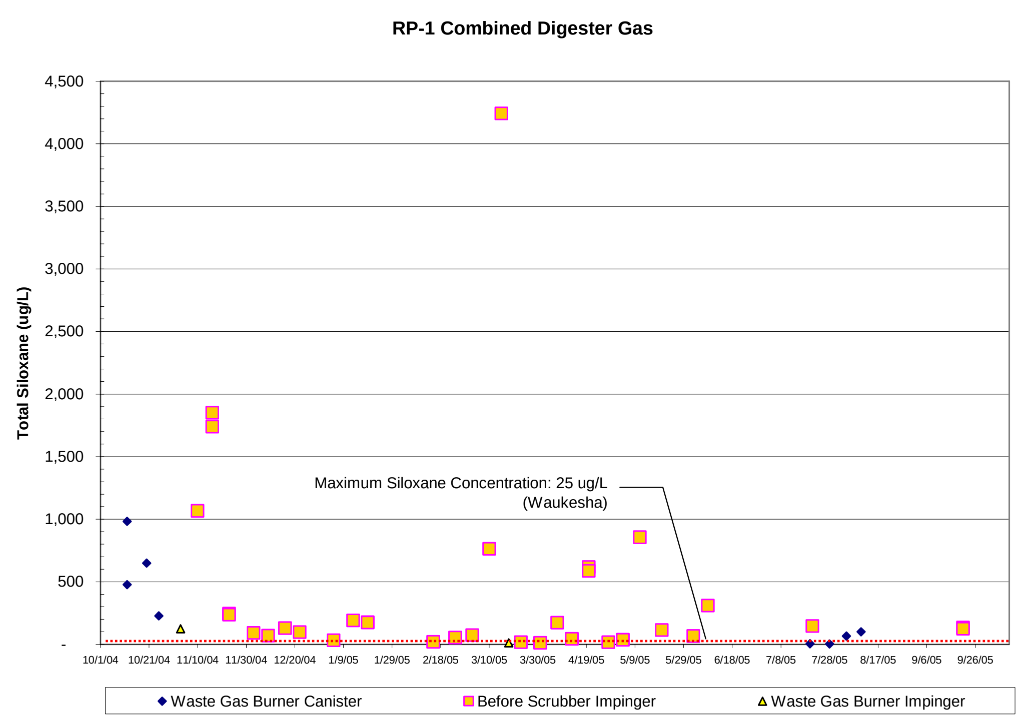


FIGURE 3-2
Total Siloxane in Digester 1 and 2 Biogas (µg/L)

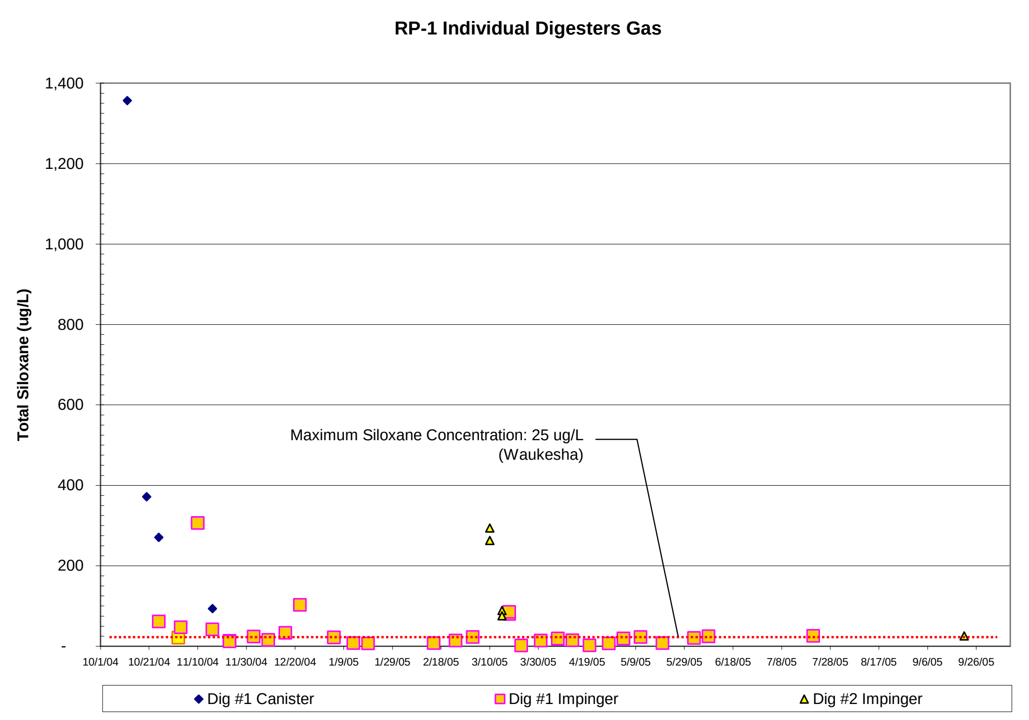


Figure 3-2 presents the total siloxane results for Digester 1 using both canister and impinger methods and for Digester 2 using the impinger method. Digester 1 is the mesophilic acid-phase digester, it is operated with low hydraulic retention time (HRT) (less than 5 days) and low pH (around 5.3) to favor acid producing bacteria from the organics in the wastewater sludge. The produced acid is further converted to methane in the following second-phase gas digesters. Digester 2 is a gas phase digester, typically operated at low thermophilic temperatures (126°F) and a HRT around 11 days. Between June and September 2005, siloxane concentrations in the gas samples collected from Digester 1 remained ranged between 20 and 26 ug/L, which is around the limit recommended for the Waukesha engines. One Digester 2 sample was collected in September and showed a similar concentration to Digester 1, at 25 ug/L. Table 3-1 provides the siloxane results from all the digester gas samples taken at the RP-1 plant since July 2004. Comparison of digesters 1 and 2 concentrations for samples collected on or close to the same days show that both digesters had similar siloxane concentrations.

TABLE 3-1
Siloxane in the RP-1 Digester Gas (µg/L) (July 2004 to September 30, 2005)

	Sampling Location															
Sampling Date	**Dig 1**		**Dig 2**		**Dig 3**	**Dig 4**	**Dig 6**	**Dig 7**	**Combined Gas Digs 1, 2, 3, 4, 6, 7 (Flare)**		**Combined Gas Digs 2, 3, 4, 6, 7 (Flare)**		**Combined Gas Digs 2, 3, 4, 6, 7 (Before Iron Sponge)**	**Combined Gas Digs 2, 3, 4, 6, 7 (After Iron Sponge)**	**Combined Gas Digs 2, 3, 4, 6, 7 (After Compressor, Engine)**	
	Can	Imp	Can	Imp	Can	Can	Can	Can	Can	Imp	Can	Imp	Imp	Can	Can	Imp
7/6/04						ND			18							
10/12/04	1,357		880		1,077	ND	3,124	455	477							
(Dup) 10/12/04									983							
10/20/04	372								650							
10/25/04	271	62							227	72						
11/2/04	21										16					
11/3/04		47										124				
11/10/04		306											1,066			9
11/16/04	94	42	78		30		70	40					1,850	191	118	
(Dup) 11/16/04													1,740		72	
11/23/04		13											245			
(Dup) 11/23/04		12											236			
12/3/04		24													91	
12/9/04		16													69	
12/16/04		33													129	
12/22/04		103													97	
1/5/05		22													32	
1/13/05		8													190	
1/19/05		7													176	
(Dup) 1/19/05															173	
2/15/05		8													20	
2/24/05		14													54	
03/03/05		23												73		
03/10/05				263										763		
(Dup) 03/10/05				294												
03/15/05				89										4,243		

TABLE 3-1

Siloxane in the RP-1 Digester Gas (µg/L) (July 2004 to September 30, 2005)

	Sampling Location															
Sampling Date	**Dig 1**		**Dig 2**		**Dig 3**	**Dig 4**	**Dig 6**	**Dig 7**	**Combined Gas Digs 1, 2, 3, 4, 6, 7 (Flare)**		**Combined Gas Digs 2, 3, 4, 6, 7 (Flare)**		**Combined Gas Digs 2, 3, 4, 6, 7 (Before Iron Sponge)**	**Combined Gas Digs 2, 3, 4, 6, 7 (After Iron Sponge)**	**Combined Gas Digs 2, 3, 4, 6, 7 (After Compressor, Engine)**	
	Can	Imp	Can	Imp	Can	Can	Can	Can	Can	Imp	Can	Imp	Imp	Can	Can	Imp
(Dup) 03/15/05				76												
03/18/05		80										12				
(Dup) 03/18/05		85														
03/23/05		2												16		
03/31/05		14												12		
04/07/05		18												172		
(Dup) 04/07/05		19														
04/13/05		15												44		
04/20/05		2												617		
(Dup) 04/20/05														586		
04/21/05																
04/27/05																
04/28/05		7												17		
05/04/05		19												36		
(Dup) 05/04/05		19												36		
05/09/05																
05/11/05		23												855		
05/20/05		8												114		
6/2/2005		20											66			
6/8/2005		25											309			
7/20/2005									5							
7/21/2005		26											145			
7/26/2005																
7/28/2005									3							
8/4/2005									65							

TABLE 3-1

Siloxane in the RP-1 Digester Gas (µg/L) (July 2004 to September 30, 2005)

	Sampling Location															
Sampling Date	**Dig 1**		**Dig 2**		**Dig 3**	**Dig 4**	**Dig 6**	**Dig 7**	**Combined Gas Digs 1, 2, 3, 4, 6, 7 (Flare)**		**Combined Gas Digs 2, 3, 4, 6, 7 (Flare)**		**Combined Gas Digs 2, 3, 4, 6, 7 (Before Iron Sponge)**	**Combined Gas Digs 2, 3, 4, 6, 7 (After Iron Sponge)**	**Combined Gas Digs 2, 3, 4, 6, 7 (After Compressor, Engine)**	
	Can	Imp	Can	Imp	Can	Can	Can	Can	Can	Imp	Can	Imp	Imp	Can	Can	Imp
8/10/2005									100							
9/1/2005																
9/9/2005																
9/20/2005																
9/21/2005				25									135			
(Dup) 9/21/2005													124			

Notes:
ND = not detected.
Dup: duplicate samples.
Can = Canister Method, Imp = Impinger Method.

To convert µg/L to ppmv, use: ppmv = µg/L *23.68/333.69/1,000.

