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FINAL REPORT
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Conduct a Nationwide Survey of Biogas Cleanup Technologies and Costs

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EXECUTIVE SUMMARY

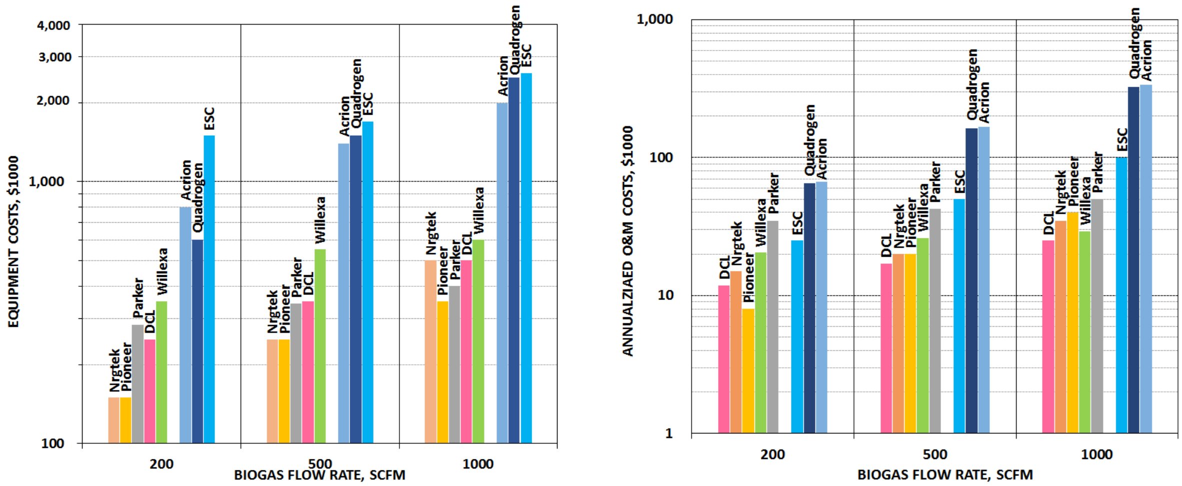
The objectives of this project are to conduct a nationwide survey of landfill and digester gas ("biogas") cleanup technologies and costs and develop a biogas cleanup system cost estimator toolkit as a Microsoft Excel computer based interactive document. This work will assist landfill and biogas facilities to determine the costs of the equipment required to meet SCAQMD's future Rule 1110.2 emissions limits for internal combustion engines (ICEs) operating on biogas. The following was completed:

- Analyses of Gas Compositions
- Survey of Biogas Cleanup Systems Technologies
- Cost Estimates of Biogas Cleanup Systems
- Development of a Biogas Cleanup System Cost Estimator Toolkit
- Prepare User Instruction Manuals & Conduct Toolkit Training for SCAQMD Staff
- Provide Toolkit Technical Support

Gas Composition Analyses
GTI conducted a literature search for sources of raw biogas composition data and heating values. Data for over 575 samples in the GTI database derived from approximately 47 LFG, 22 WWTP, and 21 dairy sources located across the US were compiled in Excel spreadsheets. In particular, the above data included siloxane analyses from these sites and others across the US.

Survey of Biogas Cleanup Systems Technologies
An extensive literature/internet search was conducted to identify and obtain information on biogas cleanup systems mainly focusing on siloxane removal technologies for engines. This resulted in over 100 references that were compiled in an Excel spreadsheet. It was found that the requirements for engine selective catalytic reduction (SCR) catalysts and fuel cells are 1 to 2 orders of magnitude more stringent than the engine original equipment manufacturer gas cleanliness standards. In order to facilitate the survey process a vendor questionnaire was developed and issued to 15 companies identified as siloxane system removal system manufacturers or equipment suppliers. Only nine surveys (from Willexa Energy, DCL America, Pioneer Air Systems, ESC, Unison, Acrion, Quadrogen, Nrgtek and Guild) were either partly or completely filled out and returned.

Biogas Cleanup System Costs
Both capital and O&M costs for the nine surveyed vendor systems varied widely between the individual siloxane-only removal and between each of the all-contaminants-removal systems–the reasons for this are not readily determined due to the limited data provided by the vendors, and the reluctance of some of the respondents to provide proprietary data due to the either the competitive nature of the business, or insufficient data and current technical expertise. In any case, siloxane removal systems capable of meeting the requirements of SCR-catalyzed engines will greatly increase the initial costs of a biogas power plant as well as increasing the demand for on-site maintenance (including siloxane monitoring) in the future. Maintenance on the gas processing equipment will be critical as the cost associated with even short-term breakthrough will be excessive due to potential failed SCR catalyst, fuel cells, or microturbines. A comparison of the vendor survey capital equipment and operating & maintenance costs is shown graphically below.



Siloxane Removal System Costs from Vendor Survey Questionnaire Results

<u>Development of a Biogas Cleanup System Cost Estimator Toolkit</u>
A toolkit cost template was developed as an Excel-based calculation spreadsheet that estimates capital (equipment) costs, annual operation and maintenance costs and annualized cost for a siloxane removal system based on user input data consisting of biogas volumetric flow and siloxane content. Toolkit development was based only on vendor survey cost data since this would be a more realistic source of procuring data as opposed to using possibly outdated and/or unverifiable literature data. A sample toolkit output is shown in the table below.

<u>Prepare User Instruction Manuals & Conduct Toolkit Training for SCAQMD Staff</u>
A “User's Instruction Manual for the Biogas Cleanup System Cost Estimator Toolkit” was prepared that includes documentation for program installation and operation, inputs, calculational schemes and output of results. A training class on the use of the Biogas Cleanup System Cost Estimator Toolkit for SCAQMD staff was held on July 9, 2014. Also, GTI will provide biogas cleanup system cost estimator toolkit technical support to SCAQMD to ensure the continuous use and operation of the toolkit until the completion of the term of this contract.

Complete details of the above effort are presented in the final report. Based on the execution of the project the following conclusions and recommendations can be drawn.

Example Spreadsheet Output of Siloxane Removal System Cost Calculation

	Value	Units
Input Value and Units	**1,000**	**SCFM**
Biogas Higher Heating Value (HHV)	**500**	Btu/ft^3
Engine Efficiency	**32**	%
Inlet Flow Rate	1,000	SCFM
Engine Power	2,813	kW
Engine Power	3,773	bhp

Input either SCFM, kW or BHP.

Input either flowrate or engine power.

SILOXANE-ONLY REMOVAL (SOR) SYSTEM CAPITAL AND ANNUAL COSTS CALCULATOR

Cost Items	Cost Factors	Factor	Removal System Cost ($)	Default Factor
DIRECT CAPITAL COSTS (DCC):				
(1) Siloxane Removal System Equipment Cost (SRSEC)	Calculated by program		467,586	
(2) Auxiliary Equipment	5% of equipment cost (SRSEC)	**5.0%**	23,379	5%
(3) Freight	5% of SRSEC	**5.0%**	23,379	5.0%
(4) Sales Tax	10% of (SRSEC+auxiliary+freight)	**10.0%**	46,759	10.0%
Subtotal: **Total Equipment Cost (TEC)**	(1) + (2) + (3) + (4)		561,103	
(3) Direct Installation Costs				
(a) Foundation and Structural Support	8% of TEC	**8.0%**	44,888	8.0%
(b) Handling & Erection	14% of TEC	**14.0%**	78,554	14.0%
(c) Electrical	4% of TEC	**4.0%**	22,444	4.0%
(d) Piping	2% of TEC	**2.0%**	11,222	2.0%
(e) Insulation	1% of TEC	**1.0%**	5,611	1.0%
(f) Painting	1% of TEC	**1.0%**	5,611	1.0%
Subtotal: **Total Direct Installation Costs (DIC)**	(a) + (b) + (c) + (d) + (e) + (f)		168,331	
Total DCC:	TEC + DIC		729,434	
INDIRECT CAPITAL COSTS (ICC):				
(1) Indirect Installation Costs (IIC)				
(a) General Facilities	5% of TEC	**5.0%**	28,055	5.0%
(b) Engineering and Home Office Fees	10% of TEC	**10.0%**	56,110	10.0%
(c) Process Contingency	10% of TEC	**10.0%**	56,110	10.0%
(2) Other Indirect Costs (OIC)				
(a) Siloxane Monitor	Engineering Estimate	**$75,000**	75,000	75,000
(b) Startup and Performance Testing	1% of TEC	**1.0%**	5,611	1.0%
(c) Spare Parts	1% of TEC	**1.0%**	5,611	1.0%
(d) Contractor Fees	10% of TEC	**10.0%**	56,110	10.0%
Total ICC:	IIC+OIC		282,608	
PROJECT CONTINGENCY	15% of (DCC+ICC)	**15.0%**	151,806	15.0%
RETROFIT COSTS	0% of TIC	**0.0%**	0	0.0%
TOTAL CAPITAL INVESTMENT (TCI):	DCC+ICC+Project Contingency+Retrofit Costs		1,163,849	
DIRECT OPERATING COSTS (DOC):				
(1) Operating Labor				
(a) Operator			21,900	
hr/shift		**0.5**		0.5
Pay Rate		**$40**		$40
Operating Hours		**8760**		8760
(b) Supervisor	15% of operator cost	**15.0%**	3,285	15.0%
(2) Maintenance (labor and material)	1.5% of TCI	**1.5%**	17,458	1.5%
(3) Siloxane Removal System Media Replacement + Energy Requirement	Calculated by program		27,164	
(4) Siloxane System Periodic Testing	Engineering estimate	**$24,000**	24,000	$24,000
Total DOC:	(a) + (b) + (2) + (3) + (4)		93,807	
INDIRECT OPERATING COSTS (IOC):				
(1) Overhead	60% of (operator labor (1) + maintenance (2))	**60.0%**	25,586	60.0%
(2) Property Taxes	1% of total capital investment	**1.0%**	11,638	1.0%
(3) Insurance	1% of total capital investment	**1.0%**	11,638	1.0%
(4) Administration	2% of total capital investment	**2.0%**	23,277	2.0%
(5) Capital recovery costs (CRC)	CRF x TCI		165,732	
Capital recovery factor (CRF)	0.1424			
Interest rate		**7.0%**		7.0%
Annualization years		**10**		10
Total IOC:	(1) + (2) + (3) + (4) + (5)		237,872	
Recovery Credits (RC)	Engineering Estimate	**$0**	0	$0
TOTAL ANNUAL COST (TAC):	DOC + IOC - RC		331,679	
TOTAL ANNUAL COST PER kWh			0.013	
TOTAL ANNUAL COST PER MMBtu			1.26	
TOTAL ANNUAL COST PER MSCF			0.63	

- Vendor interaction and issuance of the survey questionnaire were found to be the most effective techniques in obtaining cleanup system information and cost data.
- A personal interview with Brad Huxter of Willexa Energy gave useful insights into their own and other vendors siloxane removal systems and confirmed some of the costs in the survey.
- Utilize feedback from toolkit users to improve and update the toolkit.
- Extend a more comprehensive version of the toolkit to other applications such as turbines, fuel cells, and substitute natural gas.
- Further develop the toolkit as a web application to allow for continuous upgrade and improvement by vendors, engines and biogas facility operators, etc. This would also promote dialog between users and vendors.
- Provide incentives to promote more field testing of available cleanup systems.
- Continue to strive for obtaining the most up to date information from cleanup technology developers.

PROJECT OBJECTIVES

The objectives of this project are to conduct a nationwide survey of landfill and digester gas ("biogas") cleanup technologies and costs and develop a biogas cleanup system cost estimator toolkit as a Microsoft Excel computer based interactive document. This work will assist landfill and biogas facilities to estimate the potential costs of the equipment required to meet SCAQMD's future Rule 1110.2 emissions limits for internal combustion engines (ICEs) operating on biogas. The project work will be accomplished in six tasks per the schedule presented in Table 1.

Table 1. Project Schedule

Task #	Task	Duration
1	Gas Composition Analyses	3 months
2	Survey of Biogas Cleanup Systems Technologies	3 months
3	Biogas Cleanup System Costs	3 months
4	Development of Biogas Cleanup System Cost Estimator Kit	3 months
5	Biogas Cleanup System Cost Estimator Toolkit Training and User Instruction Manuals	3 months
6	Technical Support and Management	12 months
Draft Final Report		
Final Report		

The project team included GTI as prime contractor and Vronay Engineering Services as subcontractor, providing cleanup system vendor interactions and cost procurement.

INTRODUCTION AND BACKGROUND

Siloxanes, organic man-made compounds containing carbon, hydrogen, oxygen, and silicon, are found in a wide variety of household and industrial products. Domestic products containing siloxanes include cosmetics, while industrial usage includes cleaners such as dry-cleaning solvents and a variety of down-the-drain household products such as shampoos, soaps, deodorants and laundry detergents. These compounds enter wastewater treatment systems and landfills as they are disposed. Due to site-specific characteristics and variability in consumer product use, siloxane concentrations in biogas will vary significantly as a function of time and location. Despite their beneficial attributes in consumer products, when vaporized in landfill and wastewater processes they become entrained in the biogas stream.

In the process of combusting the biogas these siloxane compounds disassociate reducing to silica (sand) and oxygen. This free silicon readily deposits on the hot surfaces of engine and exhaust system components in the form of a white silica powder. Over time, silica deposits on engine components increases maintenance requirements and negatively impact system efficiency. However, when these deposits occur on the matrix of exhaust gas catalysts, fuel cells or microturbines, premature failure is imminent, sometimes within hours. This is notable in Table 2 below, which specifies the maximum allowable siloxane content in the biogas stream as provided by various engine manufactures and SCR catalyst systems suppliers. With regard to siloxane content and combustion engines, without an exhaust catalyst, total siloxane content in the fuel is only an issue of maintenance intervals whereas for an application requiring a catalyst, complete removal of these compounds is a requirement.

In the case of internal combustion engine or turbine applications where selective catalytic reduction or oxidation catalysts are being considered or required for emission control, siloxane removal is a necessity. There are numerous examples where SiO_2 deposits from siloxanes have

Table 2. Specified Limits of Siloxane in the Fuel Stream[1]

Manufacturer	Gas Inlet Siloxane Content, mg/m^3 (ppbv)
Caterpillar	28 (5600)
Jenbacher	10 (2000)
Waukesha	25 (5000)
Deutz	5 (1000)
Solar Turbines	10 (2000)
Ingersoll Rand Microturbines	0.06 (12)
Capstone Microturbines	0.03 (5)
SCR	<0.5 (<100)
Cormetech SCR	0.38 (76)

resulted in catalyst deactivation in hours or days. The inability to continuously monitor siloxanes coupled with their rapid destructive effect makes this a difficult application. It is important to note that there are other constituents present in the biogas that can also foul the catalyst, further complicating the study of siloxane impact[2].

The increased use of biogas equipment sensitive to otherwise benign biogas constituents, such as siloxane compounds and other halogenated compounds, has created an industry that is offering varying degrees of cleanup solutions for these contaminants from the gases. Primary constituents include siloxanes. While lean-burn reciprocating engines and compression-ignition dual-fuel engines are relatively insensitive to siloxanes and require no cleanup or only a modest cleanup[3], other technologies gaining popularity such as microturbines and fuel cells are much more sensitive to siloxane and other contaminants. Concurrently, in order for some types of engines, for example, compression-ignition and digester gas fueled engines, to meet lowering NOx and particulate matter emissions nationally, many have been fitted with exhaust gas after-treatment technologies. Such systems include Selective Catalytic Reduction (SCR) systems which are intolerable of any measurable amount of these contaminants.

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[1] Wheless, E.P. and Pierce, J. 2004. *Siloxanes in Landfill and Digester Gas Update*, SWANA 27th Landfill Gas Conference, March 22-25.

[2] *Ibid*.

[3] For reciprocating engines, the issue of siloxane cleanup is one of a trade-off between maintenance intervals and gas system cleanup costs. To date, most operators' engines, particularly at landfills, have found the increased maintenance intervals preferable and less costly than the option to highly clean the "free fuel" gas.

Industry experience with applying SCR technology on digester gas and landfill gas fueled engines has been in most if not all cases negative. This dates back to the early 1990's with dual-fuel engines operated in Bay Park, Long Island, New York, in a wastewater treatment plant up to recent test data in a pilot study of spark-ignited engines operated by the Sanitation District of Orange County, CA. In addition to the lack of efficacy of the exhaust gas after-treatment equipment over any duration of time, the tremendous costs related to the installation, operation, and maintenance of this equipment has, in many cases, resulted in the lack of use of the cogeneration systems and/or the flaring of the biogas or else suing for lowered emissions limits.

Companies, primarily growing out of vendors that already offer compressed air cleanup systems, have emerged with impressive claims for gas contaminant removal efficiencies. To date, industry experience with using available gas cleanup equipment as an enabling technology to fit or retrofit digester gas fueled engines with SCR has resulted in dissatisfied operators and less than expected performance results. These negative experiences are well publicized in the industry. During the summer and fall of 2012, there have been reported failures of the gas cleanup system and of the immediate consequential failure of the SCR (pilot system). However, SCR with biogas gas cleanup systems deployed at the Orange County Sanitation District WWTP (SCAQMD) and Ox Mountain landfill (BAAQMD) were successfully operated on IC engines for power generation.

The industry, as well as the SCAQMD, has realized the need to obtain more information about biogas composition and cleanup technology. Currently, there appears to be no proven NOx or CO reduction system technology capable of operating on digester gas containing any measureable level of siloxanes.

SCOPE OF WORK

The scope of work listed below encompasses gathering detailed information on biogas composition, cleanup system technologies, and cleanup system costs. Sources of this information were from:

- Existing national studies
- Other published research/literature
- New site surveys of biogas facilities
- GTI's extensive database obtained from its own laboratory analyses of actual biogases
- Cut sheets and internet sites for siloxane removal system vendors, vendor surveys, and interviews.

The information gathered through this research was assembled and used to develop a cost estimator toolkit for estimating the costs of a cleanup system based on the composition of the biogas, the level of components being removed in the gas and the desired level of the components at the output of the gas stream of the system.

The work scope was conducted in the following six tasks and the original proposed activities are described in detail below:

- Task 1-Gas Composition Analyses
- Task 2-Survey of Biogas Cleanup Systems Technologies
- Task 3-Biogas Cleanup System Costs

- Task 4-Development of a Biogas Cleanup System Cost Estimator Toolkit
- Task 5-Biogas Cleanup System Cost Estimator Toolkit Training and User Instruction Manuals
- Task 6-Technical Support and Management

Task 1-Gas Composition Analyses

1.1 CONTRACTOR shall collect data on the constituents present in biogas at various facilities across the United States. This data collection shall be a representative sample from existing national studies, published research, new site surveys and CONTRACTOR's database of laboratory analyses of actual biogases. The biogas constituents shall include ranges and amounts, but not be limited to, the following:

a) CH_4, CO, CO_2 and H_2O vapor
b) Higher hydrocarbons (e.g., benzene, terpenes)
c) Sulfur gases (inorganic and organic sulfur compounds, e.g., H_2S, mercaptans)
d) Silicon compounds (e.g., siloxanes, silicon dioxide)
e) Halogenated compounds
f) Ammonia
g) Metals (e.g., Hg, As, Bi, Sb)
h) Particulates and dust

1.2 CONTRACTOR shall determine the calorific value data of the various gases.

1.3 CONTRACTOR shall ensure the data collection is importable into Microsoft Excel in logical engineering units with intuitive tag names and references and shall be provided to SCAQMD for written approval prior to finalizing data collection.

Task 2-Survey of Biogas Cleanup Systems Technologies

2.1 CONTRACTOR shall provide survey documents in Tasks 2.2 -2.6 to SCAQMD for review and written approval prior to commencement of nationwide survey.

2.2 CONTRACTOR shall compile and ensure survey data collection is importable into Microsoft Excel in logical engineering units with intuitive tag names and references.

2.3 CONTRACTOR shall conduct personal interviews both in person and/or by telephone of existing manufacturers and developers of biogas cleanup equipment as well as their customers and owners and operators of biogas cleanup systems at facilities across the United States.

2.4 CONTRACTOR shall use existing national studies, published research, new site surveys and CONTRACTOR's database of laboratory analyses of actual biogases as sources of biogas cleanup systems.

2.5 CONTRACTOR shall collect and compile survey information on biogas cleanup systems which shall include, but not be limited to:

a) Types of technology and commercial availability
b) Functional description and operation
c) Cost, including capital, installation, operational and maintenance
d) Specification of constituent removal system
e) Size and footprint of the physical system
f) Capacity limitations and scalability of the technology
g) System efficiency for a given biogas composition and flow rate
h) Maintenance required
i) Cleanup system waste disposal management strategy used
j) Methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas
k) Anticipated benefits in reductions of emissions/wastes
l) Explanation of each constituent removal system detailing its functional process

m) Effectiveness of each technology analyzed in terms of its ability to remove targeted constituents listed in Task 1 and how each parameter listed above impacts system cost.

2.6 For the use of Selective Catalytic Reduction/Non Selective Catalytic Reduction for biogas engines, the focus of the cleanup systems shall be on removal of trace contaminants, particularly siloxanes and halogenated compounds, from the biogas supply.

2.7 CONTRACTOR shall provide preliminary survey results to SCAQMD for review.

Task 3 -Biogas Cleanup System Costs

3.1 CONTRACTOR shall detail the costs of the various biogas cleanup systems identified in Task 2 including:

a) Hardware
b) Installation
c) Operation
d) Maintenance and repair
e) Waste management

3.2 CONTRACTOR shall ensure the biogas cleanup system cost data collection is importable into Microsoft Excel in logical engineering units with intuitive tag names and references and shall be provided to SCAQMD for written approval prior to finalizing biogas cleanup system cost data collection.

Task 4 -Development of Biogas Cleanup System Cost Estimator Toolkit

4.1 CONTRACTOR shall utilize information gathered in Tasks 1, 2, and 3 to develop a biogas cleanup system cost estimator toolkit and shall be provided to SCAQMD for written approval in the initial development stage.

4.2 CONTRACTOR shall develop a biogas cleanup system cost estimator toolkit in hard copy format and as a Microsoft Excel computer based interactive document that will provide a preliminary determination of the following:

1) Type of cleanup device based on the constituents for removal in the biogas stream and an estimation of the capacity, size and cost of the system media for a prescribed contaminate;
2) Biogas cleanup capability of the system in terms of system downstream contaminant concentrations;
3) Total cost including the cleanup equipment installation, operation, and maintenance costs based on the database of existing systems and manufacturer's data created in Tasks 1, 2 and 3.

4.3 CONTRACTOR shall develop a biogas cleanup system cost estimator toolkit that includes:

a) In the case for biogas cleanup systems for engines, the increased servicing intervals, reduction of oil consumption, and increase in engine efficiency shall be taken into account to offset the annual operating costs.
b) A formal decision-making process for determining the use of biogas cleanup technologies to manage the quality of the biogas for the engines and the engine emissions.
c) A template for recording the breakdown of capital and investment costs.
d) A determination of additional conditioning of biogas stream needed in order to apply the selected technologies that include, but are not limited to, compression, pressure regulation and metering.

4.4 CONTRACTOR shall provide preliminary biogas cleanup system cost estimator toolkit to SCAQMD for review and written approval prior to finalizing. The biogas cleanup system cost estimator toolkit, in every draft and final version and format, shall be the sole property of SCAQMD.

Task 5-Biogas Cleanup System Cost Estimator Toolkit Training and User Instruction Manuals

5.1 CONTRACTOR shall develop a User's Instruction Manual for the Biogas Cleanup System Cost Estimator Toolkit.

5.2 CONTRACTOR shall ensure the User's Manuals includes documentation citing the sources for factors used in the toolkit as well as instructions and step-by-step procedures to assist others with the use of the toolkit.

5.3 CONTRACTOR shall provide five (5) hard copies and an electronic pdf file of the User's Manual for review and written approval by SCAQMD.

5.4 CONTRACTOR shall conduct training classes on the use of the Biogas Cleanup System Cost Estimator Toolkit for SCAQMD staff and shall submit the training plan to SCAQMD for review and written approval prior to commencement of the training classes.

5.5 CONTRACTOR shall conduct the training classes and shall be arranged to be suitable with SCAQMD schedules consisting of two training sessions of half day duration each at SCAQMD headquarters in Diamond Bar, California.

Task 6 -Technical Support and Management

6.1 CONTRACTOR shall provide Biogas Cleanup System Cost Estimator Toolkit technical support to SCAQMD to ensure the continuous use and operation of the toolkit as it was designed and intended under this contract until the term of this contract.

6.2 CONTRACTOR shall organize and conduct progress meetings and ad hoc meetings, as required, if problems arise that lead to a change in the original scope of work or project schedule.

TASK RESULTS

The results of the work conducted in the six tasks are summarized below.

