Electric Power Generation Using A Phosphoric Acid Fuel Cell On A Municipal Solid Waste Landfill Gas Stream

Technology Verification Report

by

Sushma Masemore and Steve Piccot
Greenhouse Gas Technology Verification Center
Southern Research Institute
P.O. Box 13825
Research Triangle Park, NC 27709

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EPA Project Officer: David A. Kirchgessner
Air Pollution Prevention and Control Division
National Risk Management Research Laboratory
Research Triangle Park, NC 27711

Prepared For:

U.S. Environmental Protection Agency
Office of Research and Development
Washington, D.C. 20460

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM VERIFICATION STATEMENT

TECHNOLOGY TYPE:	**LANDFILL GAS CLEANUP AND PHOSPHORIC ACID FUEL CELL SYSTEM**
APPLICATION:	**POWER PRODUCTION FROM WASTE LANDFILL GAS**
TECHNOLOGY NAME:	**GPU AND PC25 ™ 200 kW FUEL CELL**
COMPANY:	**INTERNATIONAL FUEL CELLS CORPORATION**
ADDRESS:	**195 GOVERNORS HIGHWAY** **SOUTH WINDSOR, CONNECTICUT 06074**
PHONE:	**(860) 727-2388**

PROGRAM DESCRIPTION

The U. S. Environmental Protection Agency's (EPA) Office of Research and Development has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of promising environmental technologies. Under this program, third party performance testing of environmental technology is conducted by independent Verification Organizations. Their goal is to objectively and systematically evaluate technology performance under strict EPA quality assurance guidelines. The EPA's Air Pollution Prevention and Control Division has selected Southern Research Institute as the independent Verification Organization to operate the Greenhouse Gas Technology Verification Center (the Center). With the full participation of the technology developer and users, the Center develops testing plans, and conducts field and laboratory tests. The test results are analyzed, peer reviewed, and then distributed to industry, regulatory, vendor, and other groups interested in the data.

TECHNOLOGY DESCRIPTION

For several years, International Fuel Cells (IFC) Corporation has employed the commercially available phosphoric acid fuel cell (PC25™) to generate electricity from natural gas. This fuel cell unit can also be used at municipal solid waste landfills to convert landfill gas into electric power. This application requires a supplemental gas treatment unit (GPU) to remove sulfur and halide compounds present in the landfill gas (LFG). The combined GPU and PC25™ Fuel Cell system provides a means for utilizing waste landfill gas, thus, reducing methane emissions and other air pollutants.

The design of the GPU is dictated by the gas purity requirements of the fuel cell, and the composition and physical properties of the incoming LFG. The cleaned waste gas is then converted into electric power for on-site use or distribution to an electric grid. In the GPU, hydrogen sulfide is first removed via adsorption on an activated carbon bed, which is used to catalyze the conversion of H_2S into elemental sulfur. Additional water, heavy hydrocarbons, sulfides, and other contaminants are removed through the removal system consisting of a low temperature cooler, carbon bed, dryer bed, and particulate filter. A heat exchanger is used to ensure the gas temperature meets fuel cell inlet requirements. The PC25™ fuel cell consists of a fuel processing system, an electrical conversion system, and a thermal management system. In the fuel processing section, treated LFG is

converted to hydrogen and carbon dioxide for introduction into the fuel cell stack. The fuel treatment process consists of a low temperature fuel preprocessor which removes the residual contaminants from the treated gas, a fuel reformer, and a low temperature shift converter where the exhaust from the reformer is further processed. The hydrogen from the process fuel stream is then combined electrochemically with oxygen from the air to produce electricity in the fuel cell stacks. The DC current produced is converted into AC in a power-conditioning package. The PC25™ is designed to produce 200 kW of electric power from natural gas. With LFG, the PC25™ unit generates less power due to lower heating value of LFG.

VERIFICATION DESCRIPTION

This verification statement summarizes the results of tests conducted to verify the performance of a combined GPU and PC25™ fuel cell system operating on LFG. These tests were conducted at two sites where the LFG flow rates, composition, heating value, and contaminant levels are representative of the U.S. landfill population. The performance of the GPU was evaluated by comparing the sulfur and halogen concentrations in the GPU outlet gas with the levels required to effectively operate the fuel cell. The GPU operating availability was determined by dividing the length of time the unit was available by the total operating time of the GPU. The emissions characteristics of the GPU flare, which is used to combust the contaminants collected by the GPU, were measured to evaluate hazardous air pollutants emitted into the atmosphere. The performance of the fuel cell was evaluated by demonstrating the LFG to energy conversion process and by quantifying the power output. Total energy conversion efficiency of the power generation equipment, fuel cell availability, and fuel cell exhaust emissions were also measured.