3.3 Summary of Baseline Digester Gas Siloxane Levels

Gas samples were taken from individual digesters as well as combined gas line in various locations such as combined gas at flare, before and after the iron sponge system, and after the gas compressor. Two methods were used for measuring the siloxanes content of digester gas—the canister method and the impinger method. Eight selected siloxane compounds most commonly found in biogas were analyzed and the total siloxane calculated. The siloxane results obtained from July 2004 through September 2005 (baseline phase) indicate that:

- Siloxane levels in the combined gas varied significantly from 3 to 4,243 µg/L over the entire period. Siloxane levels were often significantly higher than operation requirements for microturbine and generator engines and therefore the gas requires treatment.
- The siloxane levels ranged from 25 to 3,124 µg/L for digesters 2, 3, 6, and 7 from two rounds of tests using canister method and additional impinger sampling conducted on Digester 2. Digester 1, the mesophilic acid digester, has had siloxane levels ranging from 2 to 1,357 µg/L using both Impinger and Canister methods. Digester 4, the manure digester, had nondetectable siloxanes from tests performed in July and October 2004.

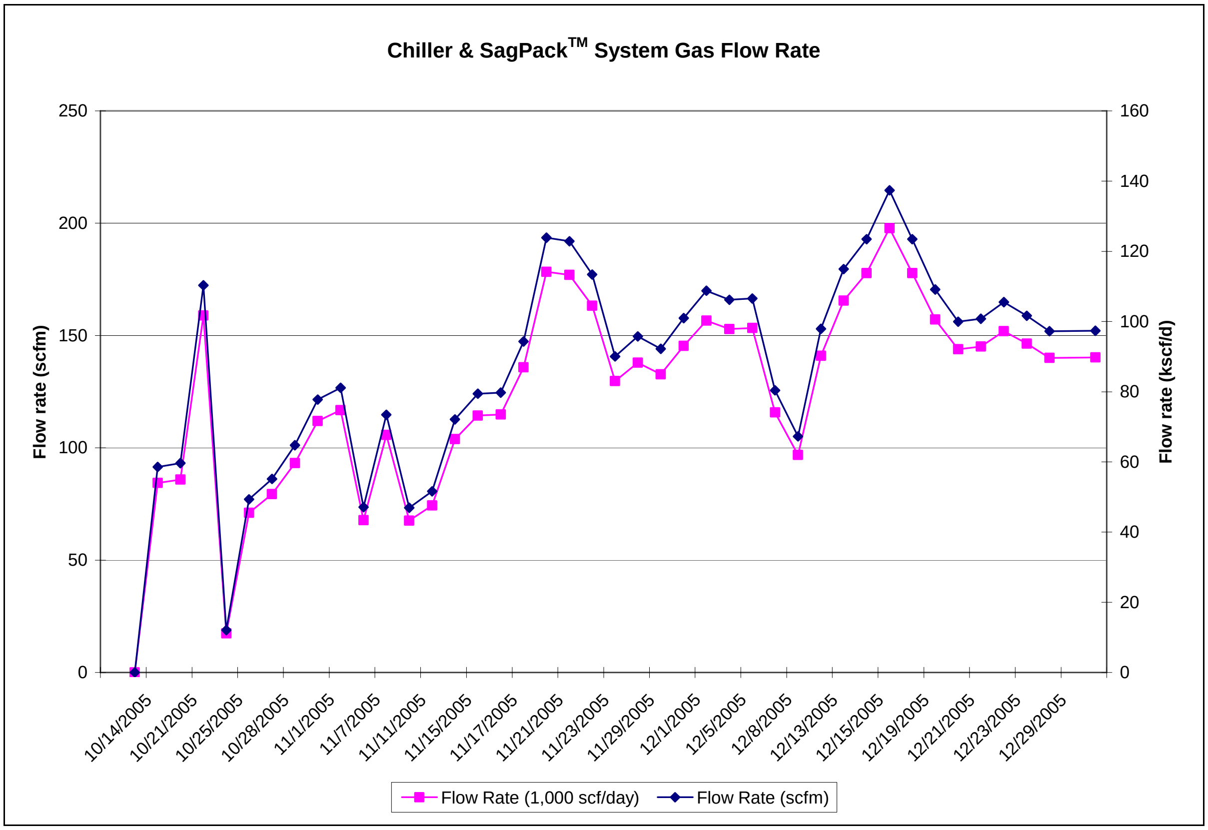
3.4 Chiller/SagPack System Performance

The chiller and SagPack system was installed on a sidestream of the combined gas stream at RP-1, downstream, of the gas compressors. The treated gas was originally intended to be used to operate the existing microturbines. However, due to maintenance issues with the microturbines the piping was modified to allow the treated gas to be returned to the main gas loop. The system was re-started after these modifications in October 2005 and collection of the pilot test samples commenced in November 2005 after commissioning the system.

The chiller was expected to serve the dual purpose of removing moisture and some siloxanes from the digester gas. The SagPack system consisted of two vessels operated in parallel to allow comparison of a graphite carbon media and a proprietary polymer-based HOX media developed by Applied Filter Technology.

Figure 3-3 shows the gas flow through the chiller and SagPack system during the pilot test. The system was designed to treat flows up to 120 scfm. The chiller was operational 98 percent of the time. The down time was due to gas quality issues observed in the co-generation digester gas samples. It was originally thought that the drop in apparent BTU content may have been due to the chiller system, even though it was only treating a portion of the digester gas. However, digester gas analysis showed a high proportion of nitrogen in the sample, which suggested that drop in BTU content was due to a leak in the sample collection system.

FIGURE 3-3
Chiller and SagPack System Gas Flow Rate



3.4.1 Gas Drying Performance

Figure 3-4 shows the relative humidity in gas samples prior to the chiller, after the chiller and after the two SagPack Vessels. Relative humidity is defined as the percentage of moisture in a gas compared with the maximum amount of moisture that could be contained in the gas at that temperature. As a result of temperature changes between the different gas sampling points, the maximum moisture content at each sample point will vary, and this is reflected in the fact that there is little difference in the relative humidity. Typically digester gas is saturated with moisture. However, as the chiller was downstream of the compressor, the relative humidity in the inlet was considerably lower, averaging 36 percent. It is recommended that gas to the SagPack system is maintained below 40 percent so that the life of the media is not reduced. The average relative humidity to the SagPack system was 35.3 percent, with a couple of samples slightly over 40 percent.

FIGURE 3-4
Chiller and SagPack System Relative Humidity

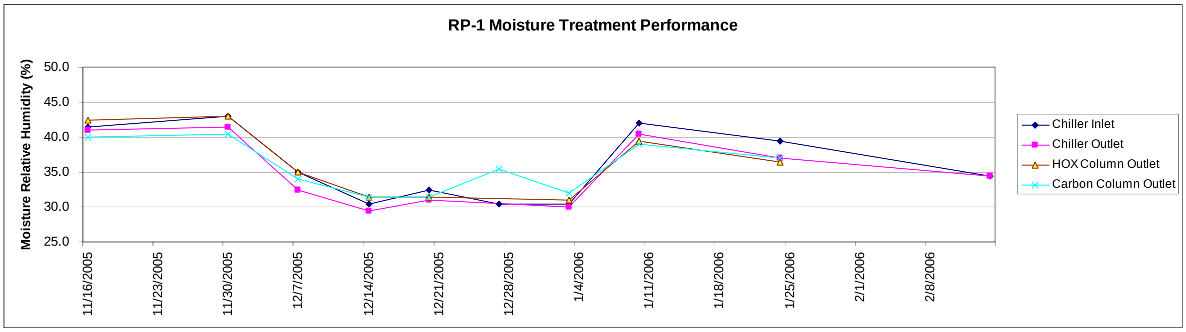


Figure 3-5 shows the moisture content of gas samples into and out of the chiller and SagPack and Figure 3-6 shows the average of sampling conducted during the pilot test. On average the chiller provided 8 percent moisture removal, despite the low humidity in the inlet stream. There was no significant change in moisture concentration through the SagPack vessels, which indicates that moisture was not reducing the active sites on the gas treatment media.

FIGURE 3-5
Chiller and SagPack System Gas Moisture Concentration

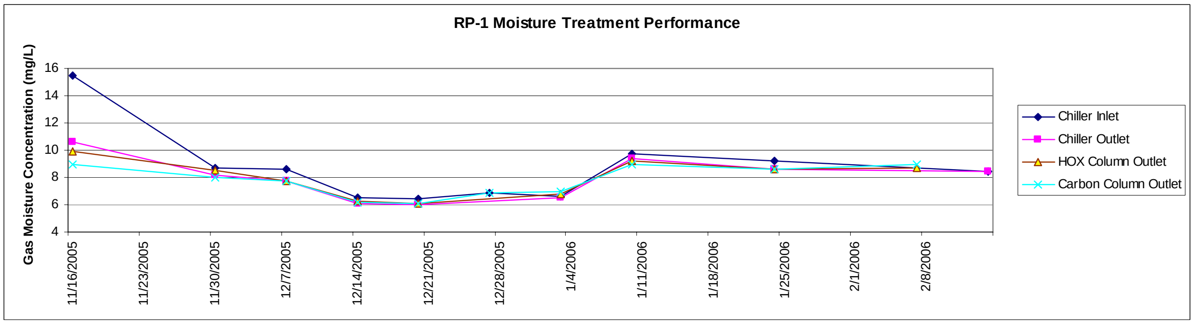
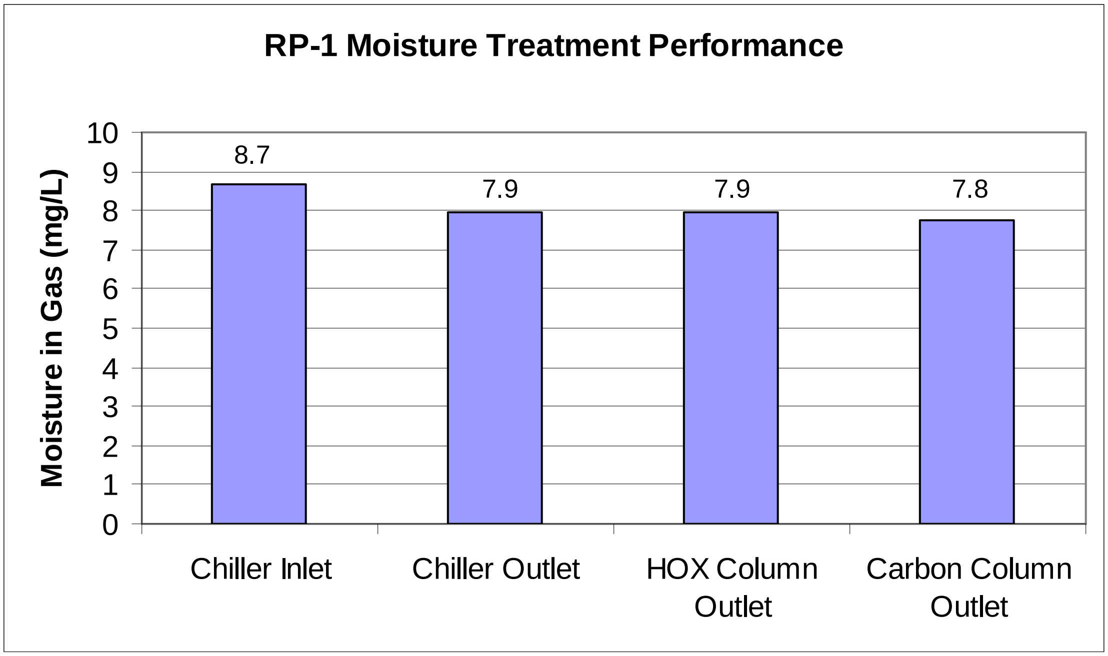