Task 1. Gas Composition Analyses

Raw biogas composition data were collected from various sources. Within the scope of this task a majority of the data was obtained from GTI's in-house laboratory analyses of actual raw biogas samples conducted during the period 2005-2013 from three types of sites: landfills, WWTPs and dairy farms located across the US. The calorific value of the GTI biogas samples were estimated using the compositional analyses data per ASTM D3588-98(03) standard practice on a dry basis at base conditions of 0°F and 14.73 psia. An exhaustive literature search was also conducted but yielded only limited compositional data. The biogas constituents in the data included all of those listed in the above "Task 1.1 Objectives", except for H_2O vapor, terpenes, silicon dioxide and particulates and dust; an explanation of these exceptions is given below.

Because biogas is normally collected from headspace above a liquid surface or moist substrate, it is usually saturated with water vapor. The fractional volume of water vapor depends on temperature and pressure at the gas collection site and can be easily calculated to yield the standardized volume of dry gas. Water can have a significant effect on biogas combustion characteristics such as flame temperature, flammability limits, heating value, and air-fuel ratios of biogas. For example, an analysis of the Ft. Lewis, WA, WWTP digester gas, indicated   4% by volume water vapor[4].

Terpenes are hydrocarbons comprised of repeating isoprene (CH2=C(CH3)CH=CH2) units and classified according to the number of isoprene units they contain (Table 3). The concentrations of these compounds in the biogases analyzed by GTI were not speciated, but quantified as decanes (C10), pentadecanes (C15) and eicosanes+ (C20+), in the Extended Hydrocarbons analysis group as per Table 4.

Table 3. Terpenes Classification

# Isoprene Units	# C Atoms	Group
2	10	Decanes
3	15	Pentadecanes
4	20	
5	25	Eicosanes+
6	30	
8	40	

The raw gas composition data were entered into a Microsoft Excel spreadsheet file (entitled "Biogas Composition Data") and stored on a disc and submitted to SCAQMD along with the 1st quarterly report. Three spreadsheets, entitled "Landfill", "WWTP" and "Dairy" were populated with the following data for each gas sample: site location, site name or ID#, data source, constituents and calculated calorific/heating value. For the GTI data, due to confidentiality agreements executed with the site owners/operators for whom biogas samples were analyzed, each site was identified only by an ID# and no specific (only a general) site location was given in the spreadsheets. A preliminary version of this spreadsheet file was submitted to the SCAQMD project manager on 9/10/13 for approval of its format (this approval was subsequently received by GTI in an email on 9/11/13). The biogas constituents were classified in the spreadsheet into most or all of the following nine groups (Table 4):

Table 4. GTI Analysis Group Classifications for Biogas Constituents

Analyses Group No.	**Constituents**
1	Major Component (e.g., CH_4, CO_2, N_2, O_2)
2	Extended Hydrocarbons (e.g., benzene, hexanes, octanes)
3	Sulfur (e.g., H_2S, COS, dimethyl sulfide)
4	Halocarbons & VOCs (e.g., CFCs, methylene chloride, vinyl chloride)
5	Target Aromatics (e.g., 1,3,5-trimethylbenzene, naphthalene)
6	Total Organic Silicon/Siloxanes (e.g., L2, D4)
7	Aldehydes & Ketones (e.g., acetone, acetaldehyde, butanal)
8	VOCs/SVOCs (e.g., styrene, o-xylene, dichlorobenzene)
9	Volatile Metals (e.g., mercury, arsenic, zinc)

[4] "Hydrogen Fueled Material Handling Equipment (MHE) and Hydrogen Vehicle Fueling Station Pilot Project at the U.S. Army Forces Command, Fort Lewis, WA," CTE Contract N00164-09-C-GS18, Gas Technology Institute Project 20874 (2010).

The above nine groupings represent different analytical tests used by GTI to determine the respective concentrations of the constituents. A detailed description of these tests is presented in previous GTI reports[5,6]. Each constituent's CAS number and LDL are provided when available.

Siloxanes composition data for biogases sampled from two landfills and eight WWTPs were condensed from GTI and Vronay Engineering (GTI's sub-contractor) databases in a separate worksheet file entitled "Siloxanes" and stored on the same disc as referred to above. The temporal variability of the silicon compound concentration data is represented graphically in Figures 1-3. It should be noted that the two spreadsheet files ("Biogas Composition Data" and "Siloxanes") are intended to be dynamic documents and can be updated over the project duration as additional data are obtained (and within project time and budget constraints).

Raw biogas can also contain particulates and dust, and any products of chemical interactions between the concomitant species in the raw biogas. Silicon dioxide (SiO_2) or silica, is typically formed when siloxanes in the biogas are incinerated but could also be present in the raw biogas as a component of the particulate matter. These parameters were not tracked for in the GTI projects from which the reported data were extracted and no data were found in the conducted literature search.

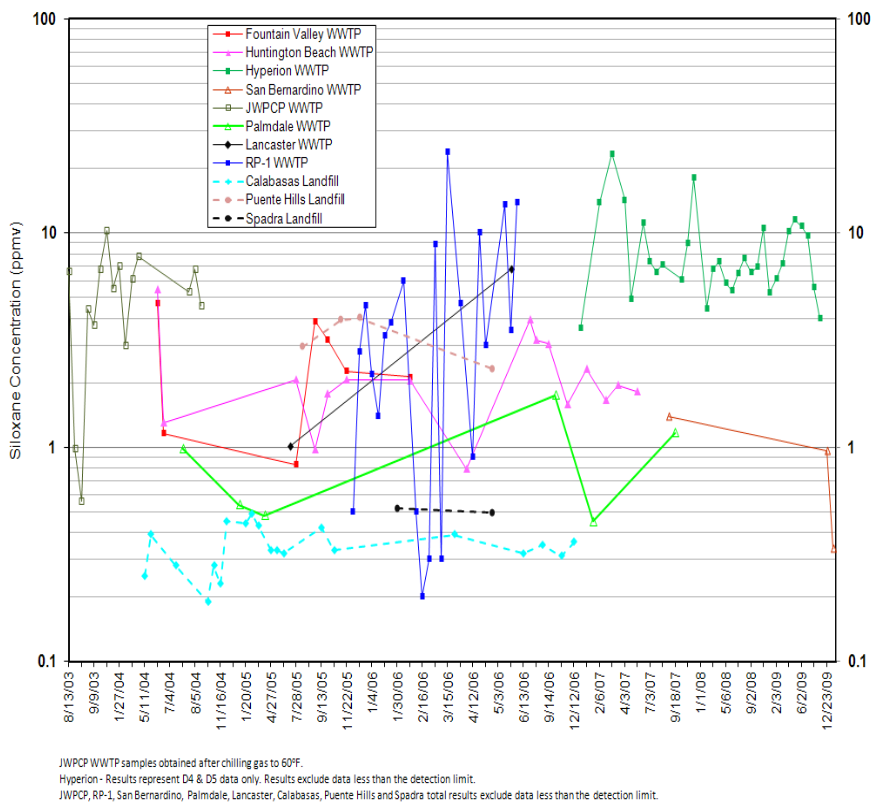

Figure 1. Siloxanes in several CA landfill and WWTP digester gases from 2003-2009[7]

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[5] Guidance Document for the Introduction of Landfill-Derived Renewable Gas into Natural Gas Pipelines–Final Report, # GTI-12/2007, GTI Project 20792, 2 May 2012.

[6] Saber, D.L. and Cruz, K., "Laboratory Testing and Analysis Reporting–Task 2," GTI Project Number 20614, Oct. 2007-June 2008, issued 30 Sept. 2009.

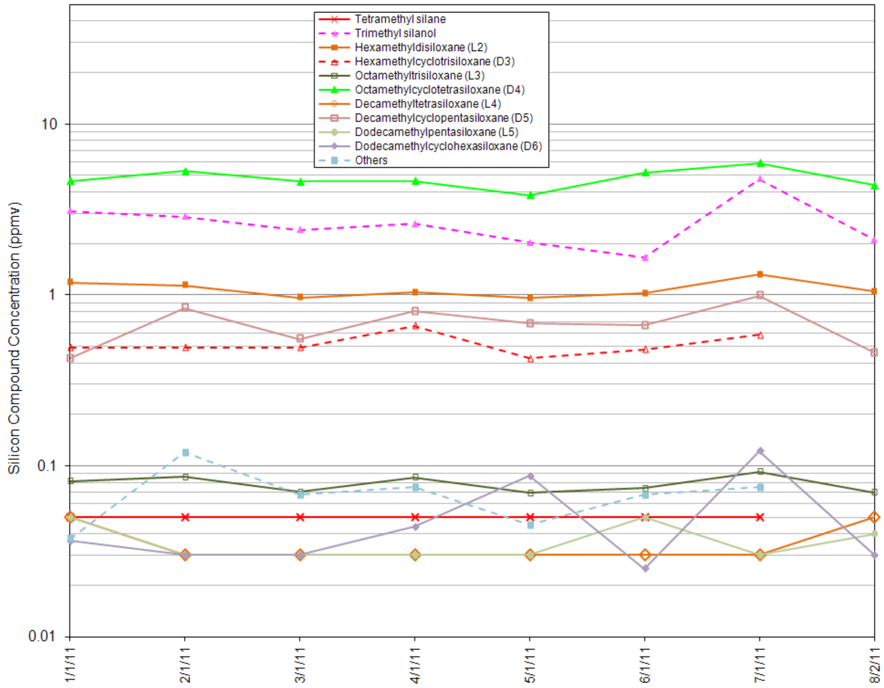

Figure 2. Silicon compounds in a Southeast US landfill gas during 2011

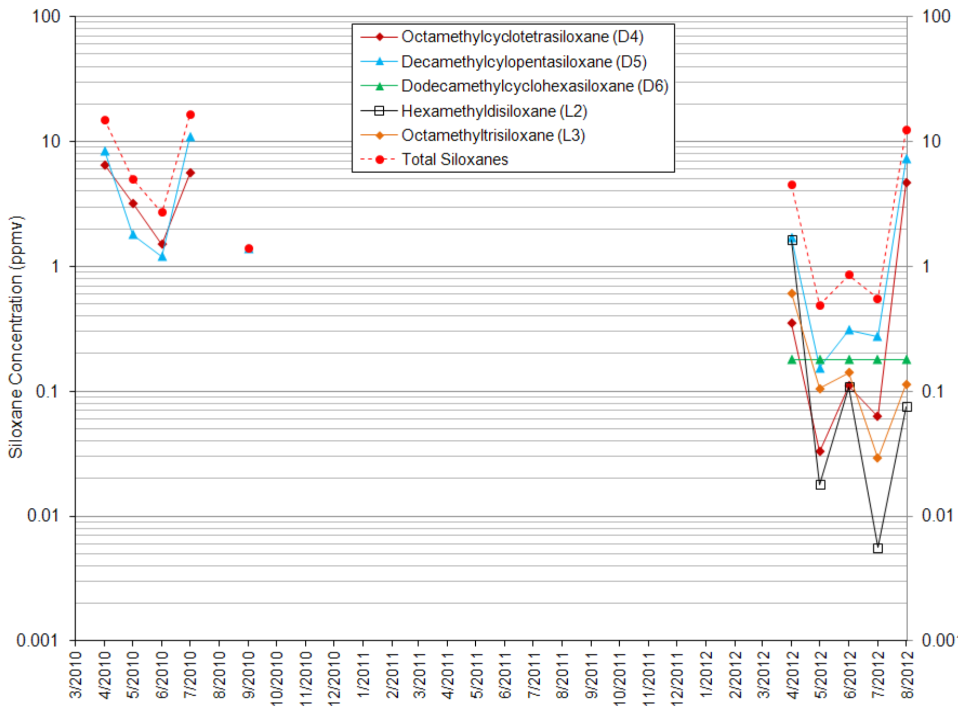

Figure 3. Siloxanes in the San Bernardino, CA, WWTP digester gas during 2010-2012

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[7]Rothbart, D., Rule 1110.2, Rule 1110.2, Estimated Estimated Retrofit Costs to Achieve Retrofit Costs to Achieve Proposed Bi Proposed Biogas Limits, Los Angeles County Sanitation Districts Air Quality Engineering Section, Oct. 26, 2010, http://scap1.org/Air%20Reference%20Library/10-26- 10%20Rule%201110_2%20Retrofit%20Cost %20Presentations. pdf (accessed 7 Jan. 2015).

In addition to containing primarily methane and carbon dioxide, biogas also has varying amounts of condensates (water or higher hydrocarbons), hydrogen sulfide, organic sulfur compounds, volatile organic compounds including organic halides, volatile metal and silicon compounds (siloxanes) and various amounts of nitrogen and oxygen as contaminants. Removal of these contaminants via gas pretreatment is required to either meet the power generator equipment manufacturer's requirements for fuel gas quality and/or to meet air emissions permit requirements.

Task 2. Survey of Biogas Cleanup System Technologies

Literature/Internet Search

A literature/internet search was conducted to identify biogas cleanup systems (focusing on siloxane removal technologies) based on existing national studies, published research, new site surveys, biogas cleanup system design reports, budgetary proposals, and feasibility studies. Based on the literature search performed (over 100 references were found and compiled in an Excel spreadsheet in the 2nd quarterly project report and listed here in Appendix A) the following manufacturers and developers of biogas cleanup equipment for various applications (fuel cells, engines, turbines, etc.) were identified and contacted for further information.

1. Willexa Energy, Charlotte, NC.
2. DCL America Inc., The Woodlands, TX (head office in Concord, Ontario, Canada).
3. Parker NLI, Haverhill, MA.
4. Venture Engineering and Construction, Pittsburgh, PA.
5. C.C. Jensen, Inc., Atlanta, GA, subsidiary of C.C.Jensen A/S, Denmark.
6. Quadrogen Power Systems, Inc., Vancouver, BC.
7. Unison Solutions, Dubuque, IA.
8. 2G Cenergy Power Systems Technologies, Inc., Orange Park, FL.
9. Environmental Systems & Composites, Inc., Redmond, WA.
10. Pioneer Air Systems TCR, Wartburg, TN.
11. Theia Air, LLC, West Chester, PA.
12. AFT/Robinson Group, Bothell, WA.
13. Guild Associates, Dublin, OH.
14. Nrgtek, Orange, CA.
15. Xebec Absorption, Inc., Blainville, Quebec, Canada.
16. Acrion Technologies, Cleveland, OH.
17. Carbtrol Corp., Bridgeport, CT.
18. Western Biogas, Tustin, CA.
19. Broadrock Renewables LLC, Tarrytown, NY.
20. MiscoWater, Pleasanton, CA.

Detailed vendor cut sheets for the above companies obtained from their internet sites were also provided in the 2nd quarterly report to this project along with information including functional description/process operation and benefits of the cleanup systems for additional emissions/wastes reduction. The information gathered from this literature search, particularly siloxane removal system cost data, was also identified and used for the Task 3 (Biogas Cleanup System Costs) effort. The first seventeen companies in the above list were identified as potential siloxane system removal system manufacturers or equipment suppliers. The remaining companies were regarded as biogas cleanup vendors and/or engineering firms that have installed these systems.

Vendor Data from GTI Database

In a previous GTI project entitled "Guidance Document for the Introduction of Landfill-Derived Renewable Gas into Natural Gas Pipelines," three specific cleanup technologies were investigated: Physical Solvent, Pressure Swing Adsorption (PSA), and Gas Separation Membrane. While the gas cleanup technologies were divided into the three categories based on their CO_2 removal technology, these systems utilized multiple unit operations designed to remove other biogas components as well. These add-on units are located either upstream or downstream from the main cleanup system. The complete set of analytical data for these cleaned biogases was provided in an Excel file format separately attached to the 2nd quarterly report. Twenty-seven samples of high-BTU landfill-derived renewable gas from 7 different landfill sites were collected and analyzed. The specific gas cleanup system that was used is documented in the above report for each site sampled.

In the above referenced project for siloxanes, below detectable levels were observed in 22 of the above 27 samples, and ranged from 0.1 to 0.4 mg Si/m^3 in 5 of the 27 samples. The only species found was D4 (octamethylcyclotetrasiloxane). Other relevant study findings are:

- No vinyl chloride was detected. Dichlorodifluoromethane (CFC-12 or Freon-12) was found in 6 of 27 samples and chloroethane was found in 3 of 27 samples, both in the 0.1- to 2.3-pmv range.
- Volatile organic compounds (VOC), including hydrocarbons heavier than methane, were at single digit ppmv levels or below the detection limit (BDL). A subset of VOCs is the family of aromatic hydrocarbons that include benzene, toluene, ethyl benzene, and xylene (BTEX). No benzene or ethyl benzene was found in any samples. Toluene and xylene were found in three and two samples, respectively, at levels no more than 1.4 ppmv.

Siloxane Removal Systems Vendor Survey

In order to facilitate the survey process, a vendor questionnaire was developed (Figures 4 and 5) and issued. The companies identified as siloxane system removal system manufacturers or equipment suppliers were provided with questionnaires and nine (Willexa Energy, DCL America, Pioneer Air Systems, ESC, Unison, Acrion, Quadrogen, Nrgtek and Guild) were completed and returned. Where possible, vendors were contacted and follow-up made by telephone and/or email. The information obtained from the questionnaires was compiled and presented in Appendix B. Table 5 summarizes selected vendor product information and their experience based on number of years in business and number and types of biogas treatment installations.

Site Visits

All selected manufacturers of siloxane removal systems included in the survey were contacted in an attempt to set up a site visit of installed hardware. Only two vendors and three landfill gas facility operators replied to this request resulting in site visits to the East Bay Municipal Utility District in Oakland, CA, Ameresco Ox Mountain (Half Moon Bay, CA) and Chiquita Canyon (Castaic, CA) power generation facilities. Summaries of these site visits are presented in Appendix C.

Figure 4. Vendor Survey Questionnaire (part 1 of 2)

SCAQMD Contract #13432-Survey of Biogas Cleanup System Technologies and Costs

Company Information	
Company Name	
Contact Name	
Contact Title	
Contact E-Mail	
Contact Phone/fax	
Siloxane Treatment System General Information	
Product Name and Type	
When was the product introduced?	
Number of Installations - worldwide	
Number of Installations - US	
Number of Installations in AQMD districts (Southern California)	
Number of installations on SCR or NSCR equipped reciprocating engines	
Are the sites with SRC/NSCR available for visitation?	
For California applications, what are methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas?	
Siloxane Treatment System Technical Information	
Type (activated carbon, regenerative, etc.)	
System siloxanes removal efficiency (as %, mg/ml, ppm)	
What other trace biogas components are simultaneously removed along with siloxanes and to what levels?	
Electrical power or supplemental fuel requirement for regenerative systems.	
Does the system require a flare(s)? Flare cost and flare fuel costs?	
Regeneration off-gas composition flow to the flare and hours per day?	
Media life (for passive or regenerative systems).	
What is the total system pressure drop?	
Does the system have siloxanes break-through detection? If so what method?	
Does your firm offer media change out, disposal and installation of fresh media?	

Figure 5.Vendor Survey Questionnaire (part 2 of 2)

What cleanup system waste disposal management strategy will be used?			
Siloxane Treatment System Specifications			
What information is needed for sizing and quoting a system?			
System Design Flow	200 scfm	500 scfm	1000 scfm
Annualized- or SCFM-basis- annualized O&M costs for the following systems:			
Equipment costs for these systems:			
Approx. size and footprint of these physical systems:			
Capacity limitations and scalability of the technology			
How is system removal efficiency affected for a given biogas composition as a function of flow rate?			
Any additional information			
Engine Exhaust Requirements			
Are any of the systems installed on reciprocating engines that are subject to emission requirements (with or without SCR/NSCR)?			
What are the allowable emission limits of the exhaust (e.g., for NOx, CO, PM, etc)?			

Available Siloxane Removal Technologies

From a review of the survey data (Appendix B) it was determined that systems offered by three vendors–Quadrogen, Acrion and ESC–of the nine could potentially remove all biogas contaminants (Table 6), while the systems from the remaining six appear to be suited for removing only siloxanes to the required levels for SCR post-combustion catalyst. The contaminants considered in this project for the cleanup systems are siloxanes, H_2S and reduced sulfur compounds and non-methane organics compounds. While it is known the six systems will reduce most or all of the contaminant concentrations, there are insufficient data to guarantee the removal efficiency of contaminants other than siloxanes. It is important to note that the same three vendors, Quadrogen, Acrion and ESC, offer systems thatmay also meet the target SCR system siloxane requirements. Also, it is assumed for the purposes of the toolkit that: a) the biogas feed to the six siloxane-only removal systems has been preconditioned at the site to a level where it is acceptable for use in a reciprocating engine and b) for the three all-contaminant removal systems, moisture, sulfurs, halides, and other contaminant compounds removal are included in the total equipment cost in addition to siloxane removal and polishing.

Table 5. Summary of the Vendor Experience

Vendor	Product Name	Product Type	Date Product Introduced	Number of Installations worldwide	Number of Installations in US	Number of Installations in AQMD districts (Southern CA)	Number of installations on SCR or NSCR equipped reciprocating engines	Sites with SRC/NSCR available for visitation?
Willexa Energy	PpTek BGAK Siloxane Reduction System	Regenerative polymer media cassettes (two systems in series)	2005	>80[a]	0	0	7[a] (not in North America)	With enough notice. Note that they are not in North America.
DCL America	SRT System	Regenerative polymer media (similar to the ppTek system)	2013		2	0	0 (3 "case studies" in progress in eastern US: 2 on LFG, 1 on AD)	
Quadrogen Power Systems, Inc.	Integrated Biogas Clean-up System (IBCS) - Regenerative	Refrigeration + bulk & polishing adsorbents	2011	3	2	1	0 (but a 600-scfm unit will be delivered by January 2014)	No
Environmental Systems & Composites, Inc. (ESC)	ESC CompHeet system	Regenerative activated carbon	2005	3	2 (on fuel cells)	1	Unknown	Unknown
Unison Solutions Inc.	Activated Carbon	Activated carbon	1999	70	69	3	0	
Pioneer Air Systems	TCR System	Refrigeration + polishing activated carbon	1993	25	20			
Acrion Technologies	CO_2 Wash System	CO_2 wash column at -65°F	First commercial 2008	2	1	0	0	No
Nrgtek Inc.	Siloxane Removal System	Liquid scrubbing (membranes)	2012	1	1	1	One proposed	Yes, after 2015
Guild Associates, Inc.	Molecular Gate & Siloxasorb	PSA	2002	61[e]	58[e]	None	None	
2G Cenergy Power Systems Technologies, Inc.[b]	"H_2S & Siloxane Filter Technologies"	"Activated carbon filter media specifically developed for H_2S & siloxane removal"[d]		>4000 "CHP systems"	~100[e]	3[c]	3[c]	
Parker NLI[b]	GES Siloxane Removal System	Chiller & regenerative blended media	2007		43[c]	0	4 on landfill gas recuperated gas turbines located in eastern US (in process of quoting some siloxane removal systems for CA)	
Venture Engineering[b]	"Biogas Conditioning System"	Regenerative media comprised of activated alumina, mole sieve & silica gel.		5	5[c]	3[c]	5[c]	Possibly
Theia Air[b]	TA-BG3, TA-SV	Standard non-regenerable & regenerable carbon media.			6	0	0	
AFT[b]	SWOP	"SAG Media"	1997		167[c]	c	c	

Blank indicates no response.

[a]Sold by Pptek, Ltd. (UK), not Willexa.

[b]Did not return questionnaire; data shown are from personal communication and/or internet site.

[c]Number of these installations and/or their operational status could not be verified.

[d]Probably consumable (non-regenerative) media.

[e]Number of these systems treating siloxane-containing biogases not specified by vendor.