The first verification test was executed at the Penrose site in Los Angeles, California. This test addressed contaminant removal efficiency by the GPU, flare destruction efficiency, and the operational availability of the cleanup system. The system was then relocated to the Groton Landfill in Connecticut where its performance was verified under different operating conditions. Details of the verification may be found in the report titled *Electric Power Generation Using A Phosphoric Acid Fuel Cell On A Municipal Solid Waste Landfill Gas Stream* (EPA-600/R-98-105). The verification report may be ordered through the National Technical Information Service or downloaded from the ETV Program or Center websites (www.epa.gov/etv or www.sri-rtp.com).

VERIFICATION OF PERFORMANCE

Performance Factors for the GPU:

- Halide and Sulfur Removal Efficiency: The fuel cell requires total halogen and total sulfur levels to be <3 ppmv in the GPU outlet stream. At Penrose, the GPU exceeded the removal requirements of both contaminants, with total halides reduced from 60 ppmv to [0.032 ppmv, and total sulfur reduced from 113 ppmv to [0.047 ppmv. The Groton performance results were similar, with total sulfur levels reduced to [0.022 ppmv and total halides to [0.014 ppmv.

- Estimated Flare Destruction Efficiency and CO/NO_x Concentrations: The destruction efficiencies of non-methane organic compounds and volatile organic compounds were estimated to be 99 percent. The conversion efficiency of sulfur compounds is also estimated to be about 99 percent. These efficiencies are based on an estimation of flare gas exhaust flow because the measured flow rate was below the EPA Method 2 detection limit. The NO_x and CO concentrations at the flare outlet averaged 10.4 ppmv and 3.0 ppmv, respectively.

- Operational Availability: The GPU logged 2,297 hours at Penrose and 4,168 hours at Groton (6,465 hours total). The GPU availability for the Penrose test was 87 percent. At Groton, the GPU availability decreased to 45 percent because of leaks caused by relocating the test equipment from California to Connecticut, and a malfunctioning gas compressor added at Groton to provide pressurized inlet gas. Once these mechanical failures were corrected, the GPU availability increased to 70 percent.

Performance Factors for the PC25™ Fuel Cell:

- Electrical Output: At the Penrose site, a nominal output of 140 kW was expected to be generated from the waste gas containing 44 percent methane (heating value of 446 BTU/scf). The test verified a maximum output of 137 kW. The heating value of the Groton LFG was higher, 581 BTU/scf and 57 percent methane, resulting in higher power production from the fuel cell (165 kW).

  - Energy Conversion Efficiency: The fuel cell system energy conversion efficiency, based on lower heating values, was determined to be 37.1 percent at Penrose and 38.0 percent at Groton.

- Operational Availability: The adjusted availability for the fuel cell, which compensates for shutdowns not caused by the fuel cell, was over 96 percent at both test sites.

- Stack Emissions: The emissions from the fuel cell exhaust are consistent with the data measured from 16 other PC25™ units operating on natural gas. The average emissions were measured as follows (dry gas, corrected to 15 percent O_2): NO_x = 0.12 ppmv or 0.29 g/hr, SO_2 = non detectable (0.23 ppmv detection limit) or <0.78 g/hr, and CO = 0.77 ppmv or 1.15 g/hr.

The results of these tests satisfy the requirements set forth in the testing plan for the GPU and the fuel cell system. The GPU functioned according to its design specifications, purifying LFG to a level which was more than suitable for fuel cell use. The fuel cell produced power with no forced outages and provided consistently low secondary emissions. The electricity produced at both sites were connected to a local grid system and sold to utility companies.

Although the PC25™ 200 kW fuel cell system has been used on natural gas, this verification was the first application on LFG. This required the process design and engineering of a new GPU system to clean up the contaminants not present in natural gas. The costs for the GPU were higher at Penrose ($2,450/kW), and lower at Groton ($1,655/kW) due to reduced labor and start-up requirements. The cost for the PC25™ fuel cell was $3,000/kW. The vendor estimates that, with system simplifications, dedicated production facilities, and other cost reduction options, the GPU costs may eventually be reduced to $264/kW ($180/kW for equipment and material, $84/kW for labor). Similarly, the vendor estimates that $1,500/kW may eventually be the mature phase cost of the fuel cell. These cost estimates have not been independently verified.