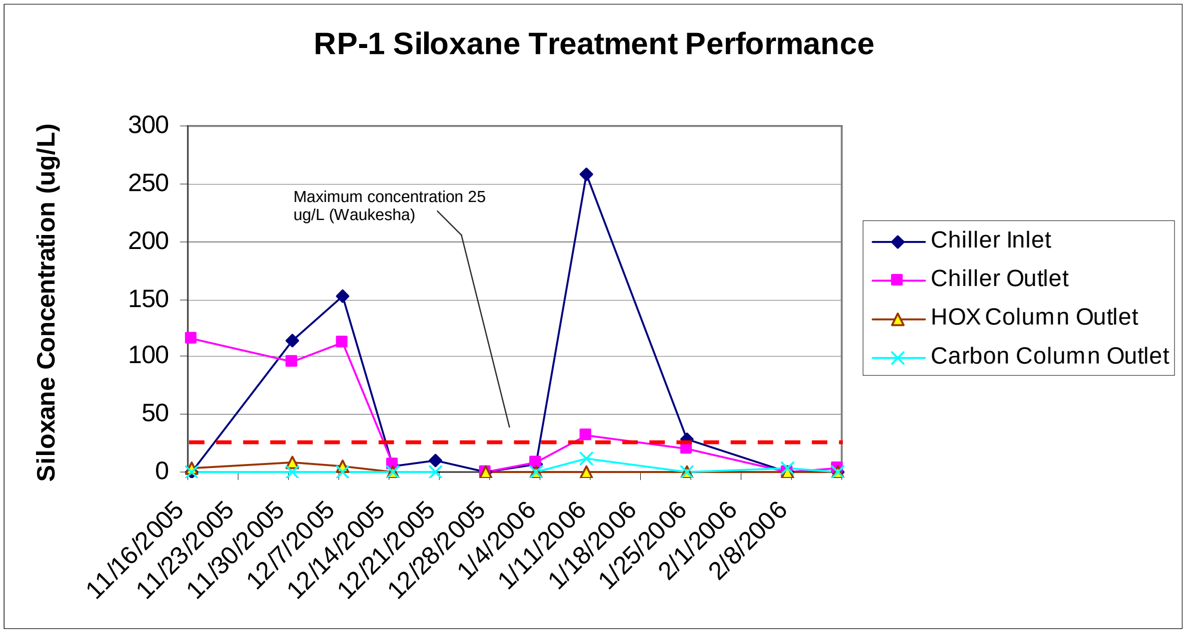
FIGURE 3-6
Chiller and SagPack System Gas Average Moisture Concentration



3.4.2 Siloxane Treatment Performance

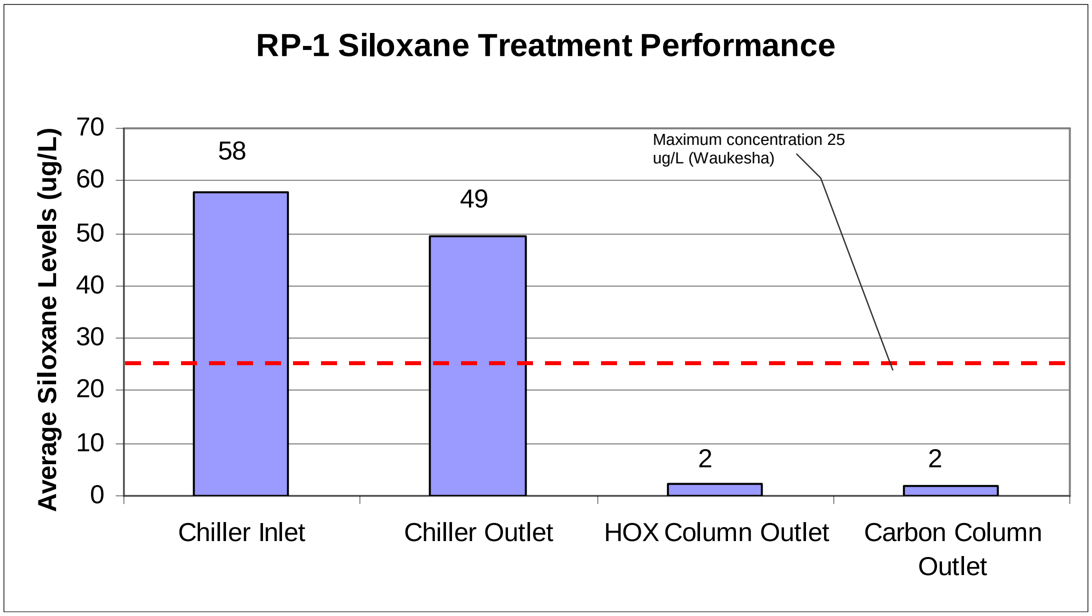
Figure 3-7 shows the siloxane concentrations in and out of the chiller and SagPack vessels. The inlet gas siloxane concentrations were variable over the pilot test period, ranging from nondetectable to 259 ug/L. The highest concentration in the outlet from the chiller was 115 ug/L, from the HOX SagPack vessel was 9 ug/L and from the carbon vessel was 11 ug/L.

FIGURE 3-7
Chiller and SagPack System Gas Siloxane Concentration



Average siloxane removal performance of the chiller and SagPack vessels are shown in Figure 3-8. The chiller provided approximately 15 percent reduction in siloxane concentration, even though the moisture removal performance was lower, at 8 percent. Both types of SagPack media provided over 95 percent removal in conjunction with the chiller. During the latter part of the pilot test, the siloxanes levels in the HOX and carbon media outlet gas were nondetectable, which indicates that either media would provide adequate gas treatment for microturbines and IC engines.

FIGURE 3-8
Chiller and SagPack System Gas Siloxane Concentration



3.4.3 Total Organic Compounds Treatment Performance

Figure 3-9 shows the trends in total organic compounds (TOC) concentrations in the digester gas before and after the Chiller and SagPack vessels. Figure 3-10 shows the average concentrations during the pilot test period. The data show that the carbon SagPack media provided approximately 87 percent removal from chiller inlet concentrations, while the HOX media provided essentially no removal. This indicates that the HOX media would likely last longer than the carbon media as it is more selective and active sites on the media would not be occupied by organics in the gas stream. It is anticipated that most of the organics would be oxidized in the IC engine or microturbine and would not affect exhaust gas emissions.

FIGURE 3-9
Chiller and SagPack System Gas Total Organic Compounds Concentration

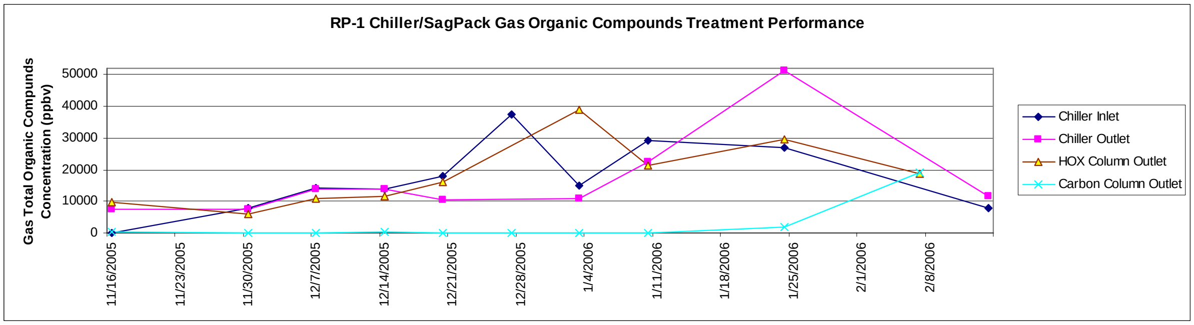
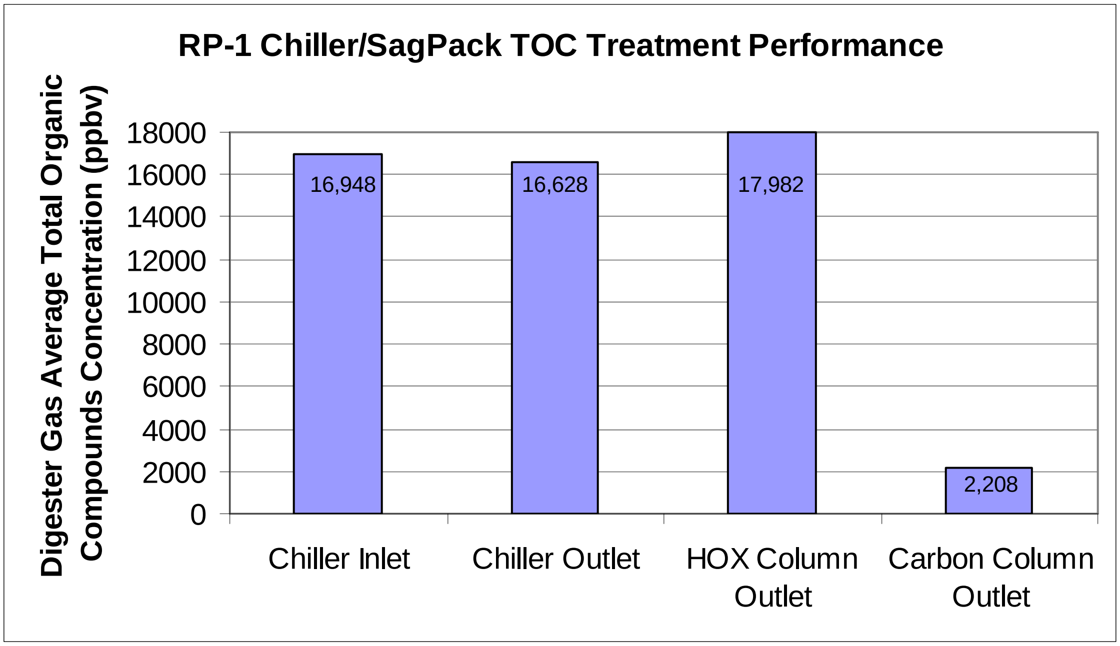


FIGURE 3-10
Chiller and SagPack System Gas Average Total Organic Compounds Concentration



3.4.4 Reduced Sulfur Compound Treatment Performance

Reduced sulfur compounds in the gas into and out of the chiller and SagPack vessels are provided in Table 3-2. The data show that both the chiller and the media provided significant removal rates for sulfur compounds, with around 40 percent removal in the chiller. The HOX media provided less removal of sulfur compounds from the chiller outlet gas stream, averaging 78 percent removal compared with 94 percent removal average through the carbon media. This confirms that the carbon media is less selective for siloxanes and the life of the media may be less than the HOX media.