Table 6. Typical Biogas-Natural Gas Characteristics[8]

Component	Natural Gas[1]	Wastewater Sludge[2]	Landfill Gas[3]	Animal Waste[4]	Industrial
Methane (% volume)	93% (minimum)	55 to 70%	45 to 60%	50 to 70%	50 – 75%
Carbon Dioxide (% volume)	1% - 1.5%	30 to 45%	35 to 40%	30 to 50%	Application-specific
Nitrogen[5] (% volume)	1% - 1.5%	no data available	0 to 3%	0 to 3%	Application-specific
H_2S and other Sulfur Compounds (ppmv)	< 20	150 to 3,000	10 to 200	Up to 5,000	Up to 30,000
Siloxanes (ppmv)	None	2 to 15	0.1 to 3.5	None expected	Application-specific
Halogenated organics (ppmv)		6.5 (varies)	5 to 70 [6]	no data available	Application-specific
Non-methane organics (% dry weight)	15% maximum	no data available	0 to 0.25%	no data available	Application-specific
Volatile Organics (% dry weight)		no data available	0 to 0.1%	no data available	Application-specific
Other organics (% volume)	2% max.	Gasoline traces	no data available	no data available	no data available
Hydrogen (% volume)		no data available	Trace to >1%		Application-specific
Oxygen[5] (% volume)	0.2% max.	None	0 to 2%	no data available	Application-specific
Carbon Monoxide (% volume)		None	0 to 0.2%	no data available	Application-specific
Humidity		100% (saturated at digester exit temperature)	100% (saturated at landfill temperature)	100% (saturated at digester exit temperature)	Application-specific
Calorific Value (LHV)	900 to 1100	500 to 640 Btu/SCF	410 to 550 Btu/SCF	450 to 650 Btu/SCF	Up to 800 Btu/SCF

1 Data Sources: Waukesha Standard Commercial Quality Natural Gas Specification and Gas Engineer's Handbook, Industrial Press, 1964.
2 Data Sources: "Digester Gas Treatment", CH2M HILL Design Guidance, December 2002; Terminal Island Wastewater Treatment Plant, City of Los Angeles, CH2M HILL, April 2002; "Unit Operations and Processes in Environmental Engineering," Reynolds, T. D., Brooks/Cole Engineering Division, 1982; "Wastewater Engineering, " Metcalf and Eddy, McGraw Hill Publishers, 1979; "Design of Municipal Wastewater Treatment Plants," Fourth Addition, Volume 3, WEF Manual of Practice 8.
3 Data Sources: "*A Review of Literature Regarding Non-Methane and Volatile Organic Compounds In Municipal Solid Waste Landfill Gas*," Soltani-Ahmadi, H, University of Delaware, 2000; "A Road Traveled: Waste Management's Landfill Gas Recovery Experience after Ten Years," Markham, M.A., Rust Environment and Infrastructure, 1997
4 Data Sources: Source: Strategies for Energy Efficient Plants and Intelligent Buildings, Chapter 19, "*Small-Scale Cogeneration for a Southeastern Dairy*," Energy Integrated Dairy Farm System Project, Georgia Tech University, Ross, C.C. and Walsh, J.L., 1987; Meredith, M. test data at PGE Salem Dairy Gas to Energy Project, 2002.
5 Most of the nitrogen and oxygen in biogas results from air in-leakage.
6 Data Source: Presentation, "FUEL CELL OPERATION ON LANDFILL GAS", R. J. Spiegel, EPA Fuel Cell Workshop, 2001, available at http://www.epa.gov/ORD/NRMRL/std/fuelcell/fuelslides/8

[8] Assessment of Fuel Gas Cleanup Systems for Waste Gas Fueled Power Generation, EPRI, Palo Alto, CA: 2006. 1012763.

Available siloxane removal systems can be generally divided into three primary system types: consumable media, regenerative media, chiller/absorption and various versions of these technologies in combination. Each of these systems has advantages and disadvantages as discussed below. Typical current installations consist of a series of gas treatment components designed to remove various contaminants in the gas stream including hydrogen sulfide and moisture as well as siloxanes.

Consumable Media

Consumable media systems typically consist of activated carbon stored in a series of canisters and are the least complex of the all surveyed systems. A compressor delivers the biogas at a pressure high enough to insure rated flow through the system as the media fouls. These systems consist of an arrangement of canisters parallel and often in series. Parallel canisters allow the unit to remain in service while the media is changed out in the offline unit. Series canisters prevent siloxane breakthrough from a single canister to reach the engine when the media is consumed. Breakthrough is the time when the adsorption bed is saturated and siloxanes start to pass through the bed without being adsorbed. Gas sampling is conducted between the two canisters in series and the media of both units is normally changed when it is determined that the media in the first canister is consumed. The cost of disposing of this media can be significant (see, e.g., Appendix C Site Visits).

This system will likely require the least scheduled maintenance due to the lack of complex machinery. The only powered equipment is the blower and associated motor, which require very little maintenance during normal operation. The valve actuators/operators can all be manual as the frequency of operation should be low as well. Due to the low-tech nature of the system it also has the lowest initial installation costs. Although there is no need for a flare on the consumable media systems, most sites will have a flare installed to reduce the chance of accidental release of biogas into the atmosphere.

Vendors utilizing this type of media include Unison, ESC (e.g., at the East Bay MUD site, Appendix C) and possibly 2G Cenergy.

Regenerative Media

The regenerative media system design requires at least two media canisters in parallel. The online canister processes the biogas and the offline canister is in regeneration mode. Typical online and purge cycle times varies between 6 and 24 hours. These systems have equipment /installation costs greater than the consumable media systems due to the increased complexity and amount of equipment.

The regeneration process normally consists of back-flowing the unit with hot purge air. The products of the purge are then discarded through a flare to eliminate the emission of greenhouse gases directly to the atmosphere. The power required to operate the flare, blower and heaters to regenerate the system are minimal when compared to the consumable media change out costs. The media in the regenerative systems are expected to have a life cycle of 3-5+ years at which time there will be a cost associated with the media replacement and disposal. The maintenance costs of these units will be greater than those of the consumable media units. The frequency of the changeover between online and purge requires increased automation to control the valve operations, purge air blower, air heater, and flare. These costs will likely increase with the age of the equipment.

Polymeric resins are being applied by some vendors in their regenerable siloxane removal systems. The primary advantages of the resins include:

- Hydrophobic properties reducing the need for humidity control, a higher adsorbent capacity over carbon, and the ability to be regenerated at much lower temperatures allowing the potential recovery of the removed volatile organic compounds (VOCs) for recycling.
- Greater physical strength resulting in reduced attrition of the media, i.e., longer service life.
- Allow contaminants to be quickly removed from the adsorbent and the resins can be regenerated more times without loss of adsorptive capacity.

Consumable media, such as activated carbon, are often used upstream of regenerative media, particulaly polymeric media, for polishing to reduce contaminant concentrations to low levels required for engine post-combustion catalysts. Regenerative systems are exemplified by the following vendors: Willexa, DCL, Parker, Venture, AFT and ESC. Examples of operating experience with these systems, in addition to those presented in Appendix C (Site Visits), are presented below.

- Willexa Energy reported in this project on successful operation of a regenerative siloxane removal system at seven locations (with 3 more under construction) in South America on Caterpillar engines equipped with DCL exhaust catalysts. These systems were installed by PpTek Ltd. (UK) and are essentially the same system offered by Willexa as their sole US representative. Two Willexa PpTek systems are currently under construction: 1) one for an existing LFGTE project in Indiana using multiple CAT reciprocating engines (no catalysts) and 2) a new LFGTE project in BC, Canada, using multiple CAT reciprocating engines (no catalysts).
- Ameresco reports that the Dominick Hunter (Parker) system using aluminum oxide and mole sieve media at their Chiquita Canyon landfill site has been in service now for two years without a media change being necessary. This followed a previous changeout by Parker of the media with a finer mesh media (that ultimately went exothermic and caused a fire in one of the vessels) and reinstallation of the original media.
- Ameresco also reported that Venture Engineering systems (essentially a modified version of the Dominick Hunter system) using aluminum oxide media are operating at their Butte County, CA (2-4 ppmv siloxanes in raw biogas), and Johnson Canyon, CA (7 ppmv siloxanes) sites and removing 99% of the siloxanes. They also report that their biggest challenges were to keep the VOC flares running, as this is the essential in keeping the media regeneration cycle consistent and that extensive human interaction was needed to accomplish this, which may also jeopardize the cycle consistency.

Chiller/Absorption

The chilling/absorption system is the least common of the existing technologies for siloxane removal, although it is often part of the overall gas treatment system. So, while many systems utilize a chiller to remove moisture from the gas stream upstream of other filtration devices, few employ the technology specifically to extract additional biogas contaminants. Pioneer Air Systems was the only manufacturer contacted that employed this process. No sites exclusively using this process were found in the US that are currently successfully operating, however, or being planned.

These systems function by reducing the temperature of the biogas to below its dew point to condense any moisture in the system. The biogas temperature is reduced to -10°F or lower, which also condenses siloxanes from the system. Pioneer Air Systems utilizes an activated carbon media as a polishing filter to remove trace siloxanes and other contaminants such as H_2S. Icing issues with the air coolers are reduced by cycling on-line and off-line coolers allowing ice to melt on the off-line unit. This system should have maintenance costs similar to regenerative units. The initial installation requirements are comparable to the cost of the regenerative systems. There is no need for a system flare, however, as with the consumable media systems a flare will likely be installed regardless to allow the plant to dispose of the biogas during engine downtimes.

Other Technologies

In the Guild process biogas is compressed and introduced to a PSA adsorption system, which removes the water, siloxanes, VOCs, H_2S and carbon dioxide, to yield a product gas that meets pipeline specifications. Guild claims that the sizing and design of their system for cleaning biogas suitable for engines can include siloxanes,VOCs, halides, and other LFG contaminants, while limiting the amount of CO_2 removed. Directionally, the process can remove 30-70% of the CO_2 while removing up to 90% of the H_2S and basically all of the siloxanes and VOCs. Guild would not provide any cost data for this system application.

Nrgtek Inc has developed a unique technology for siloxane removal from biogas based on a continuous liquid scrubber with nanofiltration/pervaporation membranes claimed to be capable of removing siloxanes from 25-40 ppm to less than their detectable limits (~0.02 ppm). The Company is currently working on a 1,000-SCFM prototype after having proven its concept on 10-SCFM and 100-SCFM pilot plant systems. As of this writing, they do not have a product available in the commercial marketplace.

Liquid scrubbing absorbents have been used in Europe and in US for landfill gas cleanup. One of these is Selexol, manufactured by Union Carbide. Because of its higher capital and operating costs, liquid scrubbing is not a realistic option for lower capacity treatment.

Siloxane Monitoring System –Breakthrough Detection

Real time gas detection will also likely be required due to the cost associated with siloxane breakthrough. Even short term siloxane contamination of the system can destroy an SCR system or fuel cell. Breakthrough detection will be a required part of the control scheme for both alarms and functionality to protect the SCR system. Characteristics of siloxane monitoring systems found from various sources are listed below.

1. Willexa Energy offers their "Checkpoint - Continuous Siloxane Monitor" to monitor siloxanes in the biogas stream (50-500 ppbv) in real time using a Fourier Transform Infrared Spectroscopy (FTIR) gas analyzer.
2. Venture Engineering offers their on-line siloxane monitoring system, namely, a "Sentry Portable GC" (PhotoVac Inc), with a claimed detection level of 50 ppbv in raw biogas.

3. MKS Instruments offers their “MKS AIRGARD” FTIR-based gas analyzer claiming detection limits of 0.2 mg/m^3 total siloxanes.
4. ThermoFisher Scientific offers the “Antaris IGS” gas analyzer utilizing FTIR technology to measure total siloxane content down to 7 mg/m^3.
5. Protea, Ltd. (UK) offers their Prot*IR* FTIR analyzer for siloxane measurements down to a 1-ppm detection limit.

This equipment is both expensive and maintenance intensive and frequent calibration checks may be required. A siloxane removal system vendor testing indicated (from personal communication) they had significant reliability issues during field testing of one of the monitors.

Task 3. Biogas Cleanup System Costs

Only nine vendors provided cost data in the questionnaires of sufficient detail to be used for the toolkit. The vendors and costs are shown in Table 7 and categorized under primary siloxane removal system type: regenerative, chiller absorption, and other (in this case membrane) and further divided into capital (equipment) and operating and maintenance (O&M) for three levels of biogas flows: 200, 500 and 1000 SCFM. These flows correspond to approximately 500, 1400 and 2900-kW biogas-fueled engines, respectively, which generally reflect the range of the engines operating within the SCAQMD (biogas) rule 1110.2 study. Capital and O&M costs from Table 7 are shown graphically as a function of biogas flowrate in Figures 6-9. Installation costs were not included in the questionnaire as most equipment suppliers do not offer installation or these costs could vary appreciably depending on who performs the installation and where every site will have different infrastructure in place. Costs for siloxane concentration determination/ monitoring equipment can also be significant, as e.g., Willexa offers their FTIR siloxane monitoring system at a cost of $75,000, while the Ox Mountain and Chiquita Canyon landfills analytical costs performed by a commercial laboratory were estimated by Ameresco to be ~$2,000 per month (Appendix C). The plotted data do not include capital costs for siloxane measurement.

A few attempts were made to verify these capital/O&M costs via “cold calls” to system end users at various sites thought to have these siloxane removal systems installed. In all instances it was not possible to reach the right person having this type of information or only partial cost data were available. During the site visits conducted in this project no capital cost data and only limited O&M data were obtained due either to the proprietary nature or unavailability of the data to the site operators.

A literature search was also conducted focusing on cost data of siloxane removal technologies from sources such as biogas cleanup system design reports, budgetary proposals, feasibility studies, etc. These data are summarized in Table 8 and were previously provided in an Excel spreadsheet format attached to the 3rd quarterly report of this project. Where available from the literature source, detailed descriptions of the gas treatment systems for the cost data in Table 8 were also provided in the same report.

Table 7. Summary of Cost Data Obtained from Siloxane Removal Vendor Survey Questionnaire

	Primary Siloxane Removal System Type																	
	Regenerative										Chiller/Absorption						Other	
Vendor	**Willexa**		**DCL**		**Venture**		**Parker**		**ESC**		**Pioneer**		**Quadrogen**		**Acrion**		**Nrgtek**	
Capital Costs	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM	Total, $	$/SCFM
200 SCFM																		
Equipment	350,000	1,750	250,000	1,250														
Monitoring	75,000	375																
Total	425,000	2,125	250,000	1,250	500,000	2,500	285,000	1,425	1,500,000	7,500	150,000	750	600,000	3,000	800,000	4,000	150,000	750
500 SCFM																		
Equipment	552,000	1,104	350,000	700														
Monitoring	75,000	150																
Total	627,000	1,254	350,000	700	500,000	1,000	342,500	685	1,700,000	3,400	250,000	500	1,500,000	3,000	1,400,000	2,800	250,000	500
1000 SCFM																		
Equipment	600,000	600	500,000	500														
Monitoring	75,000	75																
Total	675,000	675	500,000	500	500,000	500	400,000	400	2,600,000	2,600	350,000	350	2,500,000	2,500	2,000,000	2,000	500,000	500
Annualized O&M Costs																		
200 SCFM																		
Power	12,078	60	808	4	9,000	45					8,000	40						
Media*	8,400	42	10,000	50	20,000	100												
Other			1,000															
Total	20,478	102	11,808	59	29,000	145	35,000	175	25,000	125	8,000	40	65,367	327	67,235	336	15,000	75
500 SCFM																		
Power	12,078	24	2,019	4	9,000	18					20,000	40						
Media*	14,000	28	14,000	28	20,000	40												
Other			1,000															
Total	26,078	52	17,019	34	29,000	58	42,500	85	50,000	100	20,000	40	163,418	327	168,087	336	20,000	40
1000 SCFM																		
Power	12,078	12	4,039	4	9,000	9					40,000	40						
Media*	17,200	17	20,000	20	20,000	20												
Other			1,000															
Total	29,278	29	25,039	25	29,000	29	50,000	50	100,000	100	40,000	40	326,836	327	336,174	336	35,000	35

*Replacement cost

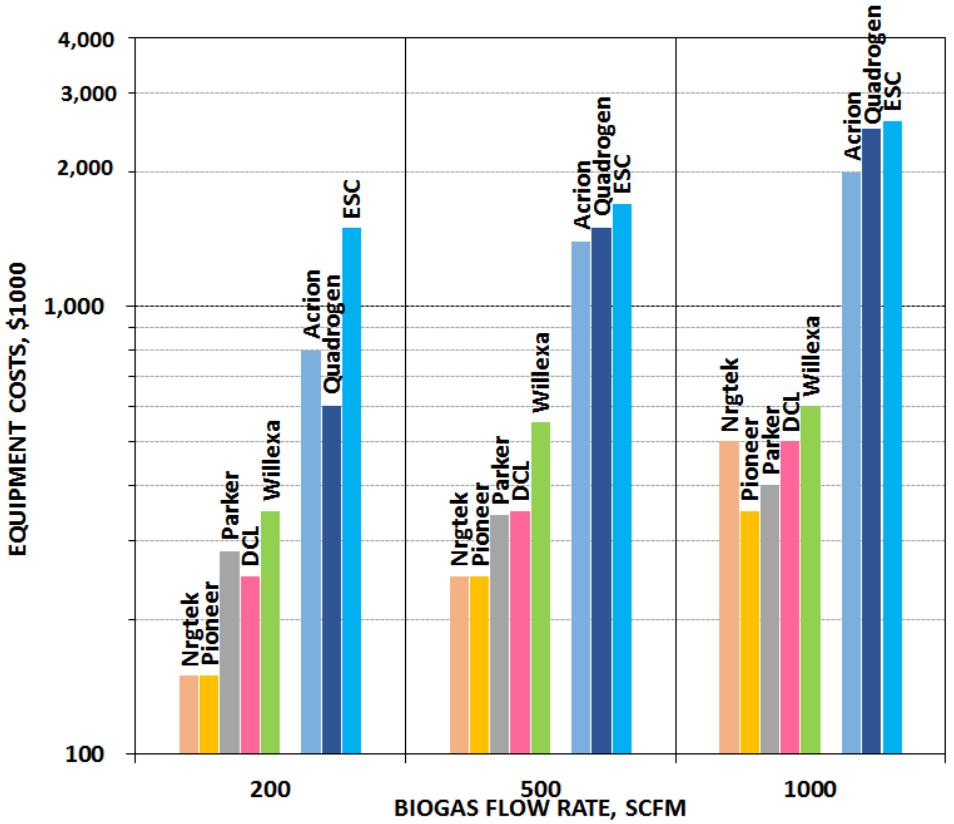

Figure 6. Siloxane Removal Systems Capital Equipment Costs from Vendor Questionnaire Results

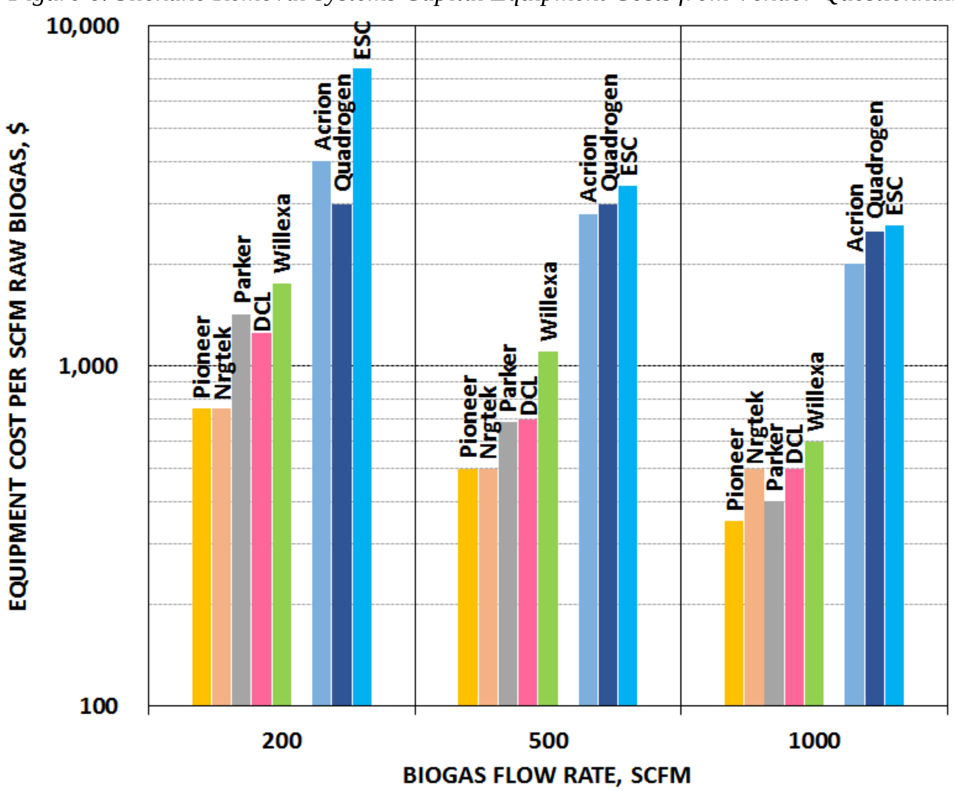

Figure 7. Siloxane Removal Systems Capital Equipment Costs per SCFM Raw Biogas from Vendor Questionnaire Results

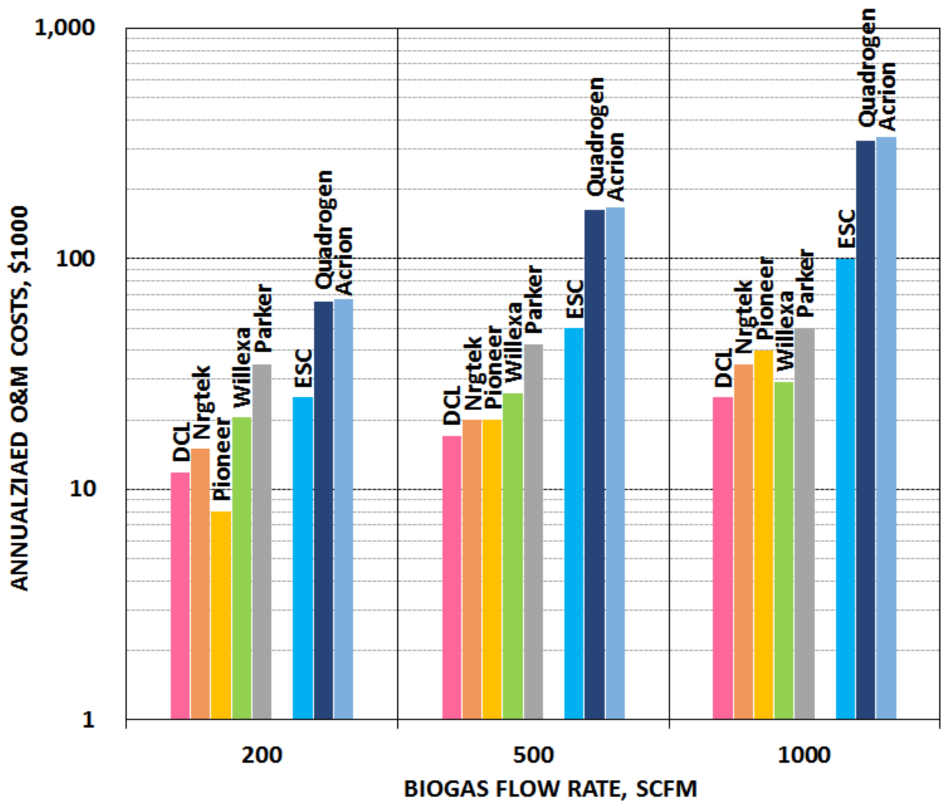

Figure 8. Siloxane Removal Systems Annualized O&M Costs from Vendor Questionnaire Results

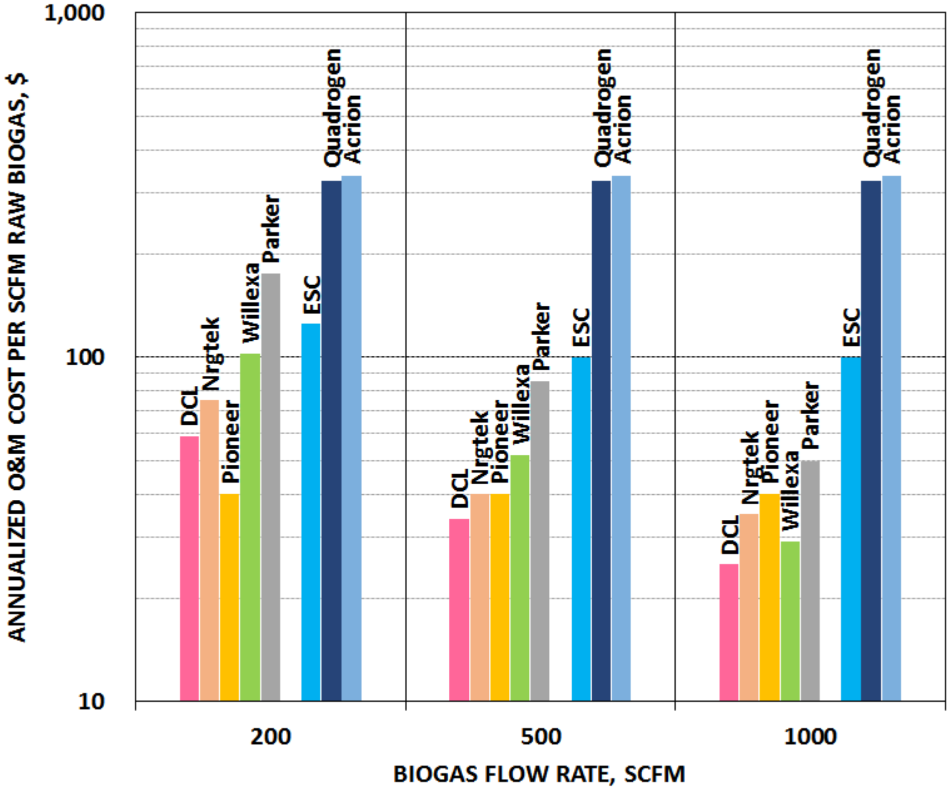

Figure 9. Siloxane Removal Systems Annualized O&M Costs per SCFM Raw Biogas from Vendor Questionnaire Results