E. Timothy Oppelt
Director
National Risk Management Research Laboratory
Office of Research and Development

Stephen Piccot
Director
Greenhouse Gas Technology Verification Center
Southern Research Institute

NOTICE: GHG Center verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. The EPA and Southern Research Institute make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always, under circumstances other than those tested, operate at the levels verified. The end user is solely responsible for complying with any and all applicable Federal, State, and Local requirements.

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ABSTRACT

The U.S. Environmental Protection Agency (EPA) and International Fuel Cells Corporation conducted a test to verify the performance of a landfill gas treatment unit and a phosphoric acid fuel cell system. The complete system removes contaminants from landfill gas and produces electricity for on-site use or connection to an electric grid. The verification test was the first use of fuel cell technology at a municipal solid waste facility. The test design was subjected to extensive review and comment by the EPA's National Risk Management Research Laboratory, landfill test site operators, and the technology developers.

Performance data were collected at two sites determined to be representative of the U.S. landfill market. The Penrose facility, located in Los Angeles, California, was the first test site. The landfill gas at this site represented waste gas recovered from four nearby landfills, comprised primarily of industrial waste material. It produced approximately 3,000 standard cubic feet (scf) of gas per minute, and had a higher heating value of 446 BTU/scf at about 44 percent methane concentration. The second test site, Groton Landfill, was located in Groton, Connecticut. This was a relatively small landfill, but with greater heat content gas (methane levels were about 57 percent and average heating value was 585 BTU/scf).

The verification test addressed contaminant removal efficiency, flare destruction efficiency, and the operational capability of the clean-up system, and the power production capability of the fuel cell system. The test verified that the clean-up system is capable of reducing total halogen and total sulfur levels to less than 3 ppmv, which are the minimum levels, required to operate the fuel cell. The GPU flare met emission requirements for sulfur, volatile organic compounds, and other hazardous air pollutants. The GPU exceeded the minimum operating requirement and logged more than 6,465 hours between the two sites. Based on the landfill gas quality, it was expected that the PC25 fuel cell would produce a minimum of 140 kW power. The power produced at Penrose was slightly below this value and peaked at 137 kW. The Groton landfill produced a maximum power output of 165 kW due to higher BTU gas. The overall fuel cell efficiency was determined to be 37.1 percent and 38.0 percent at Penrose and Groton, respectively. Additional performance results determined for the fuel cell include adjusted availability of over 96 percent at both sites, and low NO_x, SO_2, and CO emissions.

ACKNOWLEDGMENTS

The Greenhouse Gas Technology Verification Center wishes to thank Ronald J. Spiegel of EPA's Air Pollution Prevention and Control Division for assisting in preparing this report. He provided valuable information in accounting for the events and conclusions reached in the initial study. Thanks are also extended to SCS Engineers, Inc. for providing guidance in representing the landfill industry and for evaluating measurement results reported in this document. Finally, the technical expertise provided by Larry Preston of International Fuel Cells, Inc. played a critical role in evaluating the technology performance data.

LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
ASTM	American Society for Testing and Materials
BTU	British Thermal Units
DC	Direct Current
dscf	Dry Standard Cubic Feet
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
^{o}F	Degrees Fahrenheit
g	Grams
GC/FPD	Gas Chromatography / Flare Photometric Detectors
GC/MS	Gas Chromatography / Mass Spectrometry
GHG	Greenhouse Gas
GPU	Gas Pretreatment Unit
h	Hours
IFC	International Fuel Cells Corporation
kW	Kilowatt
LFG	Landfill Gas
NIST	National Institute for Science and Technology
NMOC	Non-Methane Organic Compounds
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standards
ORD	Office of Research and Development
ppmv	Parts per million, volume based
psi	Pounds Per Square Inch
QAPP	Quality Assurance Project Plan
RSD	Relative Standard Deviation
SCAQMD	South Coast Air Quality Management District
scf	Standard Cubic Feet
scfm	Standard Cubic Feet Per Minute