3.4.5 Chiller Condensate Quality

As discussed above, there was little moisture removal through the chiller, since it was located downstream of the gas compressors. Two samples were taken for laboratory analysis of the condensate quality. The data can be compared with the Digester 4 condensate pot and the biological H_2S scrubber overflow quality provided in Section 4.2 of this report. The ammonia and sulfur concentrations were relatively low in these two samples. The total solids concentrations were high, mostly in particulate form. This may have been due to deposition of siloxanes, but because no tests were conducted on the solids recovered from the condensate, this assumption was not confirmed. The pH was slightly acidic, averaging 6 between the two samples. Table 3-3 shows the chiller and SagPack system gas condensate quality.

TABLE 3-2
Chiller and SagPack System Gas Reduced Sulfur Compounds Concentration

Parameters	11/30/2005 (ppmv)	12/7/2005 (ppmv)	12/14/2005 (ppmv)	12/20/2005 (ppmv)	12/27/2005 (ppmv)	1/3/2006 (ppmv)	1/10/2006 (ppmv)	2/7/2006 (ppmv)	2/14/2006 (ppmv)	Average (ppmv)
Chiller Inlet										
Hydrogen Sulfide	483.2	0.6	7.4	6.6	21.9	6.9	6.2	NS	11.8	
Ethyl Methyl Sulfide	ND	ND	0.3	0.5	0.9	0.5	ND		ND	
Dimethyl Disulfide	ND	ND	ND	5.1	ND	ND	ND		ND	
Total	**483.2**	**0.6**	**7.7**	**12.2**	**22.8**	**7.4**	**6.2**		**11.8**	**78.0**
Chiller Outlet										
Hydrogen Sulfide	19.1	NS	8.5	3.3	NS	7.1	1.5	NS	10.0	
Ethyl Methyl Sulfide	ND		0.3	ND		ND	ND		ND	
Dimethyl Disulfide	ND		ND	3.0		ND	ND		ND	
Total	**19.1**		**8.8**	**6.3**		**7.1**	**1.5**		**10.0**	**10.3**
Removal	**96.0%**	**-**	**0.0%**	**48.4%**	**-**	**4.1%**	**75.8%**	**-**	**15.3%**	**39.9%**
HOX Outlet										
Hydrogen Sulfide	8.8	ND	ND	5.7	NS	5.8	4.2	3.3	NS	
Carbonyl Sulfide	ND	ND	ND	ND		ND	0.8	ND		
Ethyl Methyl Sulfide	ND	ND	ND	0.4		ND	ND	0.1		
Total	**8.8**	**0.0**	**0.0**	**6.1**		**5.8**	**5.0**	**3.4**		**4.2**
Removal	**53.9%**	**100.0%**	**100.0%**	**68.1%**	**-**	**69.6%**	**73.8%**	**82.2%**	**-**	**78.2%**
Carbon Outlet										
Hydrogen Sulfide	8.5	ND	ND	ND	ND	ND	ND	ND	NS	
3-Methylthiophene	ND	ND	ND	ND	ND	ND	0.1	ND		
Total	**18.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**		**2.6**
Removal	**55.5%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**99.5%**	**100.0%**	**-**	**94.4%**

ND = not detected.
NS = no sample.

TABLE 3-3
Chiller and SagPack System Gas Condensate Quality

	IEUA RP1 - Chiller Condensate						
Date	**Ammonia (N) mg/L***	**Sulfur (tot) mg/L**	**Sulfate mg/L***	**(tot) Sulfide mg/L**	**Total Solids mg/L**	**TDS mg/L**	**pH**
11/16/05	0	7.77	0	NS	852	32	5.8
11/30/05	5	14	15	0.02	1,570	99	6.1
Average	**3**	**11**	**8**	**0.02**	**1211**	**66**	**6.0**

* '0' is ND, < 1mg/L

3.5 Summary and Conclusions

The chiller and SagPack system was located downstream of the gas compressors. Therefore the relative humidity of the inlet gas stream was already reduced, averaging 36 percent. Moisture removal through the chiller was low for this reason, averaging 8 percent removal. The SagPack media did not provide any significant change in moisture levels. For a chiller to be effective for moisture removal, it would need to be located upstream of the gas compressors.

The chiller and SagPack systems proved the capability for effective removal of siloxanes during the pilot test, averaging over 95 percent removal. The chiller provided approximately 15 percent removal of siloxanes, even with little moisture removal. The chiller and SagPack vessels in combination were able to remove siloxanes to nondetectable levels, as evidenced during the latter half of the test period, over a range of flows and inlet siloxane concentrations. The system handled flow rates up to 137 scfm, slightly higher than the design flow of 120 scfm. The SagPack media require an optimum velocity, which allowed better performance during the latter part of the test as the flow rates increased. Startup of the system was easy and did not require a long acclimation period.

The carbon media also provided significant removal of organic compounds, averaging 87 percent removal, while the HOX media showed no removal. Approximately 40 percent of reduced sulfur compounds were removed in the chiller. Both types of media provided additional removal of reduced sulfur compounds from the gas stream, but the carbon media removed a greater portion, averaging 94 percent removal from the chiller outlet gas stream, compared with 78 percent removal by the HOX media. The data therefore suggest that the carbon media is less selective than the HOX media and this difference could impact the life of the media and associated long term operational costs.

SECTION 4

Biological H_2S Scrubber Performance

4.1 Digester 4 Baseline H2S Data

The biological H_2S scrubber was tested on the gas stream from Digester 4. This digester is used to process dairy manure, and ferric chloride is directly added to this digester to control the H_2S in the digester gas produced. Food waste addition commenced in April 2005, with occasional addition of salad dressing, lactose and ice cream wastes. The food waste co-digestion with manure is discussed in detail in other reports. Table 4-1 summarizes the monthly average ferric chloride addition to this digester and the average H_2S level in the digester biogas. As shown in this table, ferric chloride added to the manure digester averaged 134 gallons per day (gpd), which is approximately 1,648 lb/d with a 40 percent active solution. H_2S in the biogas ranged from 40.5 to 70.1 ppm with an average of 56.2 ppm. The mass of H_2S produced in the digester gas ranged from 0.40 to 1.03 lb/d with an average of 0.58 lb/d. Assuming the H_2S concentration in the digester gas would be 2,000 ppm without H_2S control, the estimated amount of H_2S removed by ferric injection ranged from 11.9 to 26.7 lb/d, and averaged 18.9 lb/d.

TABLE 4-1
Monthly Average of the Ferric Chloride Addition and H_2S Produced from RP-1 Digester 4

Month	Digester Feed	Feed TS	Ferric Chloride Added		Gas Produced	H_2S conc. in Dig. 4 biogas		Theoretical Remvl[2]
	gpd	lb/d	gpd	lb/d[1]	cfd	ppm	lb/d	lb/d
Jan-05	39,330	30,330	108	1,277	113,428	68.1	0.69	20.0
Feb-05	38,970	27,873	124	1,469	101,011	49.7	0.47	17.7
Mar-05	41,638	35,310	101	1,376	106,193	40.5	0.40	18.8
Apr-05	35,054	31,793	99	1,309	110,979	40.5	0.42	19.6
May-05	26,256	36,140	119	1,405	102,097	41.8	0.42	18.0
Jun-05	23,450	30,588	135	1,670	93,223	75.8	0.69	16.2
Jul-05	27,050	36,694	166	2,104	68,461	57.2	0.43	11.9
Aug-05	40,548	58,045	185	2,190	122,806	62.0	0.69	21.6
Sep-05	29,733	37,482	171	2,028	154,207	70.1	1.03	26.7
Average	**33,559**	**36,028**	**134**	**1,648**	**108,045**	**56.2**	**0.58**	**18.9**

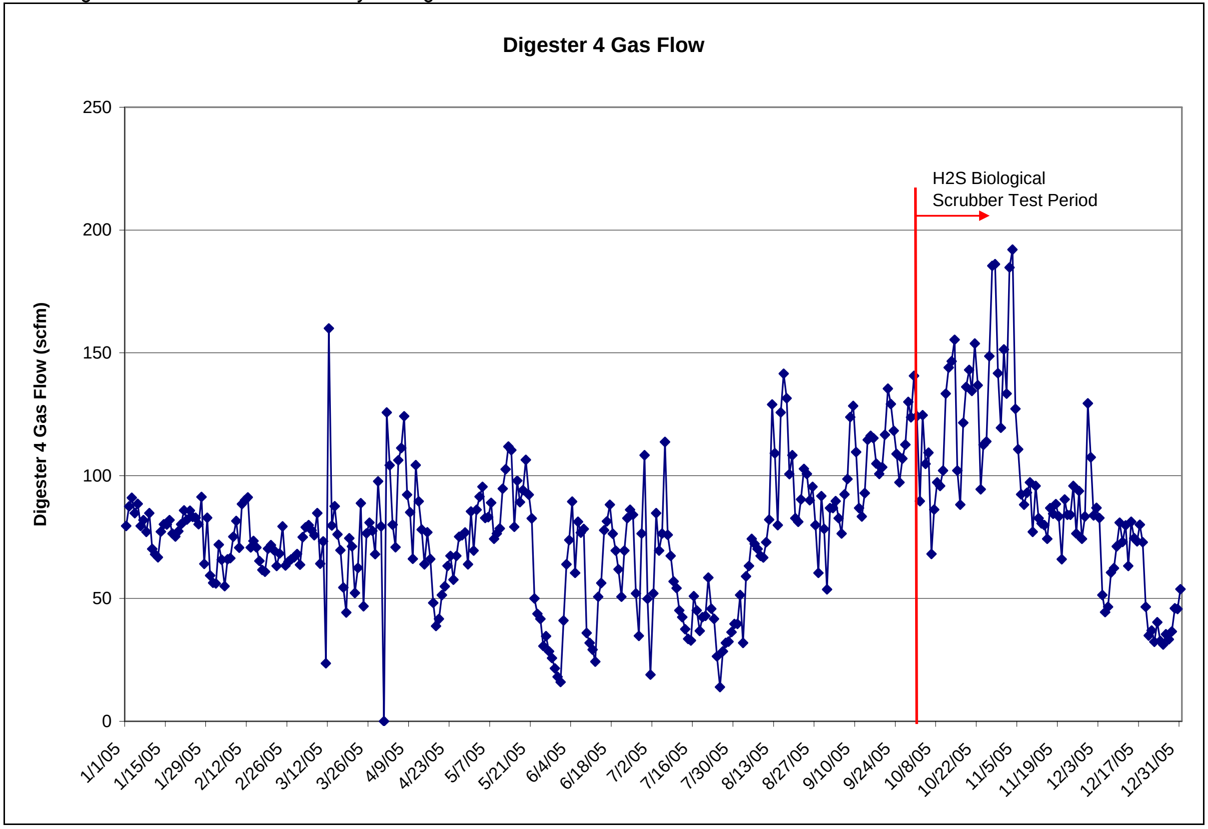
[1] Assume ferric chloride is 40 percent active by weight, and the density is 1.4176 g/cm^3 (11.8304 lb/gal at 20^0C) at 40 percent active.