Table 8. Summary of Literature Cost Data for Siloxane Removal Systems

Facility Name	Sacramento County, MSD-Carson Cogeneration Facility[1]	City of Santa Margarita, CA[1]	Bergan County Utility Authority[1]	Ocean County Utility Authority[1]	Calabasas Landfill[2]	Lancaster Water Reclamation Plant[3]	Great Neck NY WWTP[1]	Janesville WWTP[4]
Siloxane System	N/A	SAGTM (AFT)	SAGTM (AFT)	SAGTM (AFT)	Silica gel	-20°F chiller	AFT media	Silica gel
System manufacturer/supplier							Unison	Unison
Actual costs or Budget Proposal	Actual	Actual	Actual	Actual	Actual	Actual	Proposal	Actual
System Run Time	7 years w/o catalyst failure	7 years w/o reduction in turbine output						1.5 years+
Biogas Source					Landfill gas	Anaerobic digesters	WWTP	Anaerobic digesters
Fuel Flow, SCFM	1600-2500	30	200-800	350	180	62	55	140
Facility Location		Santa Margarita, CA	Little Ferry, NJ	NJ	Agoura, CA			Janesville, WI
Install Date	1996	2001	2002 (Feb.)	2003 (Feb.)	2002 (Oct.)	2005		
Capital Costs, $							$284,495	
Siloxane System								
Chiller/Moisture								
H_2S System								
Shipping								
Startup/Commisioning								
Total Capital Costs, $								
Capital Costs, $/SCFM							$5,173	
O&M Costs, $	40000	4100	35000	12000			3800	9369
O&M Costs, $/SCFM	16-25	137	44-175	34			69	67
Installed cost, $	92,000	22,000	500,000	212,000				$288,320
Installed cost, $/SCFM	45	733	625-2500	606				$2,059
O&M Costs, $/yr								
Siloxane System					60¢/kWh w/carbon; 0.21¢/kWh silica gel or $5500/yr (pg. 5)		$2,000	$4,500
Monitoring							$1,800	
Maintenance + other								$4,869
Electricity								
Chiller								
H_2S System								
Labor								
Unspecified siloxane system	$40,000	4100	35000	12000				
Total O&M Costs, $	40000	4100	35000	12000			3800	9369
Total O&M Costs, $/SCFM	16-25	137	44-175	34			69	67
Siloxane System Size	3 x 8-ft vessels (2 in series, 1 standby)	2 x 1.5-ft vessels in series	3 x 4-ft vessels in series	3 x 3-ft vessels in series	2 vessels		2 vessels (18"x6')	
System Footprint								
System Pressure Drop								
Media Weight/Life	10,000 lb/vessel	225 lb/vessel		2400 lb/vessel				
Purpose	SCR protection	Microturbine protection	Engine & OCR	Engine				
Prime Mover			Caterpillar	Waukesha	Capstone microturbines (10 x 30-kW; 250-kW net)	225-kW net Ingersoll-Rand MT 250 microturbine operating at 180 kW	Capstone	
Comments					Siloxane breakthrough detected Dec. 2003 from original carbon	"...Ingersoll Rand reportedly will discontinue use of this type of digester gas treatment with its microturbines."	Capital costs costs include moisture removal, gas compression and drying, and	
Warranty							12 mon. from startup/18 mon. from shipment	
Annual Savings, $/SCFM								
Annual Savings, $/SCFM								

Facility Name	Orange County Sanitation District-RP#1[5]	Glendale Energy[6]	Barrie[7]	Bucklin Point WWTF[8]	Jacob B. Hands WWTP[9]	Ina road WRF[10]	Ina road WRF[10]	East Bay MUD
Siloxane System	SAGTM (AFT)	Silica Gel (nonregenerative)	Refrig.+SAGTM	Activated carbon		Granular media	Activated carbon	Activated carbon
System manufacturer/supplier		Glendale Energy			Unison	AFT	ESC	ESC
Actual costs or Budget Proposal	Actual	Actual		Feasibility Study	Design Report	Design Report	Design Report	Site visit
System Run Time								
Biogas Source		Landfill	WWTP	WWTP	WWTP			WWTP
Fuel Flow, SCFM	1440	1350	172	475	95-140	900	900	4000
Facility Location	Fountain Valley, CA		Barrie, Ontario, Canada	East Providence, RI		Marana, AZ	Marana, AZ	Oakland, CA
Install Date								2011 (Nov)
Capital Costs, $								
Siloxane System				27,337	250,000	1,043,000	$1,947,000 (includes H_2S removal system)	
Chiller/Moisture				250,000	265,000	Chiller + HEXs included in siloxane cost	Compressor + HEXs included in siloxane cost	
H_2S System				40,000	140,000	Included in siloxane cost	Included in siloxane cost	
Shipping					15,000			
Startup/Commisioning					10,000			
Total Capital Costs, $				317,337	680,000	1,043,000	0	
Capital Costs, $/SCFM				669	5,787	1,159	0	
O&M Costs, $	40000	60000	34000	142992		232000	363000	300000
O&M Costs, $/SCFM	28	44	198	301		258	403	75
Installed cost, $		305,000	580,000			1,871,000	3,337,000	
Installed cost, $/SCFM		226	3,378			2,079	3,708	
O&M Costs, $/yr								
Siloxane System	40,000	60,000		68,412		146,000	233,000	300,000
Monitoring								
Maintenance + other				20,000		20,000	39,000	
Electricity						24,000	62,000	
Chiller				44,080				
H_2S System				10,500		Included in siloxane cost (H_2S media replaced yearly)	Included in siloxane cost (H_2S media replaced yearly)	
Labor						42000	29000	
Unspecified siloxane system			34000					
Total O&M Costs, $	40000	60000	34000	142992		232000	363000	300000
Total O&M Costs, $/SCFM	28	44	198	301		258	403	75
Siloxane System Size	7.5 ft D x 8 ft H vessel				2 x 6-ft D x 8-ft H vessels	4 x 4-ft D x 8-ft H vessels	4 x 5-ft D x 8-ft H vessels	
System Footprint						40 ft x 70 ft	45 ft x 60 ft	
System Pressure Drop						3-in H_2O	10-in H_2O	
Media Weight/Life	9,900 lb (3-stage media)					Siloxane media: 6,000 lb/ 152 days	Siloxane media: 18,840 lb/ 120 days	
Purpose								
Prime Mover	ICE		Waukesha ICE					turbine, 3 x 2.1-MW Enterprise dual-fuel engines
Comments								
Warranty								
Annual Savings, $/SCFM		165000						
Annual Savings, $/SCFM		122						

[1] *Microturbine Installation Feasibility Study, Great Neck Water Pollution Control District, Nassau County, NY, Project # 48302, November 2008.*

[2] *Operating Experience at Two Biogas-Fired Microturbine Facilities*, McDannel, M. et.al., County Sanitation Districts of Los Angeles County Whittier, CA, 28th Annual SWANA Landfill Gas Symposium, Coronado, CA, March 2005.

[3] *Evaluation of Combined Heat and Power Technologies for Wastewater Facilities*, EPA 832-R-10-006; Sept. 2012.

[4] *Personal communication with Joe Zakovec, City of Janesville-Wastewater Superintentent, April 1. 2014.*

[5] *Retrofit Digester Gas Engine with Fuel Gas Clean-up and Exhaust Emission Control Technology, SCAQMD Contract #10114, Pilot Testing of Emission Control System Plant 1 Engine 1,* Final Report, July 2011.

[6] *Siloxane Removal at a Small Landfill Gas to Electrical Energy Facility in the Arizona Desert,* http://www.epa.gov/outreach/lmop/documents/pdfs/conf/17th/24b_Carolan.pdf

[7] *City of Brockville Water Pollution Control Centre Congeneration Feasibility Assessment, Final Report, January 2007.*

[8] *Bucklin Point Renewable Biogas Energy Feasibility Study,* Narragenseet Bay Commission, December 2009.

[9] *Preliminary Design Report (PDR)-Final, Jacob B. Hands WWTP Combined Heat and Power Project*, January 2013.

[10] *Concept Design Report Ina Road WRF-Digester Gas Equipment Replacement Project*, Concept Design Report, Contract 10-03-B-141640-1008, April 2009.

Task 4. Development of Biogas Cleanup System Cost Estimator Toolkit

The toolkit developed is an Excel-based calculation spreadsheet that estimates capital (equipment) costs, annual operation and maintenance costs (O&M) and annual cost for a siloxane removal system per the scheme in Figure 10. In addition, an estimate was also made for the reduction in engine maintenance costs resulting from implementation of a siloxane removal system based on literature data[9,10,11], interviews and personal communications with biogas engine operators and manufacturers. The estimated savings are expressed in terms of payback years (i.e., the ratio of the siloxane system capital cost to the annual engine cost savings) in Table 9 and range from one-half year to three years at the highest (>60 ppmv) and lowest (<9 ppmv) biogas siloxane concentrations. Table 9 is incorporated into the Excel toolkit workbook in a separate spreadsheet from which the user can determine payback years by simply looking up the value in the table.

Toolkit Development

The toolkit development follows the approach shown in Figure 10 and basically consists of inputs and outputs sections. A description of the inputs section, calculational methodology and outputs section are as follows.

Inputs Section

A sample input section of the toolkit spreadsheet is shown in Table 10. The red highlighted values indicate inputs while those in black are default values. The main input is the biogas flowrate. It is entered in the first line of the spreadsheet along with its units (SCFM) from which the spreadsheet calculates the corresponding engine power in kW and BHP. Alternatively, the engine power can be entered along with its units (either BHP or kW) in the first line and the spreadsheet will calculate the required flowrate (see the calculational scheme below). Values for the biogas HHV and engine efficiency can also be input; the default values are 500 Btu/ft^3 and 32%.

The spreadsheet toolkit methodology provides generic cost categories and default assumptions to estimate the installed costs of the siloxane removal systems. Direct costs are required for certain key elements, such as the capital and O&M costs. Other costs, such as system installation, are then estimated from a series of input percentages or factors (in red font) applied to the purchased equipment costs, as shown in Table 10. The spreadsheet provides various percentage factors as default values (column 3) in Table 10, but users may enter their own values (into column 2). The default percentages used in the spreadsheet were taken from those used by industy as presented in the EPA Air Pollution Control Cost Manual[12] and shown in Appendix D for reference. The methodology is sufficiently general to be used with retrofit systems as well by inputting a retrofit

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[9] "Best Practices to Select Internal Combustion Engines and Maximize the Success of Methane to Electricity Projects," Mauricio Lopez, Electric Power Gas Division, Caterpillar, Inc., presented at Methane Expo 2013 Vancouver, Canada.

[10] "Total Biogas Quality Management," November 7, 2007, presented at Intermountain CHP Workshop on Siloxanes and Other Harmful Contaminants: Their Importance In Biogas Utilization.

[11] "Glendale Energy Siloxane Removal at a Small Landfill Gas to Electrical Energy Facility in the Arizona Desert," presented at the 17th Annual LMOP Conference and Project Expo, Baltimore, MD, January 21-23, 2014.

[12] EPA Air Pollution Control Cost Manual, Sixth Edition EPA/452/B-02-001, January 2002, United States Environmental Protection Agency Office of Air Quality Planning and Standards Research, Triangle Park, North Carolina 27711, EPA/452/B-02-001

factor (see Appendix D). This methodology provides rough order-of-magnitude-level cost estimate; the only input required for making this level of estimate is the biogas volumetric flow rate (or equivalent engine power). The order of magnitude could be improved with more detailed cost data.

Calculational Scheme

In order to facilitate estimation of the vendor cost data for use in the toolkit, a best-fit regression analysis was performed of the capital and O&M cost data versus flow rate shown above in Table 7 to obtain correlation equations for use in the toolkit. The resulting regression lines and equations are shown in Figures 11 and 12 for both sets of vendor data, i.e., from vendors offering siloxane-only removal systems and those offering all-contaminants removal systems. These equations are then applied to the user input biogas flow data in the spreadsheet using the calculational scheme shown in Table 11 for estimation of the system capital and O&M costs. The siloxane-only removal system equipment cost (SRSEC) is calculated in the spreadsheet by the following equations:

$$\text{SRSEC (\$)} = 35{,}064 \text{ x (Flow rate, SCFM)}^{0.375}$$

And for the all-contaminant removal system by:

$$\text{SRSEC (\$)} = 1741.5 \text{ x (Flow rate, SCFM)} + 653{,}537.4$$

The siloxane-only removal system O&M cost is calculated by:

$$\text{O\&M (\$)} = 2047 \text{ x (Flow rate, SCFM)}^{0.399}$$

And the all-contaminant removal system O&M cost is calculated by:

$$\text{O\&M (\$)} = 306.1 \text{ x (Flow rate, SCFM)}^{0.952}$$

The conversion between input engine BHP and kW power is performed as follows:

$$\text{BHP x } 0.7457 = \text{kW}$$

The equivalent biogas volumetric flowrate in SCFM from engine kW is calculated as follows:

$$\text{SCFM} = \text{kW x } 3414/[60 \text{ x HHV x Engine Efficiency}]$$

Outputs Section

In addition to estimating the capital (purchased equipment) and O&M costs for the siloxane removal system, the following cost categories are used to describe the Total Annual Cost (TAC) as per the scheme in Table 11:

1. Total Equipment Costs (TEC), which include the capital costs of the siloxane removal system and auxiliary equipment, instrumentation, sales tax, and freight;
2. Direct Installation Costs (DIC), which are the construction-related costs associated with installing the control device;

3. Indirect Capital Costs (ICC), which include installation expenses related to engineering and start-up;
4. Direct Operating Costs (DOC), which include annual increases in operating and maintenance costs due to the addition of the control device; and
5. Indirect Operating Costs (IOC), which are the annualized cost of the control device system and the costs due to tax, overhead, insurance, administrative burdens and capital recovery.

From these costs is estimated the Annual Cost (AC), which is the sum of the Direct Operating and Indirect Operating Costs. The methodology is sufficiently general to be used with retrofit systems as well by applying a retrofit factor (Appendix D).

Two output spreadsheets are included in the Excel toolkit workbook:
1. Siloxane-only removal system costs
2. All-contaminants removal system cost.

A sample output based on the calculational scheme is shown in Table 12.

Program Installation

In order to install the spreadsheet on a new computer, the following file should be copied:

SRSC.xls

The spreadsheets are currently unprotected and no macros are used.

Task 5. Biogas Cleanup System Cost Estimator Toolkit Training and User Instruction Manuals

- A User's Instruction Manual for the Biogas Cleanup System Cost Estimator Toolkit was prepared that includes documentation for program installation and operation, inputs, calculational schemes and output of results. Also included are estimates for the reduction in engine maintenance costs resulting from implementation of a siloxane removal system as a function of biogas siloxane concentrations.
- A training class on the use of the Biogas Cleanup System Cost Estimator Toolkit for SCAQMD staff was held on July 9, 2014.

Task 6. Technical Support and Management (June 2014-June 2015)

GTI will provide Biogas Cleanup System Cost Estimator Toolkit technical support to SCAQMD to ensure the continuous use and operation of the toolkit as it was designed and intended under this contract until the term of this contract and will organize and conduct progress meetings and ad hoc meetings, as required, if problems arise that lead to a change in the original scope of work or project schedule.

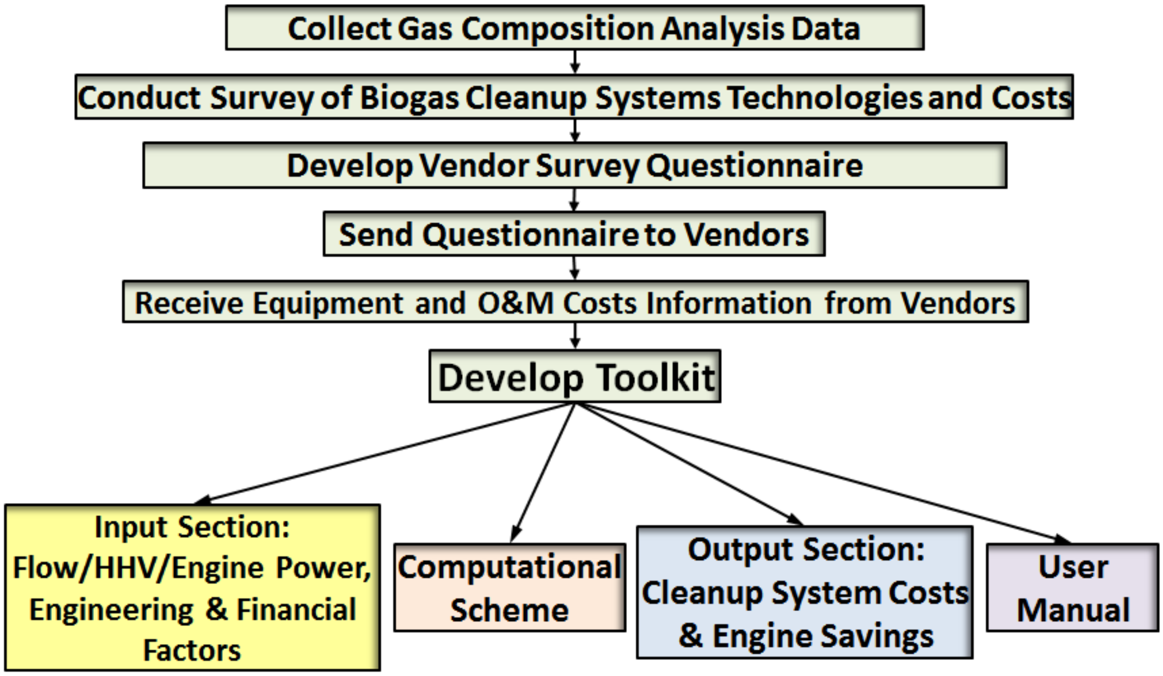

Figure 10. Flowchart of Cost Analysis

Table 9. Engine Cost Savings Calculator

Category	Siloxane Level, ppmv	Payback Years
Moderate	0.5 - <9	3.0
Heavy	>9 - <25	2.0
Severe	>25 - <60	1.0
Extreme	>60 - 140+	0.5
Savings Include (based on siloxane levels)		
Spark plugs: increase life 3x to 4x		
Engine re-build from 5000 to 40,000 hours		
Exhaust heat boiler re-tube: increase life by 3x to 4x		
Power Savings / Availability: increase of 75 to 92%		
Oil changes increase interval: 500 to 1440[13] hours		
Pre-chamber and pre-chamber check valve by 2x to 6x		

Assumptions-

1. Gas already meets engine OEM gas cleanliness standards
2. Lean Burn Engines

[13] Title 40, Part 63, Subpart ZZZZ-National Emissions Standards for Hazardous Air Pollutants for Stationary Reciprocating Internal Combustion Engines.

Table 10. Sample Spreadsheet Input Section

	Value	Units
Input Value and Units	**1,000**	**SCFM**
Biogas Higher Heating Value (HHV)	**500**	Btu/ft^3
Engine Efficiency	**32**	%
Inlet Flow Rate	1,000	SCFM
Engine Power	2,813	kW
Engine Power	3,773	bhp

Input either SCFM, kW or BHP.

Input either flowrate or engine power.

CALCULATOR		
Cost Items	**Factor**	**Default Factor**
DIRECT CAPITAL COSTS (DCC):		
(1) Siloxane Removal System Equipment Cost (SRSEC)		
(2) Auxiliary Equipment	**5.0%**	5%
(3) Freight	**5.0%**	5.0%
(4) Sales Tax	**10.0%**	10.0%
Subtotal: **Total Equipment Cost (TEC)**		
(3) Direct Installation Costs		
(a) Foundation and Structural Support	**8.0%**	8.0%
(b) Handling & Erection	**14.0%**	14.0%
(c) Electrical	**4.0%**	4.0%
(d) Piping	**2.0%**	2.0%
(e) Insulation	**1.0%**	1.0%
(f) Painting	**1.0%**	1.0%
Subtotal: **Total Direct Installation Costs (DIC)**		
Total DCC:		
INDIRECT CAPITAL COSTS (ICC):		
(1) Indirect Installation Costs (IIC)		
(a) General Facilities	**5.0%**	5.0%
(b) Engineering and Home Office Fees	**10.0%**	10.0%
(c) Process Contingency	**10.0%**	10.0%
(2) Other Indirect Costs (OIC)		
(a) Siloxane Monitor	**$75,000**	75,000
(b) Startup and Performance Testing	**1.0%**	1.0%
(c) Spare Parts	**1.0%**	1.0%
(d) Contractor Fees	**10.0%**	10.0%
Total ICC:		
PROJECT CONTINGENCY	**15.0%**	15.0%
RETROFIT COSTS	**0.0%**	0.0%
TOTAL CAPITAL INVESTMENT (TCI):		
DIRECT OPERATING COSTS (DOC):		
(1) Operating Labor		
(a) Operator		
hr/shift	**0.5**	0.5
Pay Rate	**$40**	$40
Operating Hours	**8760**	8760
(b) Supervisor	**15.0%**	15.0%
(2) Maintenance (labor and material)	**1.5%**	1.5%
(3) Siloxane Removal System Media Replacement + Energy Requirement		
(4) Siloxane System Periodic Testing	**$24,000**	$24,000
Total DOC:		
INDIRECT OPERATING COSTS (IOC):		
(1) Overhead	**60.0%**	60.0%
(2) Property Taxes	**1.0%**	1.0%
(3) Insurance	**1.0%**	1.0%
(4) Administration	**2.0%**	2.0%
(5) Capital recovery costs (CRC)		
Capital recovery factor (CRF)		
Interest rate	**7.0%**	7.0%
Annualization years	**10**	10
Total IOC:		
Recovery Credits (RC)	**$0**	$0

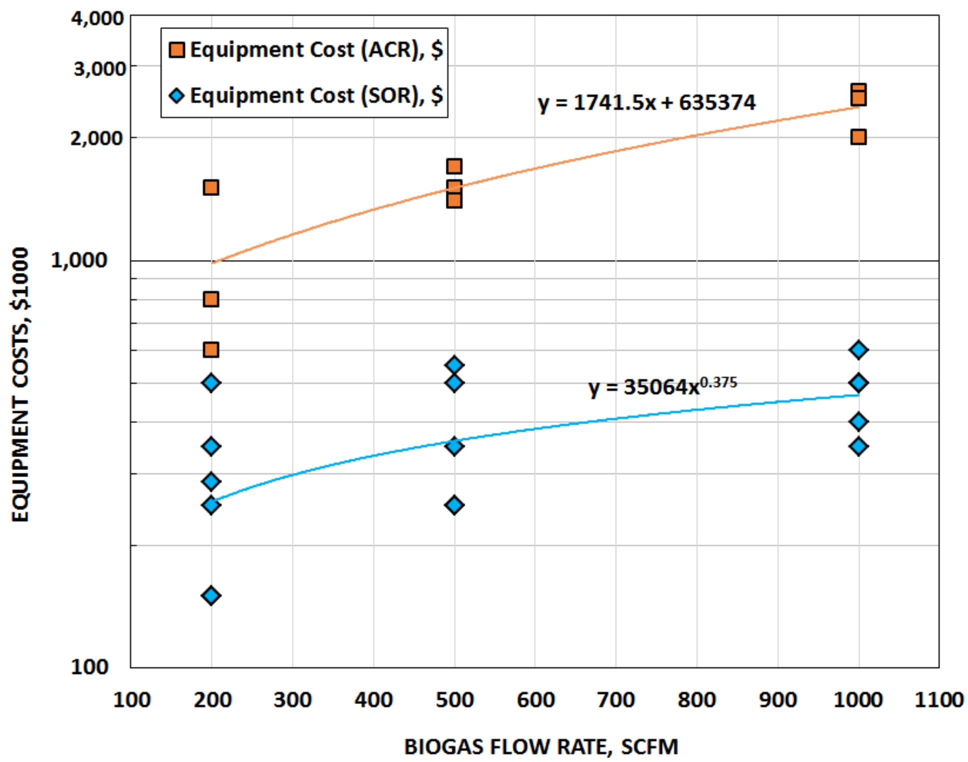

Figure 11. Best-fit Regression Analysis of Siloxane Removal Systems Vendor Capital Equipment Costs (ACR=All-contaminant removal systems, SOR=Siloxane-only removal systems)