UNITS AND CONVERSION FACTORS

		To Convert To	Multiply By
Power			
MW	Megawatt	-	-
kW	Kilowatt	-	-
Mass			
Mg	Megagrams (10^6 grams)	pounds	2,205
Tg	Terragrams (10^6 grams)	pounds	2,204,600
Volume			
SCMD	Standard cubic meters per day	scfd (standard cubic feet/day)	35.3
SL/M	Standard liters per minute	scfm (standard cubic feet/min)	0.0353
Pressure			
Pa	Pascal	psi	1.45×10^{-4}
Heating Value			
kcal/SL	Kilocalories per standard liter	BTU/scf	112

SECTION 1

EXECUTIVE SUMMARY

1.1 ETV OVERVIEW

The U. S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) has created a program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the Environmental Technology Verification (ETV) Program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. The ETV program is specifically funded by the Congress in response to the belief that there are viable environmental technologies which are not being used for the lack of credible third party performance testing.

The Greenhouse Gas Technology Verification Center (the Center) is one of twelve Centers currently operating under the ETV program. Together with EPA's partner verification organization, Southern Research Institute, the Center provides verification testing capability to GHG technology vendors, buyers, exporters, and others that have a need for performance data. The Center develops test protocols, conducts field tests, collects and analyzes data, and reports findings. Performance evaluations are conducted according to a rigorous verification plan and established protocols for quality assurance to ensure objective and systematic evaluation of innovative GHG technologies.

The Center is guided by a volunteer group of Stakeholders that have a stake in the GHG emission reduction area. The group consists of national and international experts in the areas of climate change science, policy, technology, and regulation. It also includes industry trade organizations, technology vendors and buyers, environmental technology finance groups, government research organizations, and government sponsored GHG mitigation outreach programs. These groups help the Center develop strategic plans, establish credible technology evaluation strategies, review verification results, distribute results widely, and coordinate with other GHG programs and regulatory efforts.

This document summarizes the results of a verification test conducted on a technology which generates electric power from waste landfill gas. The individual components of the technology which were verified include: (1) a landfill Gas Pretreatment Unit (GPU) and (2) a PC25™-200 kW phosphoric acid fuel cell system.

1.2 VERIFICATION OBJECTIVES

The objective of the verification test was to verify the performance of the GPU and the PC25™-200 kW fuel cell system which is manufactured by ONSI Corporation, a subsidiary of International Fuel Cell (IFC) Corporation in South Windsor, CT. The GPU performance was evaluated by measuring sulfur and halogen concentrations in the GPU outlet gas stream and then comparing these values with fuel cell operating specifications. The operational reliability of the GPU was verified by logging the continuous and total duration of operation on landfill gas. Emissions testing of the GPU flare was conducted to determine the contaminant levels of hazardous air pollutants such as sulfur dioxide, carbon monoxide, and nitrogen oxides. Fuel cell performance was evaluated by verifying the LFG to energy conversion process and by

verifying its power output, energy efficiency, availability, and exhaust emissions. Table 1-1 presents the performance claims set out to be verified.

Table 1-1. Verification Performance Goals

GPU Parameter	Performance Goal
Exit Total Sulfur Concentration	< 3 ppmv
Exit Total Halogen Concentration	< 3 ppmv
Total Duration of Operation on LFG	> 500 hours
Longest Continuous Run on LFG	> 200 hours
Adjusted Availability	No Initial Goal (to be determined from test)
GPU Enclosed Flare Exhaust Emissions	No Initial Goal (to be determined from test)
Fuel Cell Parameter	**Performance Goal**
Maximum Power Output	140 kW or more
Stable Power Output	No Initial Goal (to be determined from test)
Energy Efficiency	No Initial Goal (to be determined from test)
Duration of Operation	No Initial Goal (to be determined from test)
Adjusted Availability	No Initial Goal (to be determined from test)
Exhaust Emissions	Equal to or less than those produced from fuel cells operating on natural gas SO_2 = negligible NO_x 0.5 ppmv CO 1.1 ppmv

1.3 TECHNOLOGY DESCRIPTION

Municipal solid waste landfills are regulated to control air emissions (61 CFR 49). The current standards correspond to emissions of non-methane organic compounds (NMOCs), comprising some 100 volatile organic compounds and hazardous air pollutants contained in landfill gas (LFG). These pollutants generally represent less than 1 percent of the total composition of LFG which is primarily methane (35 to 60 percent) and carbon dioxide (40 to 55 percent), with a heat content equal to roughly one-half that of natural gas. Landfills emitting greater than 50 metric tons per year of NMOCs are required to install a LFG collection system and a treatment system capable of destroying 98 percent of the NMOCs in the gas or reducing their concentration to less than 20 ppmv. In this process, the potent greenhouse gas methane is also converted to carbon dioxide, or utilized to produce electricity or heat.