[2] Assume H_2S in the biogas would be 2,000 ppm without ferric chloride addition.

4.2 Biological H_2S Scrubber Performance

The biological H_2S scrubber was started up in early October 2005, treating the full gas flow from Digester 4, which was fed manure and some food waste. Figure 4-1 shows the flow rate through the H_2S scrubber during the test period. The scrubber was sized to handle up to 120 scfm. During the early part of the test, average daily gas flows reached over 190 scfm, and dropped off during the latter part of the test due to low feed volumes to Digester 4. The corresponding empty bed contact time ranged from 5 to 16 minutes.

FIGURE 4-1
RP-1 Digester 4 Gas Flow Treated by Biological Scrubber



After approximately 3 weeks, the ferric chloride to the digester was stopped on October 25, 2005 and the digester gas H_2S concentration increased above the range of the handheld H_2S meter, as noted in Figure 4-2. Laboratory data for digester gas H_2S concentrations in Table 4-2 show that in the samples collected, concentrations were as high as 8,351 ppmv, considerably higher than the maximum range of 1,000 ppmv that could be measured by the hand held meter on site. Figure 4-3 shows the impact of food waste addition on the H_2S production. The data show that addition of food waste increased the concentration of H_2S in the digester gas and during the baseline period the dose of ferric chloride also was increased to account for this.

FIGURE 4-2
RP-1 Digester 4 Ferric Dose and Gas H_2S Concentration

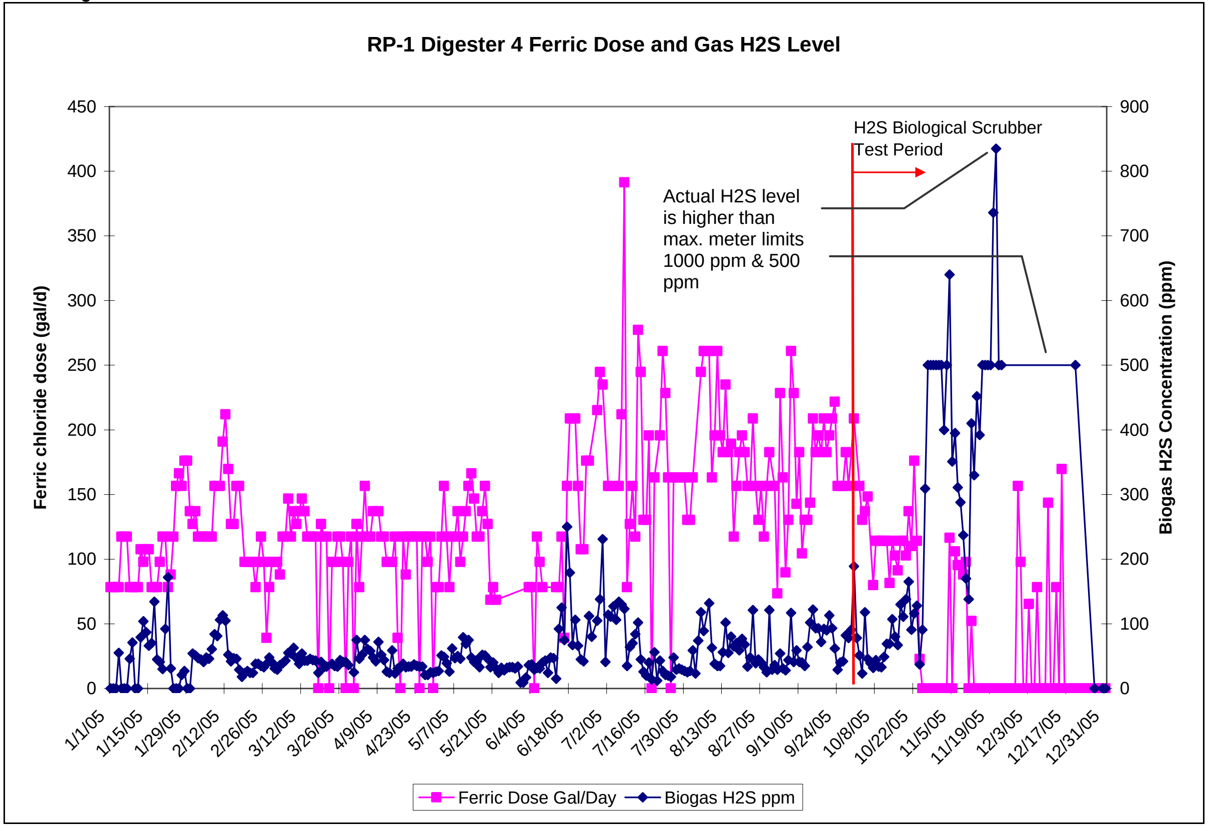
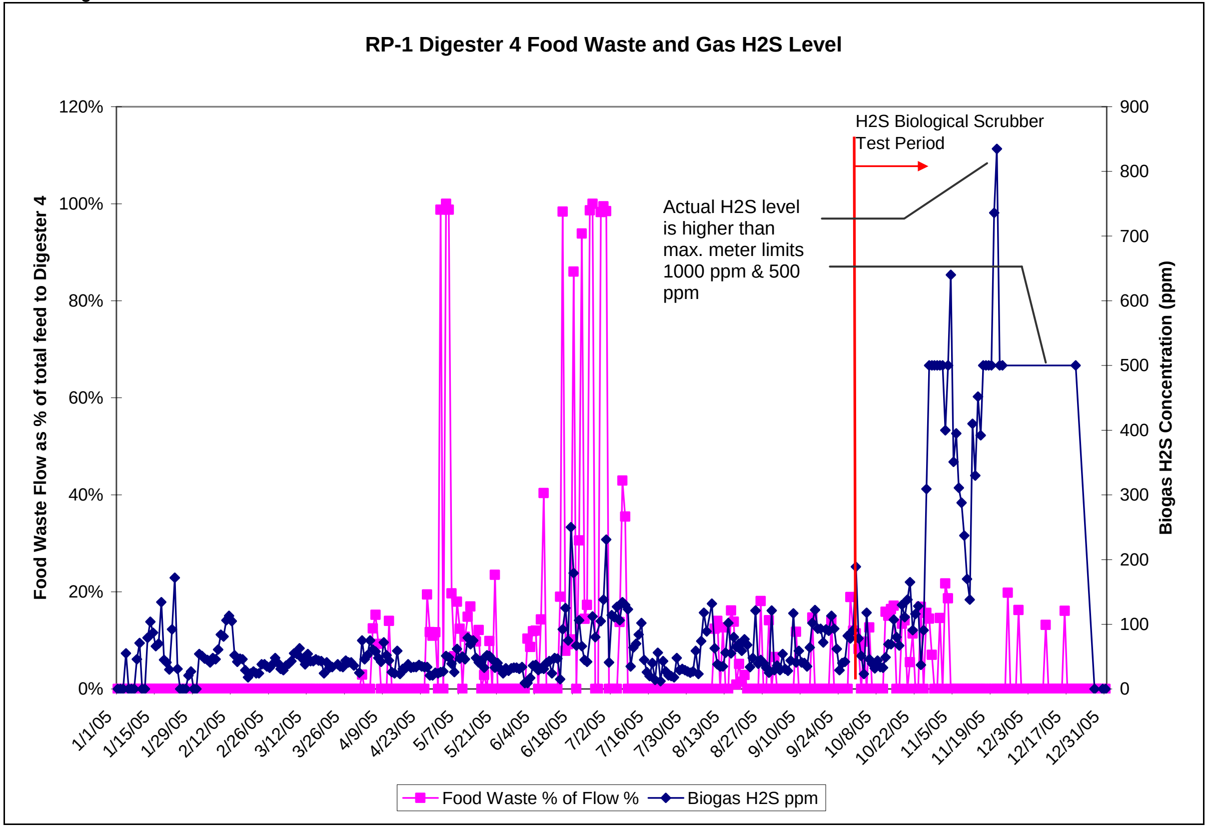


FIGURE 4-3
RP-1 Digester 4 Food Waste and Gas H_2S Concentration



4.2.1 Biological Scrubber H_2S Removal

Figure 4-4 shows the H_2S concentrations in the inlet from Digester 4, after addition of air to the gas stream, and the outlet from the scrubber. The biological scrubber provided significant removal of H_2S regardless of the inlet concentration with outlet concentrations typically below 5 ppm, even after ferric chloride addition to Digester 4 was stopped. This equates to over 99 percent removal of H_2S. Table 4-2 shows the laboratory data for sulfur compounds in the scrubber inlet and outlet gas streams and the removal through the scrubber. The data show that the scrubber provided removal of other reduced sulfur compounds as well as H_2S.