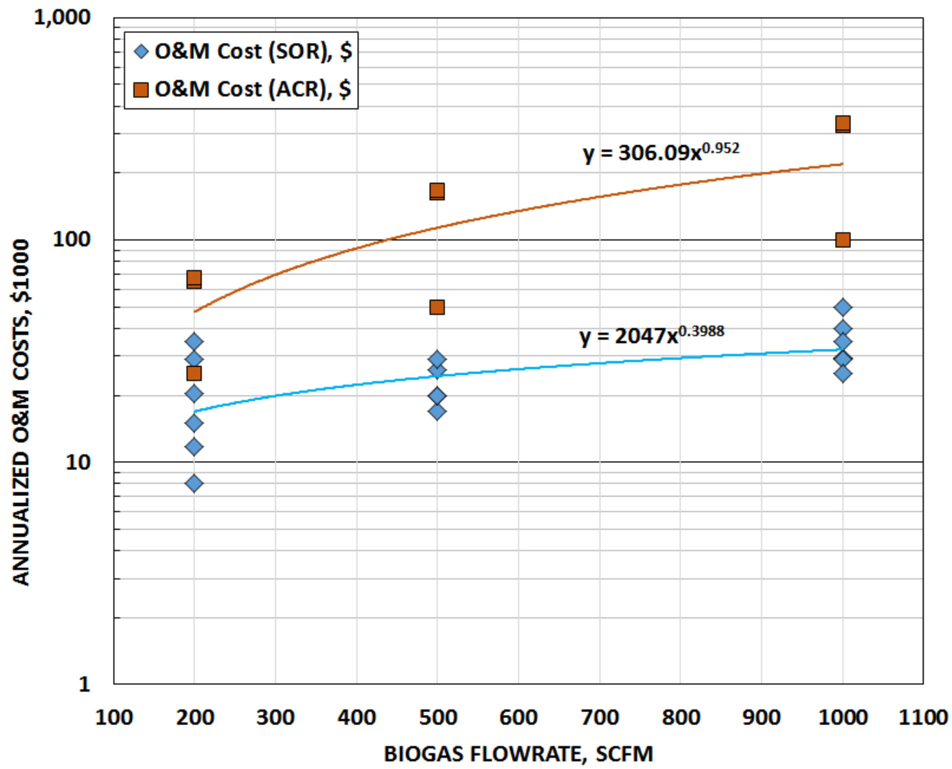

Figure 12. Best-fit Regression Analysis of Siloxane Removal Systems Vendor O&M Costs (ACR=All-contaminant removal systems, SOR=Siloxane-only removal systems)

Table 11. Calculational Scheme in Toolkit Spreadsheet

SILOXANE REMOVAL SYSTEM CAPITAL AND ANNUAL COSTS CALCULATOR	
Cost Items	**Cost Factors**
DIRECT CAPITAL COSTS (DCC):	
(1) Siloxane Removal System Equipment Cost (SRSEC)	Calculated by program (see calculational methodology section)
(2) Auxiliary Equipment	Percent input x SRSEC
(3) Freight	Percent input x SRSEC
(4) Sales Tax	Percent input x (SRSEC+auxiliary + freight)
Subtotal: **Total Equipment Cost (TEC)**	(1) + (2) + (3) + (4)
(3) Direct Installation Costs	
(a) Foundation and Structural Support	Percent input x TEC
(b) Handling & Erection	Percent input x TEC
(c) Electrical	Percent input x TEC
(d) Piping	Percent input x TEC
(e) Insulation	Percent input x TEC
(f) Painting	Percent input x TEC
Subtotal: **Total Direct Installation Costs (DIC)**	(a) + (b) + (c) + (d) + (e) + (f)
Total DCC:	
INDIRECT CAPITAL COSTS (ICC):	
(1) Indirect Installation Costs (IIC)	
(a) General Facilities	Percent input x TEC
(b) Engineering and Home Office Fees	Percent input x TEC
(c) Process Contingency	Percent input x TEC
(2) Other Indirect Costs (OIC)	
(a) Siloxane Monitor	Enginnering Estimate ($)
(b) Startup and Performance Testing	Percent input x TEC
(c) Spare Parts	Percent input x TEC
(d) Contractor Fees	Percent input x TEC
Total ICC:	IIC+OIC
PROJECT CONTINGENCY	Percent x (DCC+ICC)
RETROFIT COSTS	Percent x TIC
TOTAL CAPITAL INVESTMENT (TCI):	DCC+ICC+Project Contingency+Retrofit Costs
DIRECT OPERATING COSTS (DOC):	
(1) Operating Labor	
(a) Operator	
hr/shift	User estimated labor hours/shift
Pay Rate	User estimated pay rate ($/hr)
Operating Hours	User estimated operating hours/year
(b) Supervisor	Percent x operating labor cost (1)
(2) Maintenance (labor and material)	Percent x TCI
(3) Siloxane Removal System Media Replacement + Energy Requirement	Calculated by program (see calculational methodology section)
(4) Siloxane System Periodic Testing	Enginnering Estimate ($)
Total DOC:	(a) + (b) + (2) + (3) + (4)
INDIRECT OPERATING COSTS (IOC):	
(1) Overhead	Percent x [operating labor cost (1)+ maintenance cost (2)]
(2) Property Taxes	Percent x TCI
(3) Insurance	Percent x TCI
(4) Administration	Percent x TCI
(5) Capital Recovery Costs (CRC)	Calculated by program (CRF x TCI)
Cost Recovery Factor (CRF)	Calculated by program (see calculational methodology section)
Interest Rate	Interest rate in percent
Annualization years	Annualization period in years
Total IOC:	(1) + (2) + (3) + (4) + (5)
Recovery Credits (RC)	Enginnering Estimate ($)
TOTAL ANNUAL COST (TAC):	DOC + IOC - RC
TOTAL ANNUAL COST PER kWh	(DOC+IOC)/(kWh/yr)
TOTAL ANNUAL COST PER MMBtu	(DOC + IOC)/(MMBtu/yr)
TOTAL ANNUAL COST PER MSCF	(DOC + IOC)/(MMBtu/yr)

Table 12. Sample Spreadsheet Output of Siloxane Removal System Cost Calculation

	Value	Units
Input Value and Units	**1,000**	**SCFM**
Biogas Higher Heating Value (HHV)	**500**	Btu/ft^3
Engine Efficiency	**32**	%
Inlet Flow Rate	1,000	SCFM
Engine Power	2,813	kW
Engine Power	3,773	bhp

Input either SCFM, kW or BHP.

Input either flowrate or engine power.

SILOXANE-ONLY REMOVAL (SOR) SYSTEM CAPITAL AND ANNUAL COSTS CALCULATOR				
Cost Items	**Cost Factors**	**Factor**	**Removal System Cost ($)**	**Default Factor**
DIRECT CAPITAL COSTS (DCC):				
(1) Siloxane Removal System Equipment Cost (SRSEC)	Calculated by program		467,586	
(2) Auxiliary Equipment	5% of equipment cost (SRSEC)	**5.0%**	23,379	5%
(3) Freight	5% of SRSEC	**5.0%**	23,379	5.0%
(4) Sales Tax	10% of (SRSEC+auxiliary+freight)	**10.0%**	46,759	10.0%
Subtotal: **Total Equipment Cost (TEC)**	(1) + (2) + (3) + (4)		561,103	
(3) Direct Installation Costs				
(a) Foundation and Structural Support	8% of TEC	**8.0%**	44,888	8.0%
(b) Handling & Erection	14% of TEC	**14.0%**	78,554	14.0%
(c) Electrical	4% of TEC	**4.0%**	22,444	4.0%
(d) Piping	2% of TEC	**2.0%**	11,222	2.0%
(e) Insulation	1% of TEC	**1.0%**	5,611	1.0%
(f) Painting	1% of TEC	**1.0%**	5,611	1.0%
Subtotal: **Total Direct Installation Costs (DIC)**	(a) + (b) + (c) + (d) + (e) + (f)		168,331	
Total DCC:	TEC + DIC		729,434	
INDIRECT CAPITAL COSTS (ICC):				
(1) Indirect Installation Costs (IIC)				
(a) General Facilities	5% of TEC	**5.0%**	28,055	5.0%
(b) Engineering and Home Office Fees	10% of TEC	**10.0%**	56,110	10.0%
(c) Process Contingency	10% of TEC	**10.0%**	56,110	10.0%
(2) Other Indirect Costs (OIC)				
(a) Siloxane Monitor	Engineering Estimate	**$75,000**	75,000	75,000
(b) Startup and Performance Testing	1% of TEC	**1.0%**	5,611	1.0%
(c) Spare Parts	1% of TEC	**1.0%**	5,611	1.0%
(d) Contractor Fees	10% of TEC	**10.0%**	56,110	10.0%
Total ICC:	IIC+OIC		282,608	
PROJECT CONTINGENCY	15% of (DCC+ICC)	**15.0%**	151,806	15.0%
RETROFIT COSTS	0% of TIC	**0.0%**	0	0.0%
TOTAL CAPITAL INVESTMENT (TCI):	DCC+ICC+Project Contingency+Retrofit Costs		1,163,849	
DIRECT OPERATING COSTS (DOC):				
(1) Operating Labor				
(a) Operator			21,900	
hr/shift		**0.5**		0.5
Pay Rate		**$40**		$40
Operating Hours		**8760**		8760
(b) Supervisor	15% of operator cost	**15.0%**	3,285	15.0%
(2) Maintenance (labor and material)	1.5% of TCI	**1.5%**	17,458	1.5%
(3) Siloxane Removal System Media Replacement + Energy Requirement	Calculated by program		27,164	
(4) Siloxane System Periodic Testing	Engineering estimate	**$24,000**	24,000	$24,000
Total DOC:	(a) + (b) + (2) + (3) + (4)		93,807	
INDIRECT OPERATING COSTS (IOC):				
(1) Overhead	60% of (operator labor (1) + maintenance (2))	**60.0%**	25,586	60.0%
(2) Property Taxes	1% of total capital investment	**1.0%**	11,638	1.0%
(3) Insurance	1% of total capital investment	**1.0%**	11,638	1.0%
(4) Administration	2% of total capital investment	**2.0%**	23,277	2.0%
(5) Capital recovery costs (CRC)	CRF x TCI		165,732	
Capital recovery factor (CRF)	0.1424			
Interest rate		**7.0%**		7.0%
Annualization years		**10**		10
Total IOC:	(1) + (2) + (3) + (4) + (5)		237,872	
Recovery Credits (RC)	Engineering Estimate	**$0**	0	$0
TOTAL ANNUAL COST (TAC):	DOC + IOC - RC		331,679	
TOTAL ANNUAL COST PER kWh			0.013	
TOTAL ANNUAL COST PER MMBtu			1.26	
TOTAL ANNUAL COST PER MSCF			0.63	

SUMMARY OF RESULTS

This section summarizes results of each task, including the biogas compositional analysis and biogas cleanup systems survey, emissions reduction, reliability, operating cost and performance.

Task 1: Gas Composition Analyses

In order to facilitate the development of the cost estimator toolkit, GTI conducted a literature search for sources of raw biogas composition data and heating values. Information for over 575 samples in the GTI database derived from approximately 47 LFG, 22 WWTP, and 21 dairy sources located across the US was compiled in Excel spreadsheets. In particular, the above data and additional siloxane analyses from the literature search included numerous speciated and total siloxanes compositions from these sites.

Task 2: Survey of Biogas Cleanup Systems Technologies

- A literature/internet search was conducted to identify biogas cleanup systems (focusing on siloxane removal technologies for engines) with over 100 references found and compiled in an Excel spreadsheet.
    - The cleanup requirements for SCR and fuel cells are 1 to 2 orders of magnitude more stringent than the engine original equipment manufacturer gas cleanliness standards.
    - Twenty companies dealing with biogas cleanup equipment for various applications (fuel cells, engines, turbines, etc.) were identified and contacted for further information.
- In order to facilitate the survey process, a vendor questionnaire was developed and issued to the 17 companies identified as siloxane system removal system manufacturers or equipment suppliers.
- Nine survey questionnaires (from Willexa Energy, DCL America, Pioneer Air Systems, ESC, Unison, Acrion, Quadrogen, Nrgtek and Guild) were either partly or completely filled out and returned.
    - Available siloxane removal systems can be divided into three primary system types: consumable media, regenerative media, chiller/absorption and various versions of these technologies in combination.
    - Removal systems based on PSA adsorption and continuous liquid scrubbing with proprietary nanofiltration/pervaporation membranes are under development, but at this time a product is not available in the commercial marketplace. Liquid scrubbing absorbents such as Selexol have been used in Europe and in the US for landfill gas cleanup but because of their higher capital and operating costs are not considered realistic options for lower capacity treatment.
    - Willexa Energy reported in this project on successful operation of a regenerative siloxane removal system at seven locations (with 3 more under construction) in South America on Caterpillar engines equipped with DCL exhaust catalysts. These systems were installed by PpTek Ltd. (UK) and are essentially the same system offered by Willexa as their sole US representative. Two Willexa PpTek systems are currently under construction: 1) one for an existing LFGTE project in Indiana using multiple CAT reciprocating engines (no catalysts) and 2) a new

LFGTE project in BC, Canada, using multiple CAT reciprocating engines (no catalysts).
  - Although the other vendors claim to provide siloxane removal systems their lack of response to the survey raises various issues.
  - Venture Engineering did not return the survey, but they claim to have five units installed on SCR-catalyzed prime movers. Parker also did not return the survey but claims to have four systems installed in the eastern US. The operational state of the systems from both vendors could not be confirmed, however.
  - DCL International, primarily a catalyst manufacturer, reported that they will offer an arrangement wherein if an NSCR/SCR customer also purchases DCL's siloxane removal system they will guarantee against catalyst failure due to siloxane breakthrough and repair the catalyst in the instance of such damage. At this time, however, DCL does not have any of their siloxane removal systems installed.
  - It is likely that simple consumable media systems are not capable of meeting the requirements for SCR and may be one reason for lack of response from vendors utilizing this media.
- The regenerative, dual canister (bank) systems could potentially provide adequate protection for SCR equipped engines since rather than estimating the media changeout interval, the units can be set to regenerate more frequently than estimated.
- Maintenance on the gas processing equipment will be critical as the cost associated with even short-term breakthrough will be excessive due to failed SCR catalyst, fuel cells, or microturbines.
- Site visits were made by project personnel to the East Bay MUD WWTP in Oakland, CA, and to Ameresco Ox Mountain (Half Moon Bay, CA) and Chiquita Canyon (Castaic, CA) power generation facilities.
  - An activated carbon system from ESC provides siloxane removal for turbines and engines at the East Bay MUD site. Siloxane content is monitored and when it exceeds a design limit the carbon is replaced about every six months with fresh activated carbon.
  - The gas cleanup system at Ox Mountain (a Temperature Swing Absorption, TSA, fuel-gas regenerative, carbon-type gas cleanup system) has demonstrated adequate effectiveness to remove siloxanes and other landfill gas contaminants to levels enabling the use of an SCR catalyst.
  - The Ox Mountain gas pre-treatment + SCR have been determined to be achieved in practice BACT for NOx (Appendix C), as per Bay Area AQMD.
  - Tremendous manpower and effort are required to operate, maintain and repair the Ox Mountain cleanup system equipment to ensure that it operates successfully. Due to the cost, size and complexity of this system, it may not be cost effective for smaller POTW operators such as those currently operating within the SCAQMD.
  - At the Chiquita landfill site two turbine generator sets provide power. The gas cleanup system was provided by Parker/ Dominick Hunter and has demonstrated an average total siloxane removal efficiency of greater than 99% after more than two years in operation.

Task 3: Biogas Cleanup System Costs

- Both capital and O&M costs for the surveyed vendor systems are shown to vary widely between the individual “siloxane-only” removal and between each of the “all-contaminants” removal systems–the reasons for this are not readily determined due to the limited data provided by the survey, and the reluctance of some of the respondents to provide proprietary data due to the either the competitive nature of the business, no or insufficient data and lack of in-house technical expertise.
- Siloxane removal systems capable of meeting the requirements of the SCR-catalyzed engines will greatly increase the initial costs of a biogas power plant as well as increasing the demand for on-site maintenance in the future. Willexa, however, in a personal communication reported that the PpTek regenerable polymer media cassette system has decreased in cost over the past few years to the point that it could now be cost effective for use at sites with a minimum of two engines, which formerly required 3 to 4 engines.
- As expected the survey data indicated that biogas treatment system capital and O&M costs generally increase with flow capacity but decrease on a cost-per-volume of raw biogas treated basis, suggesting that it is more cost effective to treat one larger biogas flow to multiple engines.
- At the East Bay MUD site, e.g., annual carbon media changeout costs are about $300,000.
- Ameresco was unable to provide the project team with either capital or installation costs of their siloxane removal system at the Ox Mountain landfill.
    - Judging by the amount of equipment, however, it is estimated to be well over $1,000,000, so this type of system may not be cost effective for smaller POTW operators such as those currently operating within the SCAQMD.
    - Carbon media is replaced annually at a cost of about $100,000 (includes media removal and disposal) and is typically sent for regeneration if it is non-hazardous. If the media comes back as hazardous (typically if there are high benzene concentrations), then it can be sent to a landfill for disposal or to a landfill for use in a fuel burning process.
    - The disposal cost is $330 per truckload of approximately 20,000 lbs; hazardous disposal costs will vary depending on the composition of the media.
    - Other annualized costs include the disposal of the collected condensate “hydrocarbons” (content unknown by the plant) and overall maintenance costs, both of which Ameresco considered as proprietary information.
    - In consideration of the overall effectiveness of the system, the annualized maintenance costs seem reasonable compared to engine maintenance costs without siloxane removal considering the long engine maintenance interval achieved by the facility and the long life of both the oxidation catalysts and the SCR unit.
    - Gas samples are taken monthly from the outlet of the vessels and analyzed by a commercial lab at a cost of $2,000.
- The Chiquita landfill site gas cleanup system is made up of a combination of aluminum oxide and molecular sieves for siloxane removal. Carbon beds were originally located downstream of the siloxane vessels but have since been removed due to excessive organic fouling.
    - The cost to replace the media in all four vessels is approximately $100,000.

- Similarly to Ox Mountain Gas, samples taken monthly are analyzed at a cost of $2,000. An initial investment of approximately $150,000 was required to determine the cleaning cycle procedure by taking samples every eight hours.

Task 4: Development of a Biogas Cleanup System Cost Estimator Toolkit

- Developed a toolkit cost template as an Excel-based calculation spreadsheet that estimates capital (equipment) costs, annual operation and maintenance costs and annualized cost for a siloxane removal system based on user input data consisting of biogas volumetric flow and siloxane content.
- Toolkit development was based only on vendor survey questionnaire cost data as it would be a more realistic source of procuring data as opposed to using possibly outdated and/or unverifiable literature data.
- The toolkit was submitted to SCAQMD.

Task 5: Biogas Cleanup System Cost Estimator Toolkit Training and User Instruction Manuals

- A User's Instruction Manual for the Biogas Cleanup System Cost Estimator Toolkit was prepared that includes documentation for program installation and operation, inputs, calculational schemes and output of results.
- A training class on the use of the Biogas Cleanup System Cost Estimator Toolkit for SCAQMD staff was held on July 9, 2014.

Task 6. Technical Support and Management (June 2104-June 2015)

- GTI will provide biogas cleanup system cost estimator toolkit technical support to SCAQMD to ensure the continuous use and operation of the toolkit until the completion of the term of this contract.

RESULTS

GTI met all set project objectives and results obtained were as expected.

PROBLEMS

The below listed problems were encountered during the course of the project, which impact the cost estimation level by the toolkit.

- Both capital and O&M costs are shown to vary widely within each of the siloxane-only removal all-contaminants system, which reduces the level of estimation of the toolkit.
- Vendor reluctance to provide any or complete cost data and/or firm up their cost data possibly due to either the competitive nature of the business, lack of data, or limited expertise with these systems. However, vendor contacts made at the recent Washington, DC, LMOP biogas conference were effective in encouraging some vendors to complete the questionnaire.
- Delays in vendor responses and scheduling site visits.
- Timely availability of manpower to conduct site visits.

CONCLUSIONS AND RECOMMENDATIONS

- Vendor interaction and issuance of the survey questionnaire were found to be the most effective techniques in obtaining cleanup system information and cost data.

- A personal interview with Brad Huxter of Willexa Energy gave useful insights into their own and other vendors siloxane removal systems and confirmed some of the costs in the survey.
- Utilize feedback from toolkit users to improve and update the toolkit.
- Extend a more comprehensive version of the toolkit to other applications such as turbines, fuel cells, and substitute natural gas.
- Further develop the toolkit as a web application to allow for continuous upgrade and improvement by vendors, engines and biogas facility operators, etc. This would also promote dialog between users and vendors.
- Provide incentives to promote more field testing of available cleanup systems.
- Keep pace with new cleanup technology developers.

LIST OF ACRONYMS

Acronym	Description
AQMD	Air Quality Management District
BAAQMD	Bay Area Air Quality Management District
BACT	Best Available Control Technology
BTU/Btu	British Thermal Unit
CA	California
CAS	Chemical Abstract Service registry numbers
CAT	Caterpillar
CFM	Cubic Foot Per Minute
ft^3	Cubic Foot
D4	Octamethylcyclotetrasiloxane
DG	Distributed Generation
Div.	Division
FTIR	Fourier Transform Infrared
GTI	Gas Technology Institute
hr	Hour
IC	Internal Combustion
ICE	Internal Combustion Engine
kW	Kilowatt
LDL	Lower detection limit
LFG	Landfill Gas
LFGTE	Landfill-Gas-To-Energy
LMOP	Landfill Methane Outreach Program

Acronym	Description
m	Meter
MCF	1000 Cubic Feet
mg/m^3	Milligram-Per-Cubic Meter
MW	Megawatt
MUD	Municipal Utility District
NMOCs	Nonmethane Organic Compounds
NSCR	Non-Selective Catalytic Reduction
O&M	Operation And Maintenance
OSCD	Orange County Sanitation District
POTW	Publicly Owned Treatment Works
ppb(v)	Parts-Per-Billion (By Volume)
ppmv	Parts-Per-Million by Volume
psig	Pounds-Per-Square Inch
PSA	Pressure Swing Adsorption
SCAQMD	South Coast Air Quality Management District
SCFM	Standard Cubic Foot per Minute
SCR	Selective Catalytic Reduction
TSA	Temperature Swing Adsorption
UK	United Kingdom
VOC(s)	Volatile Organic Compound(s)
Vol, v	Volume
WWTP	Wastewater Treatment Plant

APPENDIX A

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APPENDIX B

COMPARISON OF VENDOR SURVEY QUESTIONNAIRE RESULTS (Updated)

Table 13. Comparison of Survey Results (part 1 of 5)