LFG collection is a mature technology and typically involves installation of vertical wells into the landfill mass, using perforated plastic pipe. These pipes are usually connected to a manifold, and a vacuum is applied for central collection and treatment and/or utilization. The collected gas may be vented, flared, used to generate electricity and heat, or used to produce pipeline quality gas. Electric power generation with fuel cells is one such method of utilizing LFG (Roe *et al.* 1998).

The landfill gas to energy system design, offered by IFC, is based on providing a modular, packaged, energy conversion fuel cell system which can operate on landfill gases with varied compositions. The energy conversion system requires a LFG collection system, and consists of a modular gas pretreatment system and a PC25™ natural gas fuel cell power plant modified for LFG operation. The wells and collection system collect raw LFG and deliver it at low pressures

to the gas pretreatment unit (GPU). Raw LFG is treated in the GPU to remove moisture, particulates, and other contaminants to a level suitable for the fuel cell. The fuel cell power plant converts cleaned LFG to electricity and useful heat. Figure 1-1 illustrates a simplified diagram of this system, and the remaining paragraphs discuss its process description.

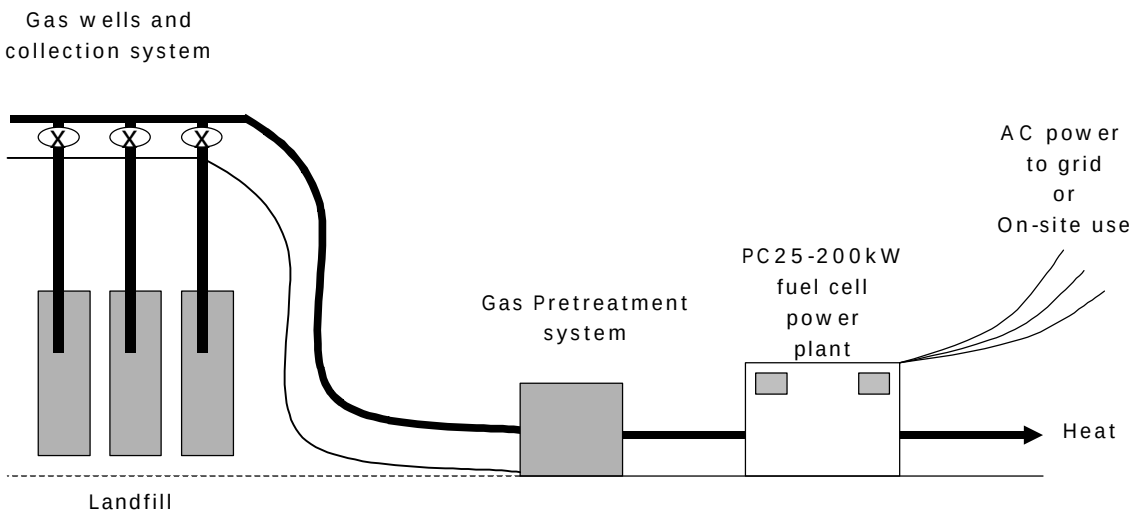

Figure 1-1. Landfill Gas Fuel Cell System

LFG exiting the GPU must contain very low concentrations of total sulfur and halogens to properly operate the fuel cell. The GPU is designed to provide the contaminant removal capability needed to meet fuel cell operating specifications. The system incorporates one non-regenerable step, plus two stages of refrigeration combined with two regenerable adsorbent steps. The first active bed of the GPU is a carbon adsorber designed to remove hydrogen sulfide (H_2S). A first-stage refrigeration condenser then removes most of the water contained in the saturated LFG and some of the heavier hydrocarbon and contaminant species.

LFG exiting the first-stage refrigeration condenser is sent to a dryer bed where its water content is reduced. This bed is regenerated every eight hours with heated, clean LFG. During regeneration, a second, fully regenerated bed takes over the identical function. The regeneration gas is subsequently incinerated in an enclosed flare. The LFG flare achieves destruction of NMOCs by maintaining the combusted regeneration gas at a temperature of at least 1400 ^{o} F for at least one second.