TABLE 4-2
RP-1 Biological H_2S Scrubber Gas Sulfur Compounds

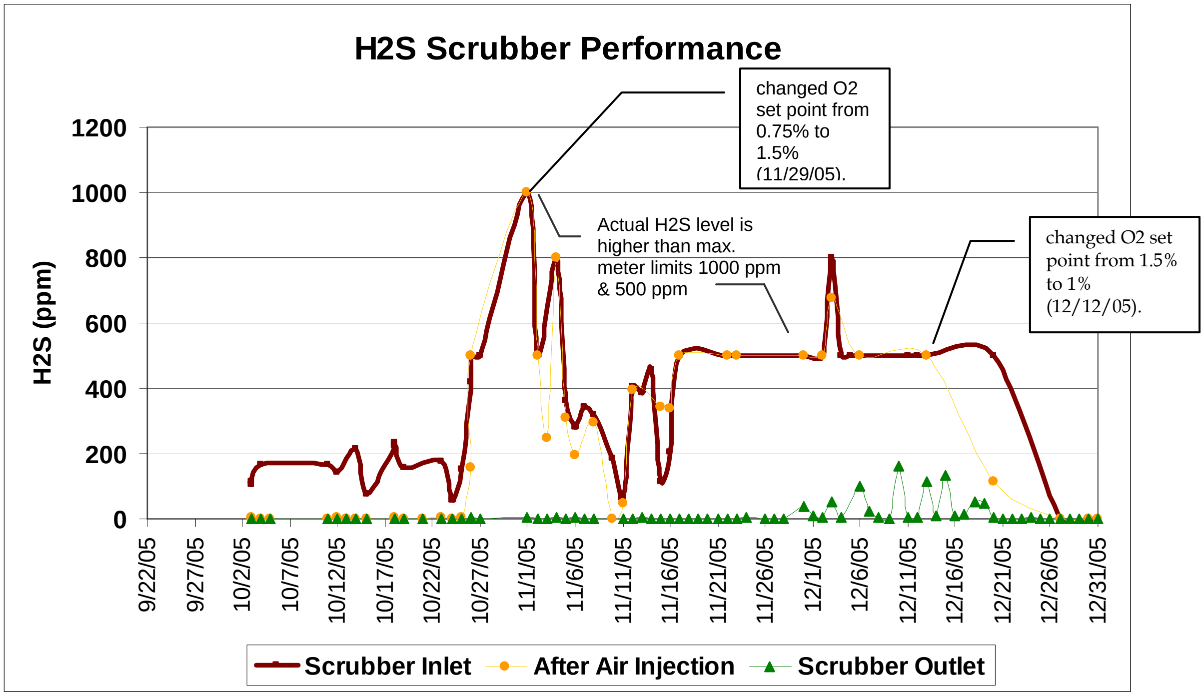
Parameters	10/26/2005 (ppmv)	11/10/2005 (ppmv)	11/16/2005 (ppmv)	11/22/2005 (ppmv)	11/29/2005 (ppmv)	11/30/2005 (ppmv)	12/6/2005 (ppmv)	12/7/2005 (ppmv)	12/14/2005 (ppmv)	12/20/2005 (ppmv)
Scrubber Inlet										
Hydrogen Sulfide	8,350.60	1,138.70	1,937.40	788	62.86	102.2	577.4	185.7	424.1	589.4
Methyl Mercaptan	ND	ND	16.5	ND	ND	ND	ND	ND	ND	ND
i-Propyl Mercaptan	ND	ND	13	ND	ND	ND	ND	ND	ND	ND
Ethyl Methyl Sulfide	ND	ND	ND	ND	ND	ND	ND	ND	3	ND
Isobutyl Mercaptan	ND	ND	ND	ND	ND	ND	ND	ND	2.5	ND
t-Butyl Mercaptan	ND	ND	ND	ND	ND	ND	ND	ND	5.6	ND
n-Butyl Mercaptan	ND	ND	ND	2.7	ND	ND	ND	ND	ND	ND
Dimethyl Disulfide	ND	ND	96.7	ND	6.06	ND	ND	ND	ND	ND
Diethyl Disulfide	6.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Total	**8,357**	**1,139**	**2,064**	**791**	**69**	**102**	**577**	**186**	**435**	**589**
Scrubber Outlet										
Hydrogen Sulfide	NS	ND	ND	ND	46.18	31.3	15.2	1.3	20.7	11.5
Ethyl Methyl Sulfide		ND	ND	ND	ND	ND	ND	ND	0.4	ND
Isobutyl Mercaptan		ND	ND	ND	ND	ND	ND	ND	0.4	ND
t-Butyl Mercaptan		ND	ND	ND	ND	ND	ND	ND	0.8	ND
n-Butyl Mercaptan		ND	ND	ND	ND	ND	ND	ND	0.3	ND
Dimethyl Disulfide		ND	0.005	ND	1.93	ND	ND	1.9	ND	ND
Diethyl Disulfide		ND	0.002	ND	ND	ND	ND	ND	ND	ND
Total	**-**	**ND**	**0.007**	**ND**	**48**	**31**	**15**	**3**	**23**	**12**
Removal %	**-**	**100.0%**	**100.0%**	**100.0%**	**30.2%**	**69.4%**	**97.4%**	**98.3%**	**94.8%**	**98.0%**

ND = nondetect.

NS = no sample.

There was a decrease in performance in early December 2005. Recirculation water is used to keep the optimal environment for the biomass in the scrubber and provide nutrient for the microbes and is critical for maintaining performance of the system. Figures 4-5 shows that a drop in the recirculation water temperature may have had an impact on the scrubber performance. The temperature dropped from over 25ºC to around 21 ºC in late November 2005 due primarily to changes in ambient temperatures and the temperature also became more variable. Around the same time there was also a drop in the pH of the recirculation water, as shown in Figure 4-6. The data suggest that for optimal performance of the biological scrubber, the recirculation water should be maintained above a pH of 4. Renewing the recirculation water allowed the pH to be adjusted back to optimal range. The biomass may also have been stressed by lack of nutrients as no additional nutrient was provided during the first two months of the test. Figure 4-7 also shows that the inlet oxygen concentration increased in early December 2005 and may also have contributed to the decrease in performance. The data indicate that an inlet oxygen concentration below 2 percent and an outlet concentration of approximately 0.75 percent are adequate for efficient performance of the biological scrubber.

FIGURE 4-4
RP-1 Biological H_2S Scrubber Concentrations



changed O2 set point from 0.75% to 1.5% (11/29/05).

Actual H2S level is higher than max. meter limits 1000 ppm & 500 ppm

changed O2 set point from 1.5% to 1% (12/12/05).