South Coast Air Quality Management District Contract No. 13432

Comparison of Returned Surveys-1

Company Information			
Company Name	**Willexa Energy**	**DCL America**	**Parker NLI**
Survey Returned	Yes	Yes (plus data from personal communication with Willexa)	No (data from personal communication and website)
Contact Name	Brad Huxter	Will Casolara - Mark Ahrendt - Glen Prisciak	Craig Dillworth
Contact Title	Exclusive Sales Agent		Engineered Systems Manager
Contact E-Mail	brad.huxter@willexaenergy.com	wcasolara@dcl-inc.com - mahrendt@dcl-inc.com - gprisciak@dcl-inc.com	cdillworth@parker.com
Contact Phone/fax	704-560-8895	905-660-6450	410-591-5594
Siloxane Treatment System General Information			
Product Name and Type	PpTek BGAK Siloxane Reduction System	SRT System	GES Siloxane Removal System
When was the product introduced?	2005	2013	2007
Number of Installations - worldwide	>80	--	
Number of Installations - US	0	2	~43
Number of Installations in AQMD districts (Southern California)	0	0	0
Number of installations on SCR or NSCR equipped reciprocating engines	7 (not in North America)	0 (3 "case studies" in progress in eastern US: 2 on LFG, 1 on AD)	4 on landfill gas recuperated gas turbines located in eastern US (they are in process of quoting some siloxane removal systems for CA)
Are the sites with SRC/NSCR available for visitation?	With enough notice. Note that they are not in North America.		
For California applications, what are methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas?	Two systems in series, plus monitoring between the first and the second systems, and after the second system to predict breakthrough.	Siloxane and H_2S removal in conjunction with DCL manufactured SCR and NSCR catalysts will ensure compliance. Flareless regeneration also possible.	Two systems in parallel: one on line, one regenerating
Siloxane Treatment System Technical Information			
Type (Activated carbon, regenerative, etc.)	Regenerative (per cut-sheet: polymeric media, carbon polishing media).	Regenerative Polymer Media	Regenerative
System siloxanes removal efficiency (as %, mg/ml, ppm)	1st system: 90-95%. 2nd system: 90-95% of the remainder.	>99%	
Outlet Siloxane content (based on 100 mg/m3 inlet)	0.25 - 1.0	< 1	<0.10
What other trace biogas components are simultaneously removed along with siloxanes and to what levels?	VOC's are reduced by roughly 50% depending on the application. System requires particulate removal to 0.3 µm, but does not require chilling, dehydration or H_2S removal.	VOCs; dependent on system configuration (can tolerate up to 500 ppm H_2S)	Dehydration, VOCs, H_2S
Electrical power or supplemental fuel requirement for regenerative systems.	Electrical: Blower, heater & control system. Gas: negligible depress/purge losses.	<2% average parasitic load worst case, typically lower	Blower, heater, control system
Does the system require a flare? Flare cost and flare fuel costs.	Yes	Not required, but recommended	Yes
Regeneration off-gas flow to the flare and hours per day	Flare gas is 99% air @470 CFM for 5 hr/day/system		
Media life (for passive or regenerative systems).	5 Years (guaranteed)	>7 years prior to replacement	Average 1 to 2 years
What is the system total pressure drop?	<0.5 psi, with prefilter 0.1 psi		
Does the system have siloxanes break-through detection? If so what method?	FTIR real time monitor after 1st and 2nd stages of treatment.	Method regulated in service agreement	No
Does your firm offer media change out, disposal and installation of fresh media?	We offer assistance (i.e. overview) of change out & install. Disposal is the responsibility of the owner.	yes, if needed.	Usually a contractor removes media and Parker reloads media.
What cleanup system waste disposal management strategy will be used?	N/A	Minimal waste; disposal in accordance with local regulations	Media not hazardous unless high levels of, e.g., arsenic in biogas, as has been encountered at some California sites.
Siloxane Treatment System Specifications			
What information is needed for sizing and quoting a system?	Maximum flow rate, gas & ambient temperature ranges, gas pressure ranges, inlet siloxane, VOC & particulate levels, required outlet siloxane levels.	Application/location specifics i.e. flow rate, temperatures, gas condition, etc.; detailed questions provided in inquiry sheet	
Annualized- or SCFM-basis annualized O&M costs for the following systems:			
200 SCFM	Heater: 36kW 4 hrs per day (each). Blower: 3 hp 5 hrs per day (each). Media $8400 per year ($42K every 5 yrs).	<$1000 (for air filter exchange (for the blower), lube oil replacement and disposal (valves) or any basic maintenance) items.	$175,000 for 5 years
500 SCFM	Heater: 36kW 4 hrs per day (each). Blower: 3 hp 5 hrs per day (each). Media $14K per year ($70K every 5 yrs).	<$1000 (for air filter exchange (for the blower), lube oil replacement and disposal (valves) or any basic maintenance) items.	$212,500 for 5 years
1000 SCFM	Heater: 36kW 4 hrs per day (each). Blower: 3 hp 5 hrs per day (each). Media $17.2K per year ($86K every 5 yrs).	<$1000 (for air filter exchange (for the blower), lube oil replacement and disposal (valves) or any basic maintenance) items.	$250,000 for 5 years
Equipment/capital costs for the following systems:			
200 SCFM	Equip only: $175,000 x 2 + $75,000 (monitor)	$250,000	$285,000 (+$80,000 for a pretreatment system)
500 SCFM	Equip only: $276,000 x 2 + $75,000 (monitor)	$350,000	(from website:Guaranteed siloxane removal investment cost of 0.2-0.6¢ per kWh)
1000 SCFM	Equip only: $300,000 x 2 + $75,000 (monitor)	$500,000	$400,000 (+$285,000 for a pretreatment system)
Approx. size and footprint of the physical system			
200 SCFM	197-in L x 75-in W x 63-in H	10 ft x 15 ft	115 in H x 200 in L x 100 in D (350 scfm) Model GES 350
500 SCFM	197-in L x 75-in W x 63-in H	15 ft x 20 ft	130 in H x 200 in L x 100 in D (525 scfm) Model GES 400
1000 SCFM	197-in L x 75-in W x 83-in H	20 ft x 30 ft	155 in H x 215 in L x 120 in D (1250 scfm) Model GES 900
Capacity limitations and scalability of the technology	290 to 2470 cfm max flow per system depending on model. Multiple systems can be used in parallel for higher flow rates.	Scalable from <50 scfm to >7000 scfm	350-10,000 SCFM
How is system removal efficiency affected for a given biogas composition as a function of flow rate?	All things equal, removal efficiency decreases with increased flow rate. This can be counteracted by adding additional media cassettes and increasing regeneration frequency, however this also increases parasitic loads.	Size of system based on specified efficiency at specific flow rate. Regeneration frequency a factor of removal efficiency, not composition. Media is selective to siloxane species, unaffected by moisture, sulfur and metals.	
Any additional information you would like to include.	This is an original, patented design which uses polymeric media cassettes instead of loose desiccant like other regenerative systems.	Minimal footprint and low energy requirement/parasitic load during regeneration.	12- and 18-month and extended warranties available (all media replacement, gas sampling, system inspection, etc.)
Engine Exhaust Requirements			
Are any of the systems installed on reciprocating engines that are subject to emission requirements (with or without SCR/NSCR)?	Yes. There are seven (7) systems installed on reciprocating engines using catalysts in South America.	System can be designed to accommodate exhaust emission requirements, also based on California SCAQMD Rule 1110.2 for ICE operating on biogas. DCL manufactured catalysts capable of meeting requirements/targets can be provided along with SRT system.	

Blank cells indicate no response supplied

Table 14. Comparison of Survey Results (part 2 of 5)

South Coast Air Quality Management District Contract No. 13432

Comparison of Returned Surveys-2

Company Information			
Company Name	**Venture Engineering**	**CC Jensen**	**Quadrogen Power Systems, Inc.**
Survey Returned	No (information/data below from personal communication)	No	Yes
Contact Name	Kyle Snyder	Axel Wegner	Diego
Contact Title			(778) 371-3059
Contact E-Mail	ksnyder@ventureengr.com	axel@ccjensen.com	sales@quadrogen.com
Contact Phone/fax	412-231-5890	770-692-6001	604-221-7170
Siloxane Treatment System General Information			
Product Name and Type	Biogas Conditioning System	Activated Carbon	Integrated Biogas Clean-up System (IBCS) - Regenerative
When was the product introduced?			2011
Number of Installations - worldwide	5		3
Number of Installations - US	5		2
Number of Installations in AQMD districts (Southern California)	3		1
Number of installations on SCR or NSCR equipped reciprocating engines	5		0 (but a 600-scfm unit will be delivered by January 2014)
Are the sites with SRC/NSCR available for visitation?	Possibly		No
For California applications, what are methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas?			Quadrogen's IBCS removes all sulfur species (including organic sulfurs) to ppb(v) levels, which allows the downstream NOx catalytic converters to operate at highest performance for extended periods of time.
Siloxane Treatment System Technical Information			
Type (Activated carbon, regenerative, etc.)	Regenerative (polymeric resin, mole sieve, activated alumina) + activated carbon polishing bed		Proprietary C3P technology: (condensing, conversion, capture, polish)
System siloxanes removal efficiency (as %, mg/ml, ppm)		90%	<100 ppb(v) total siloxanes, proven for 2 years without media replacement.
Siloxane Throughput (based on 100 mg/m3 inlet	0.58 mg/m^3	10	< 0.10
What other trace biogas components are simultaneously removed along with siloxanes and to what levels?	Can tolerate up to 250 ppm H2S; prefer lower gas inlet temperatures.		All sulfur (including organic species) and chloride species to < 30 ppb(v), VOC to < 25 ppb(V), O_2 < 2.5%
Electrical power or supplemental fuel requirement for regenerative systems.	4-HP blower for supplying hot regeneration air.		Approximately 0.35 kW/scfm electrical power for sub-megawatt class equivalent flow rate (less power consumption for larger flow rate systems)
Does the system require a flare? Flare cost and flare fuel costs.	Yes, 120-V power.		No, all tail gases are combusted internally and their energy is recaptured for process heating.
Regeneration off-gas flow to the flare and hours per day			
Media life (for passive or regenerative systems).	Regenerative media: 1-2 years; Carbon polisher: 6-9 months.		>2 years, demonstrated with 80 scfm of WWTP biogas at OCSD Waste Water Treatment Plant.
What is the system total pressure drop?			
Does the system have siloxanes break-through detection? If so what method?	They are currently testing two siloxane analyzers with dubious results.		No
Does your firm offer media change out, disposal and installation of fresh media?	Yes		Yes
What cleanup system waste disposal management strategy will be used?	If material passes TCLP test, then non-hazardous disposal.		Solid waste is non-hazardous and can be safely landfilled.
Siloxane Treatment System Specifications			
What information is needed for sizing and quoting a system?			Incoming gas and required output gas flow rate, pressure, temperature, dew point, siloxanes, H2S, organic sulfur species, chlorides, and oxygen concentration.
Annualized- or SCFM-basis annualized O&M costs for the following systems:			
200 SCFM	<$29,000		2.5 - 5 ¢/kWh. Varies with input gas
500 SCFM	$29,000		
1000 SCFM	$29,000		
Equipment costs for the following systems:			
200 SCFM	<$500,000 ($30,000 for non-regenerable systems)		Varies: $400,000 - $800,000
500 SCFM	$500,000		$1,200,000 - $1,800,000
1000 SCFM	$500,000		$2,200,000 - $2,800,000
Approx. size and footprint of the physical system			
200 SCFM	10- ft x 24-ft skid		2 skids, 20 ft x 8 ft each
500 SCFM	10- ft x 24-ft skid		3 skids, 20 ft x 8 ft each
1000 SCFM	10-ft x 24-ft skid		4 skids, 20 ft x 8 ft each
Capacity limitations and scalability of the technology			Modular technology is highly suitable for scaling.
How is system removal efficiency affected for a given biogas composition as a function of flow rate?			Purity and removal efficiency unaffected. Energy efficiency improves moderately at larger scales.
Any additional information you would like to include.			Quadrogen IBCS can be tailored to meet many different purity needs, from inexpensive, low-grade protection of ICE components, to ultra-high purity output suitable for fully protecting catalytic processes.
Engine Exhaust Requirements			
Are any of the systems installed on reciprocating engines that are subject to emission requirements (with or without SCR/NSCR)			No

Blank cells indicate no response supplied

Table 15. Comparison of Survey Results (part 3 of 5)

South Coast Air Quality Management District Contract No. 13432

Comparison of Returned Surveys-3

Company Information			
Company Name	**2G Cenergy Power Systems Technologies, Inc**	**Environmental Systems & Composites, Inc. (ESC)**	**Unison Solutions Inc**
Survey Returned	No (below information from personal communication)	Yes	Yes
Contact Name		Jeffrey Wetzel	Adam Klass
Contact Title	Michael J. Turwitt, President & CEO	VP Marketing and Sales	
Contact E-Mail	mturwitt@2g-cenergy.com	jeff@escpure.com	Adam.klaas@unisonsolutions.com -
Contact Phone/fax	904-579-3217	425-497-8111/425-881-3378	563-585-0901
Siloxane Treatment System General Information			
Product Name and Type		ESC CompHeet system	Activated Carbon
When was the product introduced?		2005	Approximately 15 years ago to the industry (1999)
Number of Installations - worldwide	N/A	3	70
Number of Installations - US	N/A	2 (on fuel cells)	69
Number of Installations in AQMD districts (Southern California)	0	1	3
Number of installations on SCR or NSCR equipped reciprocating engines	0	Unknown	**0**
Are the sites with SRC/NSCR available for visitation?		Unknown	
For California applications, what are methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas?			Addition of extra vessels to siloxane removal system to ensure complete removal.
Siloxane Treatment System Technical Information			
Type (Activated carbon, regenerative, etc.)	Activated carbon, non-regenerative	Regenerative Activated Carbon	Activated Carbon
System siloxanes removal efficiency (as %, mg/ml, ppm)		>95%	Removal to less than 100-ppbv total siloxane species
Siloxane Throughput (based on 100 mg/m3 inlet			
What other trace biogas components are simultaneously removed along with siloxanes and to what levels?	Integrated treatment of H_2S + siloxane	Most all condensable VOCs to >95%, plus organic sulfur compounds	VOCs
Electrical power or supplemental fuel requirement for regenerative systems.		35 kW + 1% of gas flow	None, a small pressure drop across the system
Does the system require a flare? Flare cost and flare fuel costs.		No. Self-contained reactor.	None, a small pressure drop across the system
Regeneration off-gas flow to the flare and hours per day		N/A	
Media life (for passive or regenerative systems).		6 months to 1 year	Variable based on design criteria
What is the system total pressure drop?		1.5-2.5 psig	
Does the system have siloxanes break-through detection? If so what method?		No, but being researched.	No, must be done through sampling and lab testing
Does your firm offer media change out, disposal and installation of fresh media?		Yes	Yes
What cleanup system waste disposal management strategy will be used?		Landfill spent iron sponge, regenerate spent carbons.	The spent media can be landfilled or regenerated off site
Siloxane Treatment System Specifications			
What information is needed for sizing and quoting a system?		Gas flow, temperature, pressure, complete detailed gas analysis characterizing all contaminants and gas components.	A gas analysis, flow requirement and type of generation being used.
Annualized- or SCFM-basis annualized O&M costs for the following systems:			
200 SCFM		$25,000 (complete system)	Variable from site to site. (per vendor cut-sheets: $0.65-$1.15/GGE for CNG product)
500 SCFM		$50,000 (complete system)	
1000 SCFM		$100,000 (complete system)	
Equipment costs for the following systems:			
200 SCFM		$1,400,000 to $1,600,000	Unknown
500 SCFM		$1,600,000 to $1,800,000	
1000 SCFM		$2,400,000 to $2,800,000	
Approx. size and footprint of the physical system			
200 SCFM		900-1200 ft^2	6 ft x 12 ft
500 SCFM		1,000-1,4200 ft^2	8 ft x 16 ft
1000 SCFM		1,200-1,600 ft^2	16 ft x 16 ft
Capacity limitations and scalability of the technology	64 - 3,000 kWh (CHP)	Unlimited	Typically fixed bed non-regenerative media siloxane removal systems are limited to about 2,000 scfm or less flow. The systems are scalable through parallel trains and larger vessels.
How is system removal efficiency affected for a given biogas composition as a function of flow rate?		Controls dampen gas flow swings to produce a fairly uniform gas flow and consistent purity.	As flow rate increases the system size must also increase to accommodate the increased flow rate and maintain efficiency through the removal process.
Any additional information you would like to include.			
Engine Exhaust Requirements			
Are any of the systems installed on reciprocating engines that are subject to emission requirements (with or without SCR/NSCR)		We have some systems coming up, but present systems unknown.	No, not in CA but some in other states.

Blank cells indicate no response supplied

Table 16. Comparison of Survey Results (part 4 of 5)

VRONAY ENGINEERING SERVICES — AQMD — gti

South Coast Air Quality Management District Contract No. 13432

Comparison of Returned Surveys-4

Company Information			
Company Name	**Pioneer Air Systems**	**Acrion Technologies**	**Xebec, Inc.**
Survey Returned	Yes	Yes	No
Contact Name	Sam Baseen	Jeff Cook	
Contact Title	President	Vice President	
Contact E-Mail	sam@pioneerair.com	acrion@acrion.com	pgouin@xebecinc.com
Contact Phone/fax	423-404-0760	216-573-1185	
Siloxane Treatment System General Information			
Product Name and Type	Pioneer TCR Refrigeration Gas Dryer and Absorption Skid	CO_2 Wash Process	
When was the product introduced?	1993	First commercial 2008	
Number of Installations - worldwide	25	2	
Number of Installations - US	20	1	
Number of Installations in AQMD districts (Southern California)		0	
Number of installations on SCR or NSCR equipped reciprocating engines		0	
Are the sites with SRC/NSCR available for visitation?		no	
For California applications, what are methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas?	Chilling and Absorption		
Siloxane Treatment System Technical Information			
Type (Activated carbon, regenerative, etc.)	Chill gas to (+35°F to -10°F) and carbon adsorption	Absorption with liquid CO_2 generated from the biogas	They use siloxane removal systems procured from other vendors.
System siloxanes removal efficiency (as %, mg/ml, ppm)	>99% (per cut-sheet: with carbon adsorbers)	99.9%+	
Siloxane Throughput (based on 100 mg/m3 inlet	< 1 ppm	<0.1 ppm	
What other trace biogas components are simultaneously removed along with siloxanes and to what levels?	H_2S, chlorides, fluorides (per Pioneer cut-sheet: also VOCs, NH_3)	Organic sulfur and halogen containing compounds 99.9%+ removal	
Electrical power or supplemental fuel requirement for regenerative systems.		power for compression and refrigeration	
Does the system require a flare? Flare cost and flare fuel costs.	No	24hr, 90+% CO2, 2-7% CH4	
Regeneration off-gas flow to the flare and hours per day			
Media life (for passive or regenerative systems).	6 to 12 Months	Infinite	
What is the system total pressure drop?			
Does the system have siloxanes break-through detection? If so what method?	No	No	
Does your firm offer media change out, disposal and installation of fresh media?	Yes	Media not required	
What cleanup system waste disposal management strategy will be used?	Carbon re-cycling, low temp chilling reduces carbon usage	Flare or thermal oxidizer	
Siloxane Treatment System Specifications			
What information is needed for sizing and quoting a system?			
Annualized- or SCFM-basis annualized O&M costs for the following systems:			
200 SCFM	$8,000 (total power usage of 20 kW: 10 kW for TCR10 unit + 10 kW gas blower with after cooler)	6 kWhr/MCF	
500 SCFM	$20,000 (total power usage of 50 kW: 25 kW for TCR25 unit + 25 kW gas blower with after cooler)	6 kWhr/MCF	
1000 SCFM	$40,000 (total power usage of 100 kW: 50 kW for TCR50 unit + 50 kW gas blower with after cooler)	6 kWhr/MCF	
Equipment costs for the following systems:			
200 SCFM	$150,000	$800,000	
500 SCFM	$250,000	$1,400,000	
1000 SCFM	$350,000	$2,000,000	
Approx. size and footprint of the physical system			
200 SCFM	4 ft x 6 ft x 8 ft	30 ft x 50 ft	
500 SCFM	6 ft x 8 ft x 8 ft	30 ft x 50 ft	
1000 SCFM	8 ft x 12 ft x 8 ft	40 ft x 60 ft	
Capacity limitations and scalability of the technology		Minimum economic size 200-300 scfm	
How is system removal efficiency affected for a given biogas composition as a function of flow rate?	Exceeding rated capacity will reduce design efficiency	Not affected	
Any additional information you would like to include.		Used with turbocharged IC engines, gas turbines, CNG + LNG production	
Engine Exhaust Requirements			
Are any of the systems installed on reciprocating engines that are subject to emission requirements (with or without SCR/NSCR)	Yes	No	

Blank cells indicate no response supplied

Table 17. Comparison of Survey Results (part 5 of 5)

South Coast Air Quality Management District Contract No. 13432

Comparison of Returned Surveys-5

Company Information			
Company Name	**Guild Associates, Inc.**	**Theia Air**	**Nrgtek Inc.**
Survey Returned	Yes	No (below information from personal communication with Theia Air)	Yes
Contact Name	Mike Mitariten / Brent Siebeneck	George Federico	Subra Iyer
Contact Title	Sales Engineer (Brent Siebeneck)		President
Contact E-Mail	mike@moleculargate.com / bsiebeneck@guildassociates.com	www.Theia-Air.com	siyer@nrgtekusa.com
Contact Phone/fax	908-752-6420 / 614-649-3222	888-330-2260	714-279-9190
Siloxane Treatment System General Information			
Product Name and Type	Molecular Gate & Siloxasorb	TA-BG3, TA-SV (standard non-regenerable media)	Siloxane Removal System
When was the product introduced?	2002		2012
Number of Installations - worldwide	61		1
Number of Installations - US	58	6	1
Number of Installations in AQMD districts (Southern California)	None	0	1
Number of installations on SCR or NSCR equipped reciprocating engines	None	0	(one proposed)
Are the sites with SRC/NSCR available for visitation?			Yes, after 2015
For California applications, what are methods to achieve future emission limits of SCAQMD Rule 1110.2 for ICE operating on biogas?	The Guild systems can be designed and have demonstrated removal of siloxanes to non-detectable levels		
Siloxane Treatment System Technical Information			
Type (Activated carbon, regenerative, etc.)	Proprietary regenerative adsorbent	Activated carbon (normally non-regenerable but regenerable media offered)	Continuous liquid scrubber with nanofiltration (NF)/pervaporation (PV)
System siloxanes removal efficiency (as %, mg/ml, ppm)	The Guild systems can be designed and have demonstrated removal of siloxanes to non-detectable levels (see also Attachment A cut-sheets for details)		99.99% to <1ppmv
Siloxane Throughput (based on 100 mg/m^3 inlet	Up to 100%		
What other trace biogas components are simultaneously removed along with siloxanes and to what levels?	Optional designs include removal of VOC, H_2S and other sulfur and water vapor.	H_2S, VOCs	
Electrical power or supplemental fuel requirement for regenerative systems.	Varies		5 kW for pumps, etc.
Does the system require a flare? Flare cost and flare fuel costs.	Yes, In most cases the flares or thermal oxidizers are designed to be self-sustaining		No
Regeneration off-gas flow to the flare and hours per day	Varies with feed gas and design.		N/A
Media life (for passive or regenerative systems).	Media is regenerated and has lasted over 10 years in commercial operation.		5 years for membranes
What is the system total pressure drop?	Typically 5 psid		Negligible
Does the system have siloxanes break-through detection? If so what method?	Where desired by the customer, siloxane analysis can be provided.		No
Does your firm offer media change out, disposal and installation of fresh media?	Yes, as part of field service.		N/A
What cleanup system waste disposal management strategy will be used?	Reject gas is flared.	Self-emptying vessels, on-and off-site regeneration offered.	N/A
Siloxane Treatment System Specifications			
What information is needed for sizing and quoting a system?	Feed pressure, flow, and gas composition. Required downstream pressure, flow and composition.		Input level of siloxanes and H_2S and LFG/DG flow rates, pressures
Annualized- or SCFM-basis annualized O&M costs for the following systems:			
200 SCFM	Typically only power with minimal maintenance cost. Varies with design.		$15,000
500 SCFM	Typically only power with minimal maintenance cost. Varies with design.		$20,000
1000 SCFM	Typically only power with minimal maintenance cost. Varies with design.		$35,000
Equipment costs for the following systems:			
200 SCFM	Proprietary	<$50,000 (for non-regenerable systems)	$150,000
500 SCFM	Proprietary		$250,000
1000 SCFM	Proprietary		$500,000
Approx. size and footprint of the physical system			
200 SCFM	Varies, typically 8 ft by 50 ft		5 ft x 10 ft
500 SCFM	Varies, typically 8 ft by 75 ft		10 ft x 10 ft
1000 SCFM	Varies, typically 8 ft by 100 ft		15 ft x 20 ft
Capacity limitations and scalability of the technology	None	20-20,000 CFM	None. Technology scalable to 10,000 SCFM
How is system removal efficiency affected for a given biogas composition as a function of flow rate?	Unaffected		
Any additional information you would like to include.			
Engine Exhaust Requirements			
Are any of the systems installed on reciprocating engines that are subject to emission requirements (with or without SCR/NSCR)	None to date		

Blank cells indicate no response supplied

APPENDIX C

SITE VISIT TRIP REPORTS

SITE VISIT TRIP REPORT:
EAST BAY MUNICIPAL UTILITY DISTRICT GENERATION STATION

An activated carbon system was installed at East Bay Municipal Utility District WWTP in Oakland, CA, by Environmental Systems & Composites, Inc. (ESC). The system was designed to process 4,000 SCFM of biogas removing both moisture and siloxane. The plant was producing 8.5 MW and flaring approximately 300 SCFM of biogas the day of the site visit. The generating equipment consisted of a Solar 4.5-MW turbine and three Enterprise 6-cylinder dual-fuel engines each producing 2.1 MW.

The biogas from the digesters is extracted with a large blower (Figure 13) that discharges into the moisture removal chilling unit. This unit utilizes a refrigeration system to lower the gas temperature to below the dew point in order to condense out the water. The dry gas then passes into the siloxane removal system (Figure 14). This system consists of two sets to two canisters. The gas is designed to pass through a series of canisters which remove the siloxane. Siloxane content is monitored between these two canisters until it exceeds a design limit. When the carbon in the first of these two canisters is expended and no longer capable of removing the design amount of siloxane the pair is removed from service for media renewal, and the offline pair of canisters are placed in service. The canisters removed from service will have their media replaced with fresh activated carbon and be returned to service when the media is consumed in the other pair of canisters.

Figure.13. Biogas Compressor at East Bay MUD

The original design of the canisters called for media change out every four months. Gas testing has extended this interval to around six months with the current gas flow and siloxane content levels. Each of these media replacements costs $150,000 for the pair of canisters, for an approximate total of $300,000 in annual media replacements costs.

Figure 14. Siloxane Canisters at East Bay MUD

SITE VISIT TRIP REPORT:
OX MOUNTAIN LANDFILL POWER GENERATION FACILITY

On February 24, 2014, Vronay Engineering Services Corp. (VES) engineers visited the Ameresco-operated Ox Mountain landfill power generation facility, a biogas-fueled, reciprocating engine power plant in Half Moon Bay, California. The purpose of the site visit and inspection was to observe firsthand the reported efficacy of the landfill gas cleanup system in place at the facility as well as to discuss problems and successes with the power station personnel.

Rationale for Selecting Ox Mountain Site

Ox Mountain is one of the few sites that had the combination of the four primary interests of the instant study:

1. Moderately-sized, lean-burn reciprocating engines typical of biogas-fueled sites.
2. A Selective Catalytic Reduction (SCR) system for oxides of nitrogen (NOx) remediation.
3. A reportedly effective gas cleanup system.
4. In operation for more than four years and logging approximately 40,000 operating hours.

Site Specifications

The Ox Mountain landfill is located in the city of Half Moon Bay, CA, in an exclusive area overlooking the Pacific Ocean; it is surrounded by a number of expensive estates and prized tourist attractions including many well-known wineries. Because the cogeneration plant is located close to tourism and agribusiness centers, the emissions were required to be at minimum levels. The facility is within the jurisdiction of the Bay Area Air Quality Management District (BAAQMD), which sets very strict limits on the engines and facility due to the sensitivity of the region. The following map indicates the location of the site (Figure 15).