Following the dryer bed, the LFG proceeds to a second stage low-temperature cooler to enhance the performance of the downstream activated carbon bed. The activated carbon bed adsorbs the remaining NMOCs (including organic sulfur and halogen compounds.) This bed is regenerated every eight hours, and the regeneration gas is incinerated in the enclosed flare. Output gas is filtered to reduce carryover of dust from the regenerable beds. The treated LFG exits the filter for consumption in the fuel cell, and a small fraction of the gas is extracted and used as the regeneration gas.

In the fuel cell power plant, treated LFG is converted into electric power and heat. The fuel cell converts the chemical bonding energy of a chemical substance directly into electricity. The general PC25™-200 kW fuel cell system consists of three major subsystems: fuel processing, direct current (DC) power generation in the fuel cell stack, and DC to alternating current (AC) power conditioning by the inverter. The fuel cell extracts hydrogen from the clean LFG, and electrochemically combines with oxygen from the air to produce DC electricity and by-product water. The by-product water is recovered and used in the reformer. The heat generated in the cell stack is removed to an external heat rejection system. The DC power is converted to utility grade AC power in a power-conditioning package. The AC power can be used on site or transformed and put into the utility grid.

1.4 VERIFICATION APPROACH

Two landfill test sites were identified where verification test results would be representative of U.S. landfills. Factors for landfill site selection included LFG flow rates, composition, heating value, and contaminant levels. The Penrose site, located in Los Angeles, California, was the first location where the performance test was conducted. This site represents gas collected from a total of four nearby landfills, which is comprised primarily of industrial waste material. The LFG produced at Penrose is pressurized, thus the GPU was manufactured to accept pressurized inlet gas. All power produced by the unit was fed into the existing electrical grid for sale to the local electrical utility, the Los Angeles Department of Water and Power. Approximately 3,000 standard cubic feet (scf) of LFG per minute is produced at Penrose, with approximately 44 percent methane concentration and a higher heating value of 446 BTU/scf.

The entire GPU and fuel cell system was then relocated to the Groton landfill in Connecticut to further verify the suitability of the energy conversion equipment under different landfill site conditions. The LFG at Groton was not pressured, and since the GPU was built to accept pressurized gas, a compressor was added to meet the inlet gas pressure requirements. The gas flowrate at Groton was about 400 scfm, with methane concentration of 57 percent and higher heating value of 585 BTU/scf.

The verification tests at Penrose and Groton occurred between September 1993 and July 1997. The system was tested by IFC, TRC Environmental, Pacific Energy, and Northeast Utilities, with QA and other oversight from EPA's Air Pollution Prevention and Control Division.

The verification test at the Penrose landfill consisted of the installation, operation, and testing of the GPU and PC25™-200 kW fuel cell by IFC. The Penrose test began in September 1993 and was completed in February 1995. The first objective of the Penrose test was to verify the performance of the GPU (i.e., reduce total halides and total sulfur levels to specified amounts, and obtain emission measurements data for the GPU enclosed flare). Upon verification of the GPU, the fuel cell was installed and performance data for the complete system were obtained. Figure 1-2 illustrates the schematic of major measurement locations where test data were collected. An EPA Category II Quality Assurance Project Plan (QAPP) and a site-specific test plan were developed to address data quality requirements, measurements, calculations, and audit requirements. Table 1-2 summarizes the key measurement parameters and methods which were followed to obtain the verification data.