FIGURE 4-5
RP-1 Biological H_2S Scrubber Recirculation Water Temperature

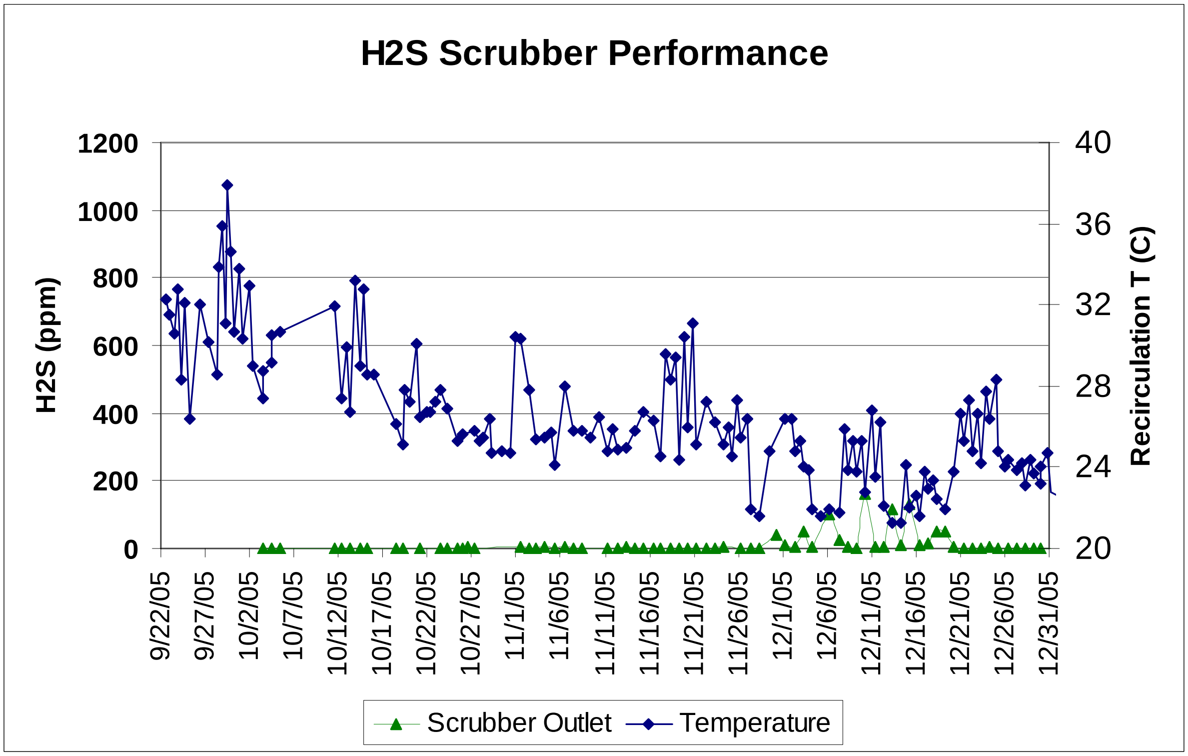


FIGURE 4-6
RP-1 Biological H_2S Scrubber Recirculation Water pH

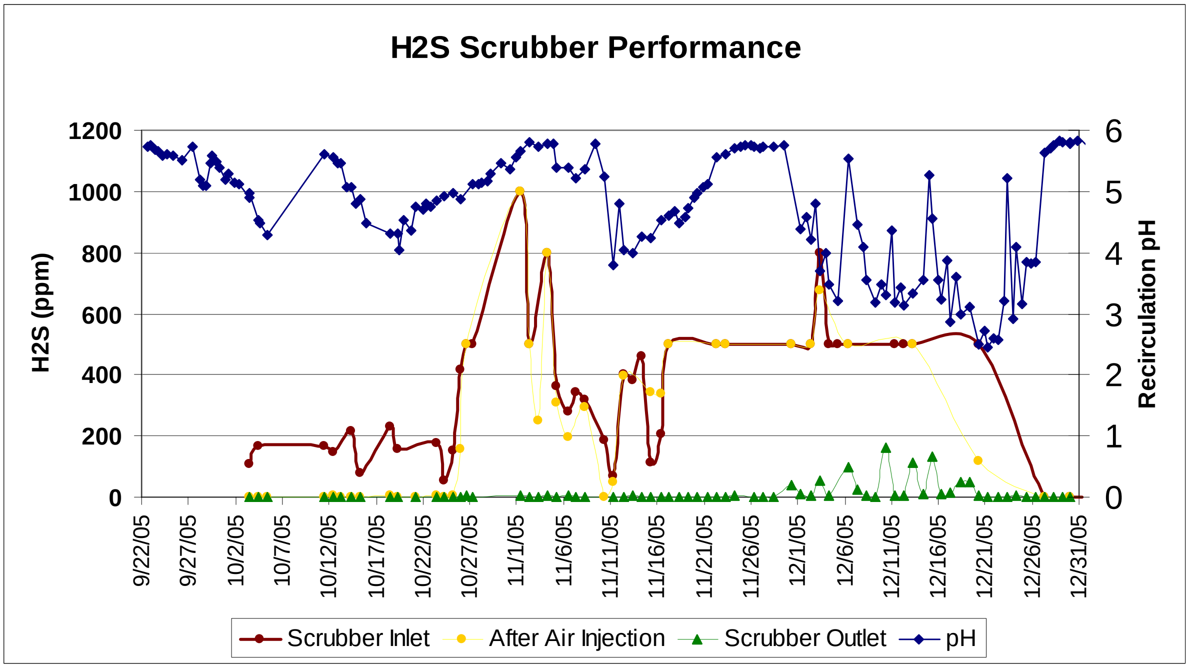
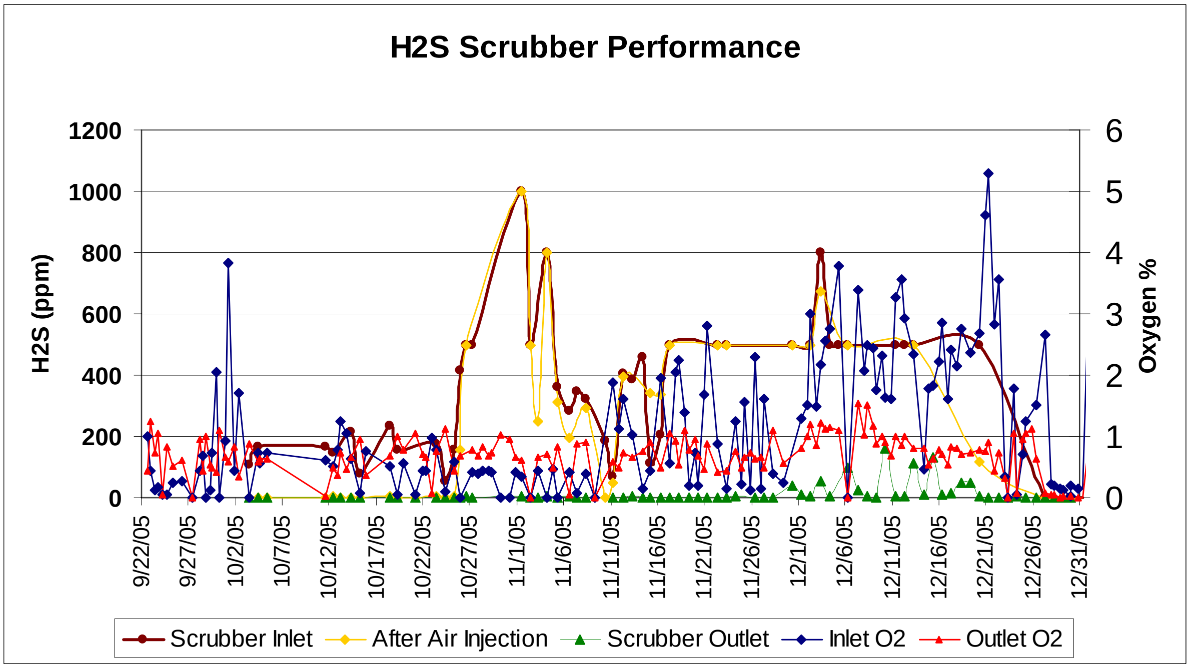


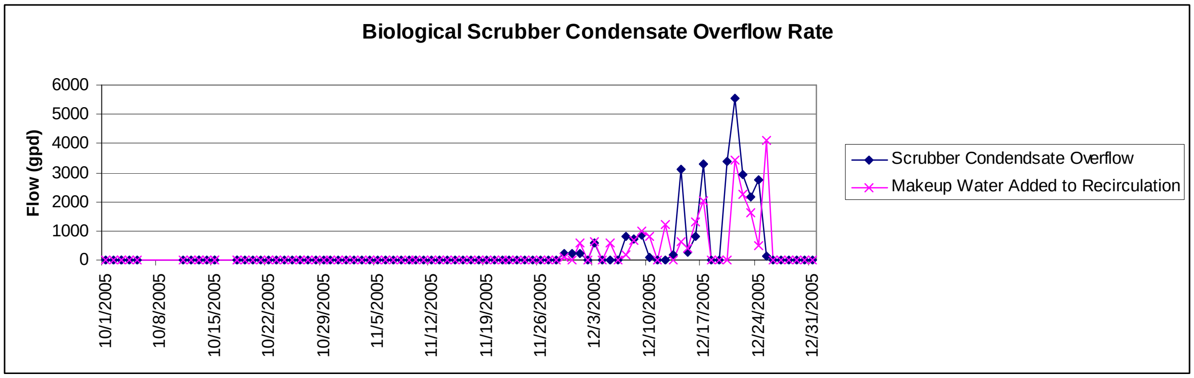
FIGURE 4-7
RP-1 Biological H_2S Scrubber Inlet and Outlet Oxygen Concentrations



4.2.2 Biological Scrubber Condensate

Figure 4-8 shows the daily condensate overflow from the H2S scrubber and the makeup water added to the recirculation water. Typically makeup water is used to control the pH and prevent it from becoming too low and inhibiting performance of the biomass in the scrubber. Makeup water was not added until the pH dropped at the end of November 2005 and appeared to be impacting performance of the scrubber, as discussed above.

FIGURE 4-8
RP-1 Biological H_2S Scrubber Daily Condensate Overflow Rate and Makeup Water



Scrubber condensate samples were collected on a regular basis and laboratory analyses conducted for sulfur compounds, ammonia, solids and pH. The results are provided in Table 4-3. The data show that the concentrations of sulfur and sulfate were highest and that most of the solids were soluble. Ammonia concentrations were usually low. This is in contrast to the condensate from the Digester 4 condensate knock-out pot located upstream of the biological scrubber, as shown in Table 4-4. Ammonia-nitrogen concentrations in this stream were high, averaging 644 mg/L compared with 9 mg/L in the scrubber condensate. The Digester 4 condensate quality showed considerably more variability than the biological scrubber. The increase in sulfur and sulfate concentrations in the Digester 4 condensate through November and December 2005 are attributed to the impact of stopping the ferric chloride feed to the digester. Owing to the hydraulic retention time in the digester, it would have taken some time for all the ferric to be washed out of the system. The data show that the condensate pot is able to provide some sulfur compound removal from the digester gas.

TABLE 4-3
RP-1 Biological H_2S Scrubber Condensate Analysis

Date	Ammonia (N) mg/L	Sulfur (tot) mg/L	Sulfate mg/L	(tot) Sulfide mg/L	Total Solids mg/L	Total Dissolved Solids mg/L	pH
11/10/05	-	60	183	-	485	478	5.3
11/16/05	34	67	199	-	511	490	4.4
11/22/05	1	51	154	0.02	508	487	5.1
11/30/05	1	53	146	0.02	484	473	5.1
12/7/05	3	63	213	0.02	560	572	3.6
12/14/05	1	42	222	1.39	508	493	-
12/20/05	1	220	660	0.02	1380	1340	2.2
12/27/05	1	67	191	0.02	75	516	5.7
1/3/06	3	31	159	0.02	476	475	5.5
1/10/06	36	36	108	0.02	1020	491	5.1
Average	**9**	**69**	**224**	**0.19**	**601**	**582**	**4.7**

TABLE 4-4
RP-1 Digester 4 Condensate Analysis

Date	Ammonia (N) mg/L	Sulfur (tot) mg/L	Sulfate mg/L	(tot) Sulfide mg/L	Total Solids mg/L	Total Dissolved Solids mg/L	pH
11/10/05	-	2	1	-	164	158	7.1
11/16/05	766	8	11	-	202	170	7.3
11/22/05	846	8	23	0.02	126	116	7.4
11/30/05	879	32	14	0.02	216	206	6.9
12/7/05	683	4	8	0.02	222	193	7.3
12/14/05	909	1	56	4.56	188	198	7.0
12/20/05	806	12	36	0.02	174	169	7.3
12/27/05	400	506	1500	0.02	2380	2320	7.0
1/3/06	307	423	1040	0.02	2130	2040	6.6
1/10/06	199	484	1450	0.02	2360	2310	6.4
Average	**644**	**148**	**414**	**0.59**	**816**	**788**	**7.0**

4.2.3 Biological Scrubber Nutrient Requirements

Operation of the biological scrubber provided evidence that maintaining adequate nutrients is critical to effective H_2S removal performance. Table 4-5 shows the frequency and amount of nutrient added in the form of manure dewatering filtrate and chemical plant fertilizer. At startup, nutrient was added to the recirculation water. No additional nutrients were provided until after performance of the scrubber decreased at the end of November 2005. On December 5, 2005, the H_2S concentration measured in the outlet from the scrubber was 99 ppmv. The recirculation water pH was adjusted by adding 600 gallons of makeup water and 50 g of fertilizer nutrient was added. After these operational adjustments, the outlet gas H_2S concentration dropped to 4 ppmv. Experience with similar biological scrubbers in Denmark has shown that weekly addition of a small amount of fertilizer or filtrate provides stable operation of the biological system.

TABLE 4-5
RP-1 Digester 4 Condensate Analysis

Date	Manure Filtrate	Fertilizer
10/2/2005	2 gal	50 g
11/28/2005	-	25 g
11/29/2005	2 gal	-
12/3/2005	-	1 tsp
12/5/2005	-	50 g
12/9/2005	-	1 tsp
12/12/2005	1 gal	25 g
12/15/2005	-	1 tsp
12/24/2005	-	1 tsp

4.3 Summary and Conclusions

The biological H_2S scrubber pilot test proved effective operation of this technology. The scrubber was able to provide 99 percent removal of reduced sulfur compounds effective treatment over a wide range of flows and inlet H_2S concentrations. It was operated at EBCTs as low as 5 minutes, similar to design of chemical scrubbers. The system handled flow rates up to 190 scfm, considerably higher than the design flow of 120 scfm. Startup of the system was easy and the biomass did not require a long acclimation period. The system provides the following advantages over other digester gas H_2S removal systems:

- No use of chemicals or chelating compounds
- No sulfide containing waste stream requiring discharge; production of elemental sulfur as re-usable product
- Operation at ambient pressure and temperature

The pilot test also highlighted the importance of the following critical operational parameters:

- Recirculation water pH should be maintained over 4.
- Regular addition of nutrients, weekly addition would be appropriate.
- Inlet oxygen concentration ≤2 percent is adequate.
- Outlet oxygen concentration of around 0.75 percent is an appropriate control point.
- Recirculation water temperature may affect the biomass kinetics and removal reaction rates.

Economic advantages of the biological scrubber are discussed in Section 5.

SECTION 5

Economic Considerations

Improved gas cleaning technologies are important to the economics of biogas projects. The gas cleaning technologies tested enable lower emitting technologies such as microturbines to be deployed and also improve the overall life cycle cost for other generation systems such as reciprocating engines. Improved gas cleaning technology is one of the most important factors in expanding biogas generation levels. Improved technology allows existing projects to operate more reliably and more projects to become economic with the installation of improved gas cleaning systems.

The goal of the gas cleaning pilot project was to develop and optimize cost effective gas cleanup systems by:

- Evaluating treatment performance and cost during operation so sewage treatment plants have greater certainty on cost and reliability of cogeneration.
- Evaluating and quantifying environmental benefits that result from using microturbines at sewage treatment plants.