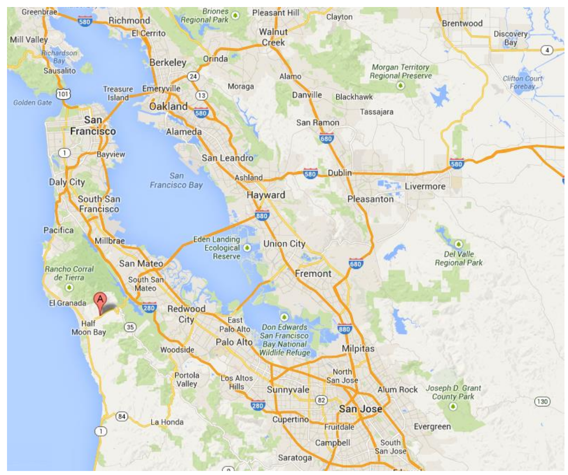

Figure 15. Ox Mountain Site Location Indicated by "A"

Power Generation Equipment

The site consists of six identical Jenbacher model series 616, spark-ignited engines rated at 1996 kW at 1500 RPM (Figure 16). The engines are each fitted with 1.2:1 ratio speed increasers to permit them to drive AVK synchronous generators at 1800 RPM (60 Hz). The engine specifications appear in Table 18. All the engines are fitted with Miratech oxidation catalysts. One engine (Unit #1) is fitted with both an oxidation catalyst and a Miratech SCR catalyst. The unit shown in Figure 17 was originally installed as a test case for BAAQMD and was monitored with a CEMS (continuous emissions monitoring system) for the first year to assess the efficacy of the technology. Plant personnel reported this was a success, although the CEMS is no longer monitored or used.


Figure 16. View of Engines from the Generator-End

Table 18. Engine Specifications

Parameter	Value
Manufacturer	GE Jenbacher
Model Number	G616GSE22
Configuration	60°vee
Bore (mm)	190
Stroke	220
Displacement Per Cylinder (liters)	6.24
Rotative Speed (RPM)	1500
Mean Piston Speed (m/s)	11 @ 1500 RPM
No. of Cylinders	16
Total Engine Displacement (liters)	99.8
Combustion Type	Spark-ignited, pre-chambered, lean-burn
Aspiration	2-stage turbocharged
Rated Power Output (kW)	1996
Current Operating Hours	≈40,000
Fuel Gas Consumption at 100% Load	600 SCFM

Figure 17. View of Exhaust System of the One Unit

(this unit previously included both oxidation and SCR catalysts)

Landfill Gas Treatment System

The overall gas cleanup system at this facility, originally designed and installed by GE Jenbacher[14], is extensive and without parallel in comparison to anything else seen in this study or by the project team. The main system is a flooded-type, Temperature Swing Absorption (TSA) fuel-gas regenerative, carbon-type consisting of 16 large canisters arranged in two banks of eight cylinders each and is capable of treating as much as 3,600 SCFM of landfill gas. Upstream of the canisters are numerous moisture dropout legs, passive filters, refrigeration drying and other in-line, passive filters and drip traps (Figure 18).

The system is extraordinarily complex and is monitored and controlled by a sophisticated SCADA (supervisory control and data acquisition) system also furnished by GE Jenbacher. Figures 19-21 show screenshots of this system. As can be seen by the SCADA system graphics, the overall system includes blowers for regeneration, a dedicated flare for the "dirty" gas, and numerous appurtenances including a special tank to which liquid hydrocarbon compounds are drained, collected, and shipped offsite (out of California) for special disposal.

Eight of the 16 canisters are in a regenerative mode at any given time, using a modest amount of fuel gas as part of the regenerative process and remaining offline while the other eight canisters are online treating the already dry fuel gas. The 16 canisters have a capacity of about 44,000 lbs. of carbon.

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[14] GE Jenbacher no longer offers gas cleanup systems and could not provide any pricing data on this system.

Figure 18. Overview of a Portion of the Gas Treatment System
(arrows indicate the two eight-canister banks)

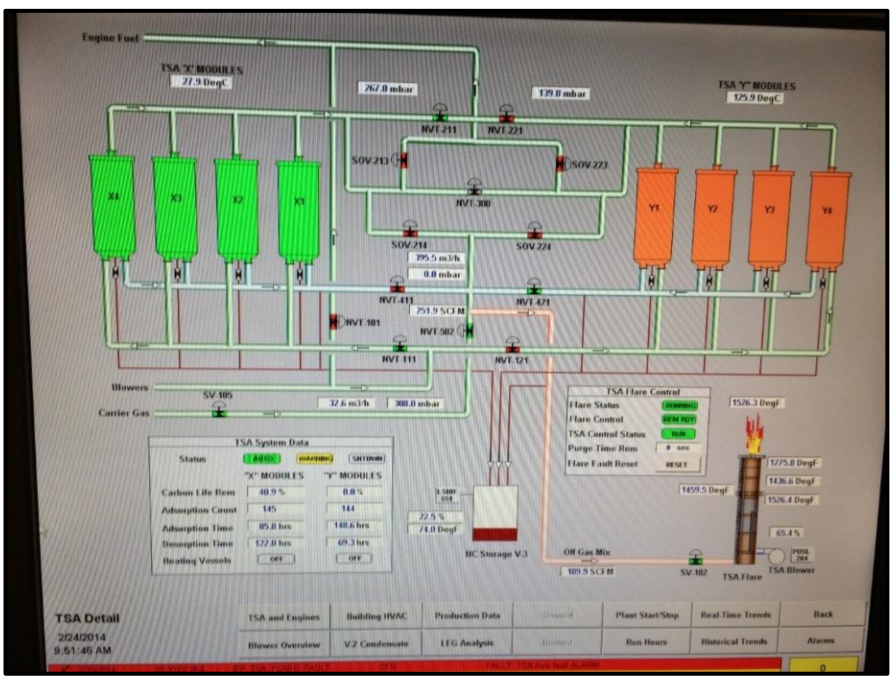

Figure 19. General Overview Screen Showing Simplified System Layout

(Note that only four of each of the eight bank canisters are displayed for clarity)

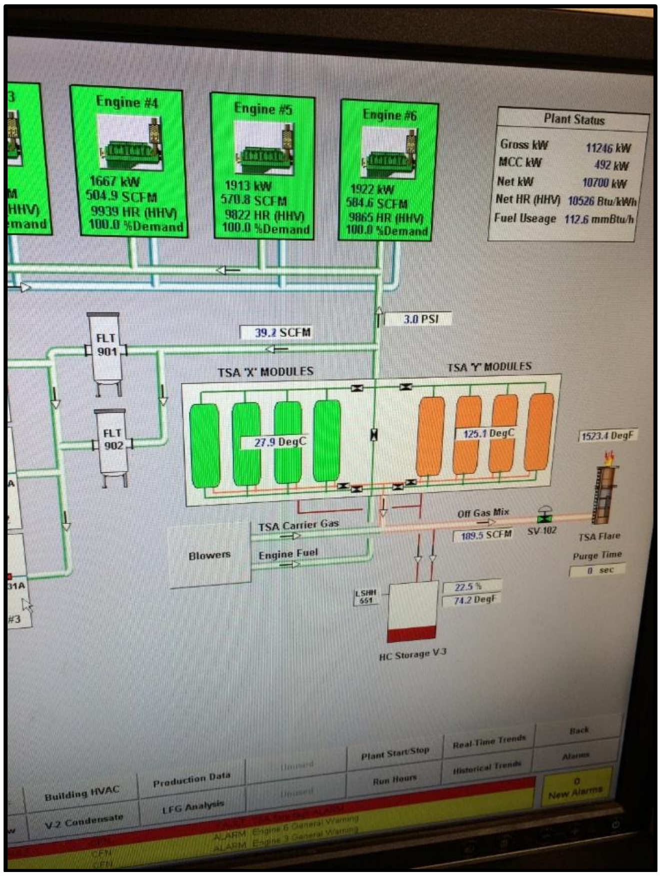

Figure 20. Screen Indicating Details of the Regenerative Blowers and System (Note the "carrier gas" is combusted in a dedicated flare)

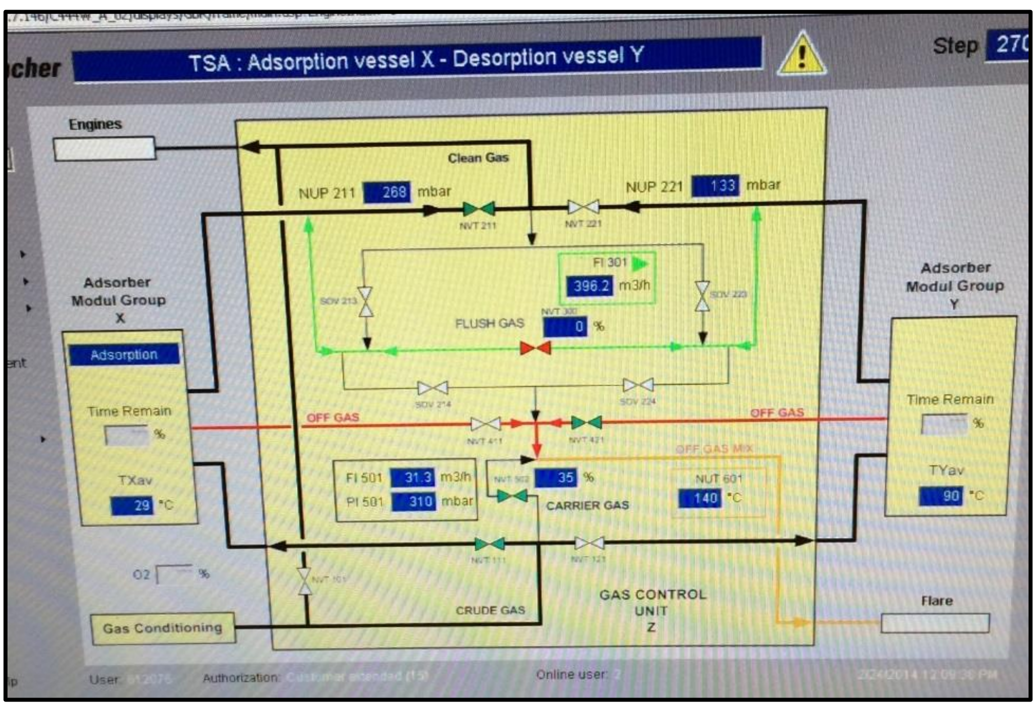

Figure 21. Graphic Display Screen for the Status of the Various Gases through the Two Eight-Canister Banks

For the carbon change out the entire plant is shut down and all 16 canisters are changed out at the same time, which requires about 5 hours. The canisters are the flooded-type, meaning that during all operating modes they remain flooded with a purge gas. A separate stream of carrier gas containing the contaminants from the carbon media is sent to a dedicated flare to consume the gas and destroy siloxanes, VOCs and other contaminants. Total gas sent to the flare is ≈190 SCFM or about 5% of the total cleaned gas produced. The large canisters are each fitted with a series of electric immersion heaters that heat the carbon media during the regeneration process to facilitate contaminant dispersal / removal and media renewal.

Discussion

Efficacy of the Gas Cleaning System

Although plant personnel initially spent a year or more resolving various problems, subsequently the system appears to have been remarkably effective. In fact, the plant has not experienced any significant contaminant-induced catalyst failures, and personnel are just now preparing to perform their first engine overhaul. This is a natural-gas-level of engine maintenance service interval (~40,000 hours) and reflects the effectiveness of the cleanup apparatus as well as the plant personnel foreman who from the time of the system's installation and commissioning has become an expert in its optimal operation.

A summary of the recent analytical results for three gas samples collected from January to December 2013 (Table 19) shows the concentrations of the various contaminants in the untreated raw landfill gas and the treated gas and their removal efficiencies obtained by the cleanup system. For the two June and December 2013 samples, total siloxane removal efficiencies were indicated to be 99.7 and 100%, or a reduction from 6,000 and 12,000 ppbv total siloxanes in the raw gas to 2.4 and 16 ppbv in the treated gas. For H_2S, removal efficiencies were 68 and 88%, or a reduction from 98 and 92 ppmv in the raw gas to 12 and 27 ppmv in the treated gas.

Costs

Ameresco was unable to provide the project team with either the capital or installation costs of the system. Judging by the amount of equipment, however, it is estimated to be well over $1,000,000. On average, the plant replaces about 44,000 lbs of carbon annually at a cost of about $100,000 (includes media removal and disposal). BakerCorp (CA) supplies the VP-60 Virgin 60 CTC activated carbon used in the plant. The carbon is typically sent for regeneration if it is non-hazardous. If the media comes back as hazardous (typically if there are high benzene concentrations), then it can be sent to a landfill for disposal or to a landfill for use in a fuel burning process. The plant is currently evaluating hazardous reactivation options as well, but it is not currently done. The disposal cost is $330 per truckload of approximately 20,000 lb; hazardous disposal costs will vary depending on the composition of the media.

Other annualized costs include the disposal of the collected condensate "hydrocarbons" (content unknown by the plant) and overall maintenance costs, both of which Ameresco considered proprietary information. In consideration of the overall effectiveness of the system, the annualized maintenance costs seem reasonable compared to engine maintenance costs without siloxane removal considering the long engine maintenance interval achieved by the facility and the long life of both the oxidation and the SCR unit.

Table 19. Summary of the Recent Analytical Results at Ox Mountain Landfill, Halfmoon Bay, CA

AccuLabs, Inc.

Air Toxic • Contaminated Soil • Water and Wastewater • Industrial and Hazardous Waste • Chemical Consultation

Date: January 18, 2014
To: Mr. S. Simmons, Mr. T. Miller and Mr. N. Hall, AMERESCO
From: E. Hsue, AccuLabs, Inc.

Summary of the Analytical Results at Ox Mountain Landfill, Halfmoon Bay, California

< Comparison of Results for the Major Components Detected for the Samples Collected on January 15, June 28 and December 31, 2013>

Client ID / AccuLabs ID / Month & Year of Monitoring	Untreated Raw Gas 13010011-01 Jan. 15, 2013	Untreated Raw Gas 13070008-01 June 28, 2013	**Untreated Raw Gas 14010001-01 Dec. 31, 2013**	None <Not Collected> Jan. 15, 2013	Treated Gas 13070008-02 June 28, 2013	**Treated Gas 14010001-02 Dec. 31, 2013**	% Change or Removal From Untreated to Treated Gas Jan. 15, 2013	% Change or Removal From Untreated to Treated Gas June 28, 2013	**% Change or Removal From Untreated to Treated Gas Dec. 31, 2013**
Major Fixed Gases		Conc. in % & ppMV			Conc. in % & ppMV				
Oxygen	0.987%	0.967%	**0.80%**	NS ** Note 2	0.94%	**0.79%**	NA * Note 1	NA	NA
Nitrogen	11.5%	6.16%	**7.73%**	NS	6.01%	**9.00%**	NA	NA	NA
Methane	32.5%	60.7%	**59.7%**	NS	61.3%	**58.9%**	NA	NA	NA
Carbon Dioxide	54.5%	32.0%	**31.6%**	NS	31.5%	**31.1%**	NA	NA	NA
Carbon Monoxide	<25 ppmV	<25 ppmV	<25 ppmV	NS	<25 ppmV	<25 ppmV	NA	NA	NA
Major Sulfur Compds	Conc. In ppMV				Conc. In ppMv				
< Effective Removal>:									
Hydrogen sulfide	248	98.2	**92.4**	NS	11.8	**26.8**	NA	88.0%	71.0%
Methanethiol (Methyl Mercaptan)	5.39	1.82	**2.00**	NS	<0.002	**2.91**	NA	99.9%	99.9%
Dimethyl sulfide	0.837	1.20	**2.88**	NS	0.003	**1.46**	NA	99.8%	49.3%
Dimethyl disulfide	0.293	0.485	**0.573**	NS	<0.002	**0.019**	NA	99.6%	99.7%
Total Sulfur with Others in ppmV	255	103	**100**	NS	11.9	**31.6**	NA	88.4%	68.4%
TGNMNEO		Conc. In ppMv			Conc. In ppMv				
< Effective Removal>:									
as Methane - TOC	2,270	762	**1,470**	NS	131	**220**	NA	82.8%	85.0%
Major VOCs Compds (Part I)		Conc. In ppbv			Conc. In ppbv				
< Effective Removal>:									
Acetone	7,830	8,510	**7,900**	NS	407	**1,690**	NA	95.2%	78.6%
Benzene	1,190	797	**1,070**	NS	13.7	**85.4**	NA	98.3%	92.0%
Heptane	3,110	1,480	**2,770**	NS	36.9	**20.9**	NA	100%	100%
Hexane	438	436	**2,080**	NS	3.07	**41.5**	NA	100%	100%
Toluene	7,850	2,300	**4,460**	NS	287	**45.1**	NA	87.5%	99.0%
Total Xylenes (o-,m-, & p-)	5,110	3,160	**5,090**	NS	921	**69.5**	NA	70.9%	98.6%
Ethylbenzene	2,780	1,450	**3,200**	NS	261	**14.9**	NA	82.0%	99.5%
Tetrahydrofuran	3,420	1,970	**4,780**	NS	13.3	**2,460**	NA	99.3%	48.5%
iso-Propylbenzene (Cumene)	903.0	1,830	**2,160**	NS	211	**3.12**	NA	88.5%	99.9%
Cyclohexane	595	396	**833**	NS	<0.23	**260**	NA	99.9%	100.0%
Naphthalene	<2.0	70.8	**238**	NS	<0.21	<0.21	NA	99.7%	99.9%

** Note 1 for "NA": Not Applicable*
*** Note 2 for "NS": No Sample Was Collected for this Quarterly Monitoring*

AccuLabs, Inc.

Air Toxic • Contaminated Soil • Water and Wastewater • Industrial and Hazardous Waste • Chemical Consultation

Date: January 18, 2014
To: Mr. S. Simmons, Mr. T. Miller and Mr. N. Hall, AMERESCO
From: E. Hsue, AccuLabs, Inc.

Summary of the Analytical Results at Ox Mountain Landfill, Halfmoon Bay, California

< Comparison of Results for the Major Components Detected for the Samples Collected on January 15, June 28 and December 31, 2013>

Client ID / AccuLabs ID / Month & Year of Monitoring	Untreated Raw Gas 13010011-01 Jan. 15, 2013	Untreated Raw Gas 13070008-01 June 28, 2013	**Untreated Raw Gas 14010001-01 Dec. 31, 2013**	None <Not Collected> Jan. 15, 2013	Treated Gas 13070008-02 June 28, 2013	**Treated Gas 14010001-02 Dec. 31, 2013**	% Change or Removal From Untreated to Treated Gas Jan. 15, 2013	% Change or Removal From Untreated to Treated Gas June 28, 2013	**% Change or Removal From Untreated to Treated Gas Dec. 31, 2013**
Major VOCs Compds (Part II)		Conc. In ppbv			Conc. In ppbv				
< Effective Removal>:									
Tetrachloroethyene (PCE)	123	164	**413**	NS ** Note 2	8.47	<0.21	NA	94.8%	99.9%
Trichloroethene (TCE)	133	96.5	**267**	NS	1.65	**8.74**	NA	98.3%	96.7%
cis-1,2-Dichloroethene	140	76.8	**468**	NS	<0.19	**320**	NA	100%	100%
Ethyl acetate	2,750	1,640	**3,200**	NS	15.3	**1,090**	NA	99.1%	65.9%
Methyl isobutyl ketone (MIBK)	618	377	**808**	NS	5.40	<0.57	NA	98.6%	99.9%
2-Propanol (IPA)	8,140	8,840	**23,500**	NS	32.0	**13,600**	NA	100%	42.1%
2-Butanone (MEK)	9,880	3,640	**7,850**	NS	84.9	**1,960**	NA	97.7%	75.0%
Styrene	152	136	**527**	NS	34.7	<0.15	NA	74.5%	100%
Ethanol	33,400	33,800	**87,100**	NS	16,500	**47,800**	NA	51.2%	45.1%
<Ineffective Removal>:									
Methylene chloride	196	41.5	**492**	NS	21.0	**14.4**	NA	49.4%	97.1%
Propylene	8,710	3,160	**13,300**	NS	1,670	**11,900**	NA	47.2%	10.5%
Dichlorodifluoroethane (F12)	405	336	**742**	NS	320	**519**	NA	4.76%	30.1%
<Completely Break Through>:									
Vinyl chloride	106	71.4	**295.0**	NS	77.2	**136**	NA	-8.12%	53.9%
< Effective Removal>:									
Major Siloxane Compounds	Conc. In ppbv				Conc. In ppbv				
Trimethyl silane	<0.01	<0.01	<0.01	NS	<0.01	<0.01	NA	NA	NA
Trimethyl silanol (TMS)	3,860	3,400	**9,890**	NS	5.51	<0.01	NA	100%	100%
Hexamethyldisiloxane (L2)	898	915	**858**	NS	1.86	**4.34**	NA	100%	99.5%
Hexamethylcyclotrisiloxane (D3)	266	231	**230**	NS	2.03	**0.46**	NA	100%	100%
Octamethyltrisiloxane (L3)	31.8	28.3	<0.01	NS	0.45	<0.01	NA	100%	NA
Octamethylcyclotetrasiloxane (D4)	406	282	**607**	NS	2.65	**1.52**	NA	99.1%	100%
Decamethyltetrasiloxane (L4)	8.74	4.73	**11.7**	NS	0.35	<0.01	NA	92.6%	100%
Decamethylcyclopentasiloxane (D5)	1,460	1,130	**567**	NS	13.1	**0.89**	NA	98.8%	100%
Dodecamethylpentasiloxane (L5)	<0.01	<0.01	<0.01	NS	<0.01	<0.01	NA	NA	NA
Dodecamethylcyclohexasiloxane (D6)	<0.01	<0.01	<0.01	NS	<0.01	<0.01	NA	NA	NA
Total Siloxanes in ppbV	6,931	5,963	12,164	NS	16.1	2.41	NA	99.7%	100%
Total Siloxanes in ppmV	6.93	5.96	12.2	NS	0.016	0.0024	NA	99.7%	100%

** Note 1 for "NA": Not Applicable*
*** Note 2 for "NS": No Sample Was Collected for this Quarterly Monitoring*

Applicability to POTW
In view of the cost of installation, complexity and maintenance of this operation, including the automation and monitoring equipment, this system may be unsuitable and not cost effective for smaller biogas engine operators and many POTW affected if current SCAQMD Rule 1110.2 natural gas level emissions are flowed down to their existing digester gas- or landfill gas-fueled engines. Less complex systems already exist in the market, although none has as yet demonstrated comparable effectiveness.

Additional Observations
The facility reported that as the on-line gas cleanup/filter bank became fouled, the performance of the oxidation catalysts dropped off rapidly–presumably due to fouling / masking of the media by the dirtier gas. However, when the cleaned cleanup bank is shifted on-line and cleaner gas is once again flowing to the engines, the oxidation catalysts "regenerate" and return to their original reduction effectiveness. This is an interesting phenomenon that is worthy of note to operators with similar systems, i.e., that the clean gas can be used to effectively regenerate the oxidation catalysts.

Conclusions

1. The gas cleanup system at Ox Mountain has demonstrated effectiveness adequate to remove siloxanes and other landfill gas contaminants to levels enabling the use of an SCR catalyst.
2. The gas pre-treatment + SCR has been determined to be achieved in practice BACT for NOx, as shown in Table 20, as per Bay Area AQMD.
3. Tremendous manpower and effort are required to operate, maintain and repair the system equipment to ensure that it operates successfully.
4. Due to the cost, size and complexity of this system, it may not be cost effective for smaller POTW operators such as those currently operating within the SCAQMD. Other, less complex systems already exist in the market, though none of those have as yet demonstrated comparable effectiveness.