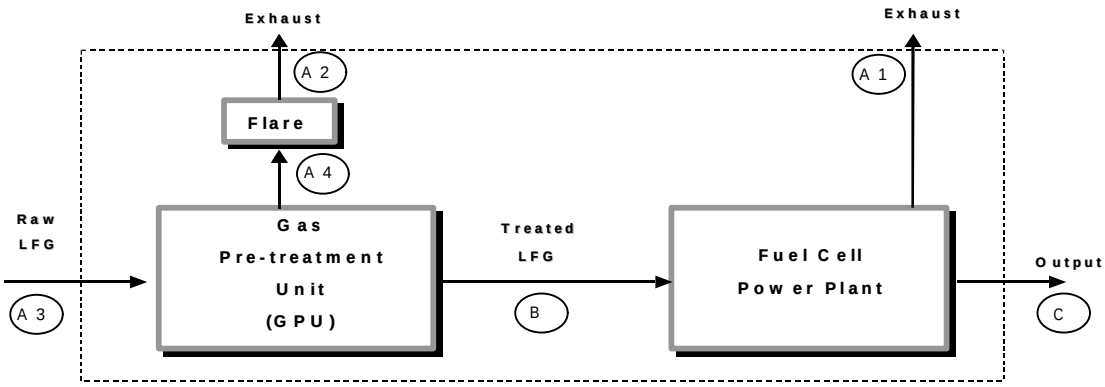

Figure 1-2. Verification Test Measurement Locations

Table 1-2. Summary of Measurement Plans

Parameter	Method	Sample Location (see Figure 1-2)	Frequency
Sulfur Compounds[1]	EPA 16 & 18	A2, A3, A4, B	Prior to start, then monthly
Volatile Organic Compounds[2] (including halides)	EPA TO-14	A2, A3, A4, B	Prior to start, then monthly
GPU Flare Exhaust Emissions[1]			3 samples on Oct. 21, 1993 (Penrose landfill only)
Total NMOC	CARB Method 25.2	A2, A4	
Particulate Matter	EPA 5 and 202	A2	
SO_2, NO_x, CO, and Diluents	EPA 6C, 7E, 10, 3A	A2	
GPU Heat Content			
Input Gas	On-Line Analyzer	A3	Monthly
Output Gas[3]	ASTM D-3588	B	Monthly
Cumulative Gas Flow Rate	Process Monitor	A2, A3, A4, B	Weekly
Fuel Cell Electrical Output	kWh Meter	C	Weekly
Fuel Cell Exhaust Emissions[1]			6 samples on Feb. 17, 1995 (Penrose landfill only)
SO_2	EPA 6C	A1	
NO_x	EPA 7E	A1	
CO	EPA 10	A1	
CO_2	EPA 3A	A1	
O_2	EPA 3A	A1	
Cumulative Gas Flow Rate	Continuous Monitor	A1	Continuous
Availability, Maintenance Req., Operation Req.	Operator Log	N/A	Monthly

[1] Source: 60 CFR 40
[2] Source: Riggin 1988 and Winberry *et al.* 1988
[3] Source: ASTM 1991

Upon completion of the Penrose test, the GPU and fuel cell were relocated to the Groton landfill to verify their performance under a different range of LFG composition. Northeast Utilities conducted the follow-on testing, including the engineering design, construction, installation, operation, and maintenance of the equipment. Quality assurance guidelines prepared for the Penrose test were generally followed at this site (GPU flare and fuel cell exhaust emission measurements were not conducted). The testing was performed between June 1995 and July 1997. Additional details on the test, including data summary and discussion of results, may be found in Trocciola and Preston, 1998a and 1998b.

1.5 VERIFICATION RESULTS AND PERFORMANCE EVALUATION

Table 1-3 summarizes the performance results. The following discussion highlights each performance parameter.

Table 1-3. Summary of Performance at the Penrose and Groton Landfills

	Units	Goal	Penrose	Groton
GPU				
Exit Total Sulfur (as H_2S)	ppmv	<3	0.047	0.022
Exit Total Halides (as Cl)	ppmv	<3	0.032	0.014
GPU Flare Emissions[1]				
NO_x	ppmv	No Initial Goal	7.5 to 14.9	
CO	ppmv	No Initial Goal	1.6 to 5.8	
NMOC	ppmv	No Initial Goal	6.8 to 11.7	
Destruction Efficiency of Sulfur Compounds	%	No Initial Goal	>99	[A]
Destruction Efficiency of VOCs	%	No Initial Goal	>99	
Particulate Matter	grains/dscf	No Initial Goal	0.015	
Total Duration of Operation On LFG	hours	>500	2,297	4,168
Longest Continuous Run On LFG	hours	>200	342	827
Gross Availability	%	No Initial Goal	87.3	45 (total) 70 (last 6 months)
Fuel Cell				
Maximum Power Output	kW	>140 kW	137	165
Stable Power Output	kW	No Initial Goal	120	140
Efficiency at Stable Output[2]	%	No Initial Goal	37.1	38.0
Total Duration of Operation on LFG	Hours	No Initial Goal	707	3,313
Adjusted Availability	%	No Initial Goal	98.5	96.5
Exhaust Emissions				
SO_2	ppmv	negligible	<0.23	
NO_x	ppmv	0.5	0.12	[A]
CO	ppmv	1.1	0.77	

[A] Performance measurement was not required at this site.
1 Results represent emission measurements conducted during hot bed regeneration (worst case conditions) and cold bed regeneration.
2 Represents the efficiency of the fuel cell only. Based on lower heating value measured per ASTM method.