The chiller had two purposes: moisture removal and siloxane removal. This was followed by a SagPack system with two vessels to test different absorption media for siloxane removal, a graphite based media and a polymer based media. A separate system tested was a biological scrubber system that removes H_2S from the gas stream.

Siloxanes in digester gas have been increasing as a result of increased use of siloxane in consumer products, which results in increased siloxanes reaching the wastewater treatment plants. In order to prevent cogeneration engine shutdowns, lower engine maintenance requirements, and reduce biogas wasting during engine down periods, siloxane removal from digester gas needs to be practiced. As the RP-1 plant does not currently have siloxane removal equipment, there was no baseline treatment cost. However, the cost of not removing siloxanes is seen in operation and maintenance (O&M) costs on the power generation equipment, including the microturbines and generator engines. Microturbines are more sensitive to gas quality than engines and the cost of not removing moisture and siloxanes can be seen in the fact that the eight micro-turbines at RP-1 have been out of service. This has resulted in equipment with a capital cost of approximately $800,000 and an electricity generation capacity of 240 kW not being used. This was especially important for this project, since the goals are to implement a system where improved digestion and increased biogas production are sought. Media capacity and useful life of these media need to be determined for a thorough technology analysis and longer-term operation of the two parallel media vessels.

The H_2S scrubber installed and tested under this project was a biological treatment unit. Because this unit is based on biological treatment, this technology reduces or eliminates chemical usage (e.g., ferric chloride addition for H_2S control) at the facility. Other advantages of the unit include easy and automated operation, and minimal operator attention and labor requirements.

Table 5-1 summarizes digester gas volumes and quality and the costs for operating the pilot chiller, SagPack vessels, and biological H_2S scrubber. For the year 2005, the average total daily gas production at RP-1 was 980,000 scfd. At a typical BTU content of 600 BTU/scf and an engine efficiency of 33 percent, this would provide an electricity generation capacity of 2.37 MWh and a heat recovery capacity of 7.35 MMBTU/hr at 30 percent heat recovery. Of the systems tested, the biological scrubber offered the most significant advantages from operational and economic standpoints. With the shutdown of the H_2S control with $FeCl_3$ addition, the H_2S concentration in the Digester 4 gas increased significantly, reaching concentrations over 8,000 ppmv, while maintaining a scrubber outlet concentration <5 ppmv at that time. The chiller did not provide significant moisture removal as it was located downstream of the gas compressors. In a full-scale installation, the chiller would be more cost effective installed upstream of the compressors. However, the chiller did provide approximately 15 percent removal in siloxanes, despite the low moisture removal volume. Both the HOX and carbon media in the SagPack vessels proved to be effective at reducing siloxane concentrations to 2 ug/L or less. Longer-term operation would be required to determine the life-cycle costs of the two media. However, the carbon media removed a greater amount of organic compounds from the gas stream indicating that it was less selective for siloxanes. This would reduce the life of the carbon media, but may have advantages if greater removal of organic and reduced sulfur compounds was required.

In summary, all of the gas cleaning systems tested performed well. In general, the biological scrubber was the most cost effective, reliable, and low labor unit, and its use eliminated the need for chemical use, thereby saving money and reducing environmental impacts. SagPak monitoring results showed siloxane removal. However, media capacity was not completely determined within the Project test period, and the unit useful life was not completely assessed.

The results of the gas cleaning tests showed that biological H_2S scrubbers could be very efficient, easy to operate, non-labor intensive, and cost-effective units for implementation at other facilities where H_2S removal from biogas is needed prior to cogeneration. Biological scrubbers, as compared to iron sponges or other more standard control technologies, reduce the life cycle cost of H_2S removal systems. By using biological media to capture the H_2S, chemical media purchases are reduced substantially. There is less solid waste generated and there is also a potential for recovering the sulfur.

Siloxane removal systems functioned reliably to remove siloxane from the gas stream. With further assessment of media useful life, these units can be readily implemented at other California facilities.

TABLE 5-1
Summary of Gas System Operation and Performance

					With Project SagPak HOX-Based		With Project SagPak C-Based		With Project Chiller		With Project H_2S Scrubber	
		Baseline	Baseline	Baseline	Inlet	Outlet	Inlet	Outlet	Inlet		Inlet	Outlet
	Units	(Jan/05 - Sep/05)	12-Oct-04	16-Nov-04	(Oct/05 - Dec/05)		(Oct/05 - Dec/05)		(Oct/05 - Dec/05)		(Oct/05 - Dec/05)	
Operational Parameters												
Biogas Production Total	cfd	892,000	230,000	640,000	1,019,000		1,019,000		1,019,000		1,019,000	
Biogas Production Digester 4	cfd	108,000	97,000	116,000	-		-		-		134,000	
H_2S	ppmv	56[1]	77[2]	26[3]	-	-	-	-	-		1,416[1]	<5[9]
Moisture	mg/L	-	16[2]	-	7.9	7.9	7.9	7.8	8.7	7.9	-	-
Siloxane	ug/L	360	730[2]	95[3]	49	2	49	2	58	49	ND	ND
Cost As Tested												
Installation Cost	$	-	-	-	53,815[4]		53,815[4]		151,570		417,860	
Annual Operating Cost	$	-	-	-	8,750		8,750		8,750		8,750	
Environmental Benefits												
SOX Reduction		-	-	-					8			
Annual Chemical/ Media Use Reduction	$/year	-	-	-	-		-		53,815		91,440	
Reliability												
Percentage of Days Operated	%	NA	NA	NA	98%		98%		98%		100%	
Economic Analysis												
Total Annual Savings (= Environmental benefits less operating costs)	$/year								$45,065		$70,450	
Present value of annual savings; 6% discount rate, 10 project life	$								$331,682		$518,518	
Net Present Value (NPV) of investment	$								$180,112		$100,658	

TABLE 5-1
Summary of Gas System Operation and Performance

					With Project SagPak HOX-Based		With Project SagPak C-Based		With Project Chiller		With Project H_2S Scrubber	
		Baseline	Baseline	Baseline	Inlet	Outlet	Inlet	Outlet	Inlet		Inlet	Outlet
	Units	(Jan/05 - Sep/05)	12-Oct-04	16-Nov-04	(Oct/05 - Dec/05)		(Oct/05 - Dec/05)		(Oct/05 - Dec/05)		(Oct/05 - Dec/05)	
Simple Payback	years								3.36		5.93	
Rate of Return (IRR)									27%		11%	

NA = Not applicable.

ND = Nondetect.

[1] Digester 4 data; with $FeCl_3$ addition for H_2S control during baseline, and without $FeCl_3$ addition after project implementation.
[2] Combined gas at the flare.
[3] Combined gas after the compressors.
[4] Price of media replacement.
[5] Price of one complete unit.
[6] No change from baseline gas loop measurements. Field test period was insufficient to determine useful life of test unit.
[7] Price of modifications to existing system and media addition $157,500.
[8] Assumes chiller saves 1 change-out per year of SagPak media.
[9] Under stable operation.

SECTION 6

Project Recommendations

A technology transfer program should be initiated to communicate the effectiveness of biological scrubbers to potential users. It should be communicated that the scrubbers perform well from a technical, economic, and environmental standpoint. Further, it should be explained that their deployment at wastewater treatment plants across the state would reduce chemical use, reduce solid waste disposal activities (required if other types of media are used), and lower the cost of using biogas.

The technology transfer program cited above could be complemented by additional testing on digester gas generated from biosolids and on systems larger than the system used in the RP-1 test. That test was on biogas from a manure digester and was equivalent to a treatment plant with a flow of about 5 to 10 million gallons per day. Running such additional testing on digester gas from biosolids would provide long-term results facilitating optimization of future full-scale systems.

Future research should be conducted to optimize a combined system of chillers and media based systems to remove siloxane and hydrogen sulfide. Removing siloxane and hydrogen sulfide as part of the moisture removal system is an option because there are dual benefits when using such moisture removal systems. Different media were also demonstrated to perform well for siloxane removal. Long-term testing would be required to determine life cycle costs for the HOX and carbon media and potential advantages of one over the other. Therefore, further testing of combined chiller/media systems, where the chiller is operating at less than 40^0F and above -40^0F, would be optimal. Additional research is merited to help define the parameters of such optimized systems.

SECTION 7

Quality Assurance and Data Analysis Procedures

This section describes quality assurance and control (QA/QC) and data analysis procedures followed for the data collected during this time period.

7.1 Quality Assurance Procedures

Two important steps in practicing QA/QC were performed. The first step ensured good sample collection and shipping methods. Prior to data collection, the appropriate sample collection points and collection times were demonstrated to the plant operators. The samples were collected by the operators in appropriate bottles provided by the laboratory that was conducting the tests. For samples sent to an external laboratory, the sample bottles were stored on ice and shipped in coolers on the same day if possible, or before 10:00 a.m. the next morning for samples taken later in the day. When same day shipping is not possible (usually weekends and evenings), the sample bottles were preserved, stored (usually at 4°C), and shipped the next morning to ensure that the appropriate procedures and holding times are met, as specified by the analytical laboratory.

The second step relates to laboratory procedures and methods. During laboratory analyses conducted by the plant's certified laboratory or by an external certified laboratory, laboratory staff demonstrated familiarity with standard sample storage, analysis, and QA/QC procedures. When immediate analysis was not possible (usually weekends and nights), the sample bottles were preserved, stored (usually at 4°C), and delivered to and analyzed in accordance with appropriate procedures and holding times, as specified by the analytical laboratory. Replicate samples and split sample analysis were conducted occasionally to verify reliability of results.

At a minimum, the laboratories' QA programs are required to meet EPA and ASTM standard. In the field, the collection of the condensate samples was done using sterilized containers. Immediately after collecting the sample, the container was labeled with the sample number, source, date, and time.

7.2 Data QA/QC and Analysis Procedures

In addition to the QA/QC of the sample preparation and laboratory analysis procedures, QA/QC and data analysis of the collected data were critical to an accurate representation of gas cleaning system performance. This included development of a daily log sheet for recording operational parameters of the chiller, SagPack and biological scrubber systems. Information from the log sheets is in a format that can be easily input into an Excel spreadsheet. On-line data collected by the plant, such as flow rates, and laboratory data were input into Excel spreadsheets.

For the gas cleaning baseline data, an Excel template was developed to host and analyze the historical monthly operational and performance data obtained from the plant for both the sludge and manure digestion systems. The summary of the monthly data from these files was input into an Excel spreadsheet to perform the calculations, such as H_2S removal percentages by ferric chloride addition and iron sponge system, and operational costs. Excel spreadsheets were also created to host the two rounds of laboratory test results.

APPENDIX A

Baseline Gas Cleaning Data

APPENDIX B

Siloxane Sampling Protocol