Table 20. BACT Determination for the Ox Mountain Landfill Power Generation Facility (Ameresco Half Moon Bay)

Reference: http://hank.baaqmd.gov/pmt/bactworkbook/96-2-4.pdf

BAY AREA AIR QUALITY MANAGEMENT DISTRICT
Best Available Control Technology (BACT) Guideline

Source Category

Source:	**IC Engine – Biogas Fired**	**Revision:**	**1**
		Document #:	**96.2.4**
Class:	**≥ 50 Hp Output**	**Date:**	**5/30/2013**

Pollutant	BACT 1. Technologically Feasible/Cost Effective 2. Achieved in Practice	TYPICAL TECHNOLOGY
POC	1. 0.12 g/bhp-hr [a, c, e, f, g, k] 2. 0.16 g/bhp-hr [i, k]	1. Gas Pre-Treatment (filtration, refrigeration & carbon adsorption) + Oxidation Catalyst [a, c, e, f, g, k] 2. Low POC Waste Gas or Gas Pre-Treatment or Gas Pre-Treatment + Oxidation Catalyst [i, k]
NO_x	1. n/s 2. 0.15 g/bhp-hr [a, c, d, e, f, g, i, j, l]	1. Gas Pre-Treatment + Selective Catalytic Reduction (SCR) [f, g, l] 2. Gas Pre-Treatment + Selective Catalytic Reduction (SCR) [a, c, d, f, i, j, l] or NOxTech [e, i, j]
CO	1. 0.89 g/bhp-hr [b, c, f] 2. 1.8 g/bhp-hr [a]	1. Gas Pre-Treatment + Oxidation Catalyst [b, c, f] 2. Gas Pre-Treatment + Oxidation Catalyst [a]
SO_2	1. 100 ppmv of total sulfur in Biogas [c, g] 2. 150 ppmv of total sulfur in Biogas [a, b, h]	1. Low Sulfur Biogas [c] or Gas Pre-Treatment with >80% H_2S Removal [g] 2. Low Sulfur Biogas or Gas Pre-Treatment [a, b, h]
PM_{10}	1. 0.07 g/bhp-hr [b] 2. 0.10 g/bhp-hr [a, c]	1. Gas Pre-Treatment (filtration and condensation) [b] 2. Gas Pre-Treatment [a, c]
NPOC	1. n/d 2. n/s	1. n/d 2. Same as POC

References and Notes for BACT Determination

a. BAAQMD Application # 12649 (Ameresco Half Moon Bay, LLC)
b. BAAQMD Application # 23333 (Potrero Hills Energy Producers)
c. BAAQMD Application # 24388 (Zero Waste Energy)
d. San Joaquin Valley APCD: Ameresco Foothill and Forward Energy Projects
e. San Joaquin Valley APCD: Cambrian Energy Woodville, LLC Energy Projects
f. South Coast AQMD: Orange County Sanitation District Demonstration Project
g. Georgia Dept. of Natural Resources: MAS ASB Cogen, LLC CHP Facility
h. South Coast AQMD: Rule 431.1, amended 6/12/98.
i. South Coast AQMD: Rule 1110.2, Table III-B, amended 9/7/12.
j. San Joaquin Valley APCD: Rule 4702, Table 2, amended 8/18/11.
k. Formaldehyde is both a POC and a toxic air contaminant (TAC) and is typically the largest contributor to the health risks resulting from biogas fired engines. Oxidation catalysts typically achieve 50% or greater control of formaldehyde emissions. Use of an oxidation catalyst will satisfy the Regulation 2-5-301 TBACT requirement.
l. For SCR systems, ammonia emissions are typically limited to an exhaust concentration 10 ppmv of NH_3 at 15% O_2 or less. [c, f]

SITE VISIT TRIP REPORT:
CHIQUITA CANYON LANDFILL POWER GENERATION FACILITY

On April 29, 2014, Vronay Engineering Services Corp. (VES) visited the Ameresco-operated Chiquita Canyon landfill power generation facility, a biogas-fueled, turbine power plant in Castaic, California. The purpose of the site visit and inspection was to see firsthand the reported efficacy of the gas cleanup system in place as well as discuss problems and successes with power station personnel.

Rationale for Selecting Chiquita Canyon Site

Chiquita Canyon has the combination of the three primary interests of the instant study:

1. Biogas-fueled prime movers (moderate-sized turbines).
2. A gas cleanup system with reported effectiveness of at least 99%.
3. In operation for more than three years.

About the Site

The Chiquita Canyon landfill is located in the city of Castaic about 45 minutes northwest of Los Angeles and minutes from the popular tourist attraction, "Magic Mountain." Because the cogeneration plant (Figure 22) is located close to tourism, the emissions limits were required to be at BACT levels. The facility is within the jurisdiction of the South Coast Air Quality Management District (SCAQMD), which set very strict limits on the engines and facility due to the sensitivity of the region. The power plant generates enough electricity to power 10,000 homes per year from landfill gas alone.

Figure 22. Overview of Chiquita Canyon Power Generation Facility

Power Generation Equipment

Two Mercury-50 Solar Turbine generator sets are located onsite. Each turbine engine is capable of producing 4600 kW, entirely off of landfill gas. The Mercury-50 gas turbine is a single-shaft

axial flow engine. It incorporates a 10-stage split case compressor, two-stage turbine assembly, Reduction Gearbox with accessory drive pads and self-contained lube oil system. The airflow rate is approximately 14,000 SCFM at a temperature of 1,200°F. The turbines, however, are not fitted with either an Oxidation Catalyst or Selective Catalytic Reduction (SCR) system.
The gas turbine fuel injector sets are rotated every three months. One set consists of eight injectors, which are sent to Solar Turbines for cleaning at a cost of $87,000 per set. The turnaround time for the cleaning is three weeks. The replacement cost of one injector is $30,000. The turbines are brought online at a set point of 200 kW and are increased in 500-kW increments every two minutes. During startup, the NOx Raw maximum limit is 18.75 ppm for 15 minutes, while the average NOx Raw is 4.3 ppm with an approximate load of 3250 kW.

Landfill Gas Treatment System

Siloxane Removal

Siloxane removal is provided by a Parker/Dominick Hunter system. The system incorporates four vessels (Figure 23), each containing 12,000 pounds of media made up of a combination of aluminum oxide and molecular sieve, and two vessels located downstream from the four vessels. The two downstream vessels previously contained carbon that has since been removed due to excessive organic fouling; the gas is now free-flowing through the two tanks. The system controller is shown in Figure 24.

Three of the media-containing vessels are in operation at one time while the fourth undergoes regeneration. Each vessel will remain online for 36 hours before entering the cleaning cycle. The six-hour cleaning cycle is comprised of a 10-step process that is performed to regenerate the media. The media is regenerated by evacuating the vessel of gas and supplying heated air to the vessel, which enables the siloxane to desorb at 400°-450°F. The siloxane-containing gas is then piped to the VOC flare to be combusted. An air purge system cools the media in the vessel. Once the regeneration cycle has completed, the vessel is placed back online and another vessel starts the automatic process, ensuring fresh media is continuously available to clean the landfill gas. An initial investment of approximately $150,000 was required to determine the cleaning cycle procedure by taking samples every eight hours.

Condensate System

The gas goes through many stages of compression, filtration and cooling as it flows through the plant. At each stage, the condensate is being captured through an integrated series of piping that leads to Separator V-101A (Figure 25), where it collects due to vacuum pressure. From vessel V-101A, the condensate is gravity fed to condensate holding tank V-120 (Figure 26). Within vessel V-120, there are two submersible pumps activated by level switches. When the level of the condensate activates a switch, a pump will turn on, pumping condensate to the main flare.

Figure 23. General Setup of Vessels for the Siloxane Removal System
(Four vessels are incorporated into the system)

Figure 24. Parker Siloxane Removal System Control Panel

Figure 25. V-101A Separator Tank


Figure 26. V-120 Condensate Holding Tank

Compression System

There are two Vilter Single Screw Compressors (Figure 27). These are positive displacement, capacity and volume-controlled, oil-flooded rotary compressors that supply compressed landfill gas to the two Mercury-50 turbines onsite. Each compressor is capable of producing a discharge pressure of 2,022 SCFM of gas flow at 305 PSIG. The typical operating set point is 255 psi for 1,500 SCFM. The VSG-2101 incorporates a Toshiba motor, heat exchanger and air-cooled glycol system.

Figure 27. Gas Compressors Arrangement

The VSG-2101 is coupled to a Toshiba 800 HP 4160 VAC motor. The Toshiba motor houses two bearings, each with a 100-Ohm platinum-bearing RTD. The windings of the motor are monitored by six 100-Ohm platinum RTDs as well, two per phase. A Shell Tube Heat Exchanger is mounted to each compressor. Its purpose is to cool the discharge oil by the use of glycol. The glycol is circulated by a 10-hp centrifugal pump and cooled by the use of air coolers.

Discussion

Efficacy and Costs of the Gas Cleaning System

Gas samples are taken monthly from the outlet of the vessels and analyzed by a commercial lab at a cost of $2,000. A summary of the recent analytical results for three gas samples collected from February to April 2014 (Table 21) shows the concentrations of the various contaminants in the untreated raw landfill gas and the treated gas and their removal efficiencies obtained by the cleanup system. For the three samples, the average total siloxane removal efficiency was indicated to be 99.3%, or a reduction from an average 8,533 ppbv total siloxanes in the raw gas to 64.3 ppbv in the treated gas. For H_2S, the average removal efficiency was 49.0%, or a reduction from an average 89 ppmv in the raw gas to 45 ppmv in the treated gas. The media are still 99% effective after more than two years in operation. The cost to replace the media in all four vessels is approximately $100,000.

Table 21. Summary of the Recent Analytical Results at Chiquita Canyon Landfill

AccuLabs, Inc.

Air Toxic • Contaminated Soil • Water and Wastewater • Industrial and Hazardous Waste • Chemical Consultation

Date: April 25, 2014
To: Mr. S. Simmons, Mr. J. Bell and Mr. N. Hall, AMERESCO
From: E. Hsue, AccuLabs, Inc.

Summary of the Analytical Results at Chiquiata Canyon Landfill, Castaic, California

< Comparison of Results for the Major Components Detected from the samples collected at Chiquita Canyon Landfill in **February, March and April, 2014 Monthly Monitoring** >

Client ID	Pre-Treated			Off-Gas			After Scrubber Step-48	After Scrubber Step-25	After Scrubber Step-12	% Removal Scrubber Step-48 vs. Pre-treated	% Removal Scrubber Step-25 vs. Pre-treated	% Removal Scrubber Step-12 vs. Pre-treated
AccuLabs ID	14-02-0025-01	14-03-0008-01	**14-04-0011-01**	14-02-0025-02	14-03-0008-02	**14-04-0011-02**	14-02-0025-03	14-03-0008-03	**14-04-0011-03**			
Month & Year of Monitoring	*Feb., 2014*	*March, 2014*	***April, 2014***	*Feb., 2014*	*March, 2014*	***April, 2014***	*Feb., 2014*	*March, 2014*	***April, 2014***	*Feb., 2014*	*March, 2014*	***April, 2014***
Major Fixed Gases	Conc. in % & ppMV			Conc. in % & ppMV			Conc. in % & ppMV					
Oxygen	1.77%	1.78%	**1.80%**	20.5%	5.27%	**19.1%**	1.67%	2.38%	**1.88%**	NA	NA	NA
Nitrogen	9.41%	9.66%	**10.3%**	78.7%	23.4%	**71.6%**	9.8%	12.3%	**14.1%**	NA	NA	NA
Carbon Dioxide	32.4%	31.1%	**32.7%**	0.138%	2.09%	**3.42%**	32.7%	33.3%	**30.7%**	NA	NA	NA
Methane	56.2%	57.2%	**54.9%**	0.030%	68.8%	**5.47%**	55.3%	51.5%	**53.1%**	NA	NA	NA
Carbon Monoxide	<25 ppmV	<25 ppmV	<25 ppmV	<25 ppmV	<25 ppmV	<25 ppmV	<25 ppmV	<25 ppmV	<25 ppmV	NA	NA	NA
Major Sulfur Compds	Conc. In **ppMV**			Conc. In **ppMv**			Conc. In **ppMV**					
< Ineffective Removal >:												
Hydrogen sulfide	86.1	89.1	**91.5**	0.405	0.846	**3.240**	46.3	43.4	**46.1**	46.2%	51.3%	*49.6%*
Total Sulfur in ppmV	101	101	**109**	0.51	1.28	**3.88**	62.1	52.1	**56.6**	38.5%	48.4%	*48.1%*
TGNMNEO	Conc. In **ppMv**			Conc. In **ppMv**			Conc. In **ppMv**					
< Effective Removal>:												
as Methane - TOC	2,950	2,950	**3,020**	235	235	**200**	715	639	**552**	75.8%	78.3%	*81.7%*
Major VOCs Compds (Part I)	Conc. In **ppbv**			Conc. In **ppbv**			Conc. In **ppbv**					
VOC-Group I < Effective Removal >:												
Acetone	19,600	17,500	**32,400**	241	908	**1,480**	<0.63	<0.63	**8,460**	100%	100%	*73.9%*
2-Butanone (MEK)	18,900	18,300	**40,300**	93.2	876	**1,010**	<0.56	91.0	**1,940**	100%	99.5%	*95.2%*
Ethanol	151,000	110,000	**145,500**	11,400	7,680	**12,400**	*<0.37*	*730*	***868***	100%	99.3%	*99.4%*
Ethyl acetate	9,160	7,930	**9,730**	*<0.45*	*331*	***461***	*<0.45*	*115*	***480***	100%	98.5%	*95.1%*
Methyl isobutyl ketone (MIBK)	1,780	1,560	**2,040**	*<0.57*	*<0.57*	*<0.57*	*<0.57*	*<0.57*	*<0.57*	100%	100%	*100%*
2-Propanol (IPA)	31,500	27,200	**31,800**	1,490	1,570	**2,520**	*<0.29*	*<0.29*	*<0.29*	100%	100%	*100%*
Ethylbenzene	2,220	2,280	**3,740**	27.5	121.0	**91.0**	9.01	84.4	**116**	99.6%	96.3%	*96.9%*
Tetrahydrofuran	5,370	4,330	**4,850**	*<0.23*	*<0.23*	*<0.23*	*<0.23*	*<0.23*	***383***	100%	100%	*92.1%*
iso-Propylbenzene (Cumene)	578	537	**1,390**	19.6	49.9	**23.6**	3.39	37.0	**7.36**	99.4%	93.1%	*99.5%*
Heptane	10,000	8,470	**9,810**	<0.20	<0.20	<0.20	4,570	2,710	**2,270**	54.3%	68.0%	*76.9%*
Styrene	265	326	**170**	<0.16	<0.16	<0.16	<0.16	<0.16	<0.16	100%	100.0%	*100%*
Total Xylenes (o-,m-, & p-)	5,040	5,410	**8,530**	87.1	257	**220**	28.7	269	**168**	99.4%	95.0%	*98.0%*
Toluene	11,800	10,600	**24,300**	152	480	**579**	2,510	1,320	**7,120**	78.7%	87.5%	*70.7%*

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Date: April 25, 2014
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< Comparison of Results for the Major Components Detected from the samples collected at Chiquita Canyon Landfill in February, March and April, 2014 Monthly Monitoring >

Client ID	Pre-Treated			Off-Gas			After Scrubber Step-48	After Scrubber Step-25	**After Scrubber Step-12**	% Removal Scrubber Step-48 vs. Pre-treated	% Removal Scrubber Step-25 vs. Pre-treated	**% Removal Scrubber Step-12 vs. Pre-treated**
AccuLabs ID	14-02-0025-01	14-03-0008-01	**14-04-0011-01**	14-02-0025-02	14-03-0008-02	**14-04-0011-02**	14-02-0025-03	14-03-0008-03	**14-04-0011-03**			
Month & Year of Monitoring	*Feb., 2014*	*March, 2014*	***April, 2014***	*Feb., 2014*	*March, 2014*	***April, 2014***	*Feb., 2014*	*March, 2014*	***April, 2014***	*Feb., 2014*	*March, 2014*	***April, 2014***
Major VOCs Compds (Part II)	Conc. In **ppbv**			Conc. In **ppbv**			Conc. In **ppbv**					
VOC-Group II < From Effective Removal to Ineffective Removal and to Completely Breakthrough >:												
Tetrachloroethyene (PCE)	225	245	**302**	<0.21	<0.21	<0.21	198	216	**122**	12.0%	11.8%	*59.6%*
Benzene	2,220	1,510	**2,680**	23.8	72.1	**108**	3,030	1,870	**1,570**	-36.5%	-23.8%	*41.4%*
Trichloroethene (TCE)	141	139	**214**	<0.19	8.74	**6.42**	255	190	**106**	-80.9%	-36.7%	*50.5%*
VOC-Group III < From Ineffective Removal to Completely Breakthrough >:												
Dichlorotetrafluoroethane (F-114)	41.4	48.9	**29.8**	<0.19	<0.19	<0.19	75.8	72.9	**32.0**	-83.1%	-49.1%	*-7.38%*
Cyclohexane	3,050	2,710	**2,950**	<0.23	<0.23	**153**	6,360	3,420	**2,170**	-109%	-26.2%	*26.4%*
Hexane	2,570	2,620	**1,960**	<0.20	<0.20	<0.20	5,590	4,130	**1,390**	-118%	-57.6%	*29.1%*
Propylene	13,200	12,700	**13,500**	140	2,540	**1,120**	18,600	20,300	**15,700**	-40.9%	-59.8%	*-16.3%*
Methylene chloride	463	511	**477**	65.6	108	**61.9**	1,020	774	**534**	-120%	-51.5%	*-11.9%*
Trichlorofluoromethane (F-11)	126	141	**121**	<0.17	<0.17	<0.17	113	123	**75.5**	10.3%	12.8%	*37.6%*
VOC-Group IV < Either Ineffective Removal or Completely Breakthrough >:												
Vinyl chloride	59.6	48.6	**48.7**	<0.17	<0.17	<0.17	111	72.0	**55.2**	-86.2%	-48.1%	*-13.3%*
cis-1,2-Dichlroethene	229	173	**259**	<0.19	<0.19	<0.19	496	327	**206**	-117%	-89.0%	*20.5%*
Dichlorodifluoroethane (F-12)	412	314	**324**	<0.18	<0.18	<0.18	800	591	**244**	-94.2%	-88.2%	*24.7%*
Major Siloxane Compounds	Conc. In **ppbv**			Conc. In **ppbv**			Conc. In **ppbv**					
< Effective Removal >:												
Trimethyl silane	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NA	NA	NA
Trimethyl silanol (TMS)	4,470	5,740	**4,140**	17.6	108	**127**	4.87	9.80	**10.2**	99.9%	99.9%	*99.8%*
Hexamethyldisiloxane (L2)	1,400	2,170	**2,860**	1.85	41.2	**61.1**	8.31	1.96	**70.9**	99.4%	99.6%	*97.5%*
Hexamethylcyclotrisiloxane (D3)	278	576	**982**	11.1	31.1	**21.2**	2.81	11.7	**13.8**	99.0%	99.5%	*98.6%*
Octamethyltrisiloxane (L3)	52.7	<0.10	**75.1**	<0.10	<0.10	<0.10	1.46	<0.01	<0.01	97.2%	NA	*100%*
Octamethylcyclotetrasiloxane (D4)	297	495	**249**	23.7	25.3	**25.7**	1.49	3.29	**2.49**	99.5%	99.3%	*99.0%*
Decamethyltetrasiloxane (L4)	8.32	7.95	<0.01	3.0	3.0	<0.10	2.00	<0.01	<0.01	76.0%	99.9%	NA
Decamethylcyclopentasiloxane (D5)	467	448	**848**	104	40.8	**23.9**	23.4	16.7	**7.55**	95.0%	96.3%	*99.1%*
Dodecamethylpentasiloxane (L5)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NA	NA	NA
Dodecamethylcyclohexasiloxane (D6)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	NA	NA	NA
Total Siloxanes in ppbV	*6,973*	*9,437*	***9,154***	*161*	*249*	***259***	*44.3*	*43.5*	***105***	99.4%	99.5%	*98.9%*
Total Siloxanes in ppmV	*6.97*	*9.44*	***9.15***	*0.16*	*0.25*	***0.26***	*0.044*	*0.043*	***0.105***	99.4%	99.5%	*98.9%*

APPENDIX D

TOOLKIT COST FACTORS AND DEFINITIONS OF COST CATEGORIES[15]

[15] EPA Air Pollution Control Cost Manual, Sixth Edition EPA/452/B-02-001, January 2002, United States Environmental Protection Agency Office of Air Quality Planning and Standards Research, Triangle Park, North Carolina 27711, EPA/452/B-02-001

TOTAL CAPITAL INVESTMENT ELEMENTS

Total capital investment (TCI) includes:

- All costs required to purchase equipment needed for the siloxane removal system (total equipment costs or TEC)
- Costs of labor and materials for installing that equipment (direct installation costs or DIC)
- Costs for site preparation and buildings,
- Other costs (indirect installation costs or IIC)
- Costs for land, working capital, and off-site facilities.

Equipment installation may also require land, but as most add-on control systems take up little space this cost would be relatively small. For those systems that do require larger quantities of land for the equipment, chemicals storage, and waste disposal, especially when performing a retrofit installation, space constraints can significantly influence the cost of installation and the purchase of additional land may be a significant factor in the development of the project's capital costs.

Direct installation costs include:

- Costs for foundations and supports, erecting and handling the equipment, electrical work, piping, insulation, and painting.

Indirect installation costs include:

- Engineering, construction and field expenses (i.e., costs for construction supervisory personnel, office personnel, rental of temporary offices, etc.);
- Contractor fees (for construction and engineering firms involved in the project);
- Start-up and performance test costs (to get the control system running and to verify that it meets performance guarantees);
- Contingencies such as redesign and modification of equipment, escalation increases in cost of equipment, increases in field labor costs, and delays encountered in start-up. Contingencies are not the same thing as uncertainty and retrofit factor costs, which are treated separately below.

Initial operational costs (the initial costs of fuel, chemicals, and other materials, as well as labor and maintenance related to startup) are included in the operating cost section of the cost analysis instead of in the capital component. Routine operation of the control does not begin until the system has been tested, balanced, and adjusted to work within its design parameters. Until then, all utilities consumed, all labor expended, and all maintenance and repairs performed are a part of the construction phase of the project and are included in the TCI in the "Startup" component of the Indirect Installation Costs.

TOTAL ANNUAL COST ELEMENTS

Total Annual Cost (TAC) has three elements: direct operating costs (DOC), indirect operating costs (IOC), and recovery credits (RC), which are related by the following equation:

$$\text{TAC} = \text{DOC} + \text{IC} - \text{RC}$$

The one-year basis allows time for siloxane monitoring and is directly usable in the financial analyses.

Direct Operating Costs (DOC): DOC can include costs for raw materials (media, reagents), utilities (steam, electricity, process and cooling water), waste treatment and disposal, maintenance materials (greases and other lubricants, gaskets, and seals), replacement parts, and operating, supervisory, and maintenance labor. If collected waste cannot be recycled or sold, it must be landfilled or disposed of in some other manner. Disposal costs are site-specific, but run $33 per ton for the Ox Mountain site, exclusive of transportation. Hazardous disposal costs will vary depending on the composition of the media but per the cost manual can be $150 per ton or more (1998 dollars).

Indirect Operating Costs (IOC): Indirect or "fixed" costs include such categories as administrative charges, property taxes, insurance, and capital recovery. The system capital recovery cost (CRC) is based on the equipment lifetime and the annual interest rate employed. The default values used in the toolkit for estimating the CRC were an estimated 10-year equipment life and an interest rate of 7 percent, which results in a calculated capital recovery factor (CRF) of 0.1424. The toolkit then estimates the CRC by multiplying the CRF by the TCI.

Recovery Credits: Direct and indirect annual costs can be reduced by recovery credits, taken for materials or energy recovered by the contaminant removal system, which may be sold, recycled to the process, or reused elsewhere at the site. The value of the credits are net of any associated processing, storage, transportation, and any other costs required to make the recovered materials or energy reusable or resalable. The materials recovered, however, may be of small quantity or of doubtful purity, resulting in their having less value than virgin material.

Siloxane monitoring cost section: Critical factors in selecting the type of analyzer or monitor for a particular application include gas concentration, ambient temperatures and the presence of contaminants that could damage or interfere with the sampling or analyzer systems. Other issues such as data availability requirements may influence analyzer selection or drive the need for two analyzers with one in a backup capacity. These issues impact equipment selection and can substantially impact capital, operating and maintenance costs. As manufactures overcome past limitations, monitors and gas analyzers are becoming more versatile. The selection of a monitor and the cost analysis should be performed on a site-specific basis.

Retrofit Cost Considerations: The installation factors used in the spreadsheet and listed in the cost manual apply mainly to systems installed in new facilities. These factors must be adjusted whenever a control system is sized for, and installed in (i.e.,"retrofitted") an existing facility. However, because the size and number of auxiliaries are usually the same in a retrofit situation, the purchased equipment cost of the control system would probably not be much different from the new plant purchased cost. Some kinds of system modifications and additional cost considerations in a retrofit could include the need for additional ductwork, piping, insulation, painting, site preparation, engineering, and lost production during shutdown. To estimate the unanticipated additional installation, the cost of the system (i.e., TCI) can be multiplied by a retrofit factor. In the cost manual the retrofit factor ranges from 1.1 to 1.5, with the multiplier selected based on the relative difficulty of the installation.

Table 22. Range of Cost Factors from the EPA Cost Control Manual

Cost Item	Cost Factor Range, %
Total Equipment Costs (TEC)	
Auxiliary equipment	10-50
Sales taxes	0-8
Freight	1-10
Direct Installation Costs (DIC)	
Foundations & supports	4-12
Handling & erection	14-50
Electrical	1-8
Piping	2-30
Insulation	1-7
Painting	1-10
Indirect Installation Costs (IIC)	
Engineering	10-20
Construction and field expenses	5-20
Contractor fees	0-10
Start-up	1-2
Model study	2-3
Performance test	1
Contingencies	3
Retrofit	10-50