1.5.1 GPU Performance

Contaminant Removal Performance

At both test sites, the GPU consistently reduced contaminants in the LFG to levels significantly below the initial goals of < 3 ppmv total sulfur and < 3 ppmv total halides.

At Penrose, the GPU reduced total halides from inlet levels of 45 to 65 ppmv in the raw LFG to very low or undetectable levels at the outlet. At about 200 hours of operation, four samples showed no detectable levels (0.002 ppmv detection limit), while one sample tested at 0.008 ppmv and one sample tested at 0.032 ppmv. At 2,235 hours of operation, six samples showed no detectable halides. The halide removal performance of the GPU enabled IFC to eliminate the addition of a halide guard bed in the fuel cell power plant.

The GPU met the performance goal of less than 3 ppmv total sulfur from an initial concentration of 110 ppmv. The exit concentration ranged between non-detectable to 0.385 ppmv. The elevated level of 0.385 ppmv represents an atypical condition resulting from a break-through occurring in the non-regenerable H_2S removal bed. This breakthrough condition causes carbonyl sulfide formation in the dryer beds. Some of the carbonyl sulfide passes through the final carbon bed, resulting in increased sulfur at the GPU exit. After a fresh H_2S removal bed was installed, the exit total sulfur level returned to non-detectable levels. This experience at Penrose established an operating procedure which requires switching the non-regenerable H_2S removal bed to a fresh bed when GPU exit total sulfur concentrations increases rapidly.

At the Groton landfill, the GPU showed acceptable sulfur and halide compound removal. Data from standard Summa canisters at normal GPU operating conditions showed no detectable sulfur or halides at about 5,805 hours total GPU operation. The continuing low exit levels of sulfur and halide compounds indicated that the original GPU bed design life of 8,000 hours is likely to be achieved.

GPU Flare Emissions

As part of the South Coast Air Quality Management District's (SCAQMD) permit requirements, 18 permit conditions were required to construct and operate the GPU enclosed flare. Details on these conditions may be found in Trocciola and Preston, 1998b. The GPU flare met mechanical and operational permit requirements. Specifically, pollutant measurements conducted on the GPU flare demonstrated that the destruction efficiency in the flame was greater than 99 percent for both non-methane organics and sulfur compounds during the hot regeneration cycle of the carbon bed. Flare emissions of nitrogen oxides (NO_x) averaged about 0.056 lb/million BTU. This is below the 0.6 lb/million BTU NOx emissions currently required by the SCAQMD. Total particulate matter, including back-half organic and inorganic fractions, averaged 0.015 grains/dscf.

GPU Availability

The GPU operated for 2,297 hours at Penrose and 4,168 hours at Groton. The total operating time of 6,465 hours well exceeded the minimum verification goal of 500 hours. The longest continuous runs at the Penrose and Groton were 342 and 827 hours, respectively.

The GPU gross availability was determined to be 87.3 percent for the Penrose landfill. During this test, the GPU experienced a total of three shutdowns which resulted in lost time. Reasons for these shutdowns include: the loss of coolant temperature control in the d-limonene loop, loss of flare flame sensor, condenser tank overfill from high condensate influx at the site, and lockup to the programmable logic (PLC) controller due to a control valve position switch being out-of-limits. All causes were identified and corrected, and no outstanding operational issues remained.

The gross availability of the GPU for the Groton test was determined to be 45 percent. Most of the GPU shutdowns occurring during the first six months were one-of-a-kind mechanical failures, and were attributed by leaks resulting from the equipment being moved from California to Connecticut. All leaks and mechanical failures were corrected, and did not reoccur. The primary cause of periodic failures was the added compressor which provided the needed pressurized gas. It is estimated that a downtime of about 1,050 hours resulted from the malfunctioning compressor valves. If these downtimes are removed from the GPU operating hours, because the compressor is not part of the GPU system design, the gross availability increases to 56 percent.

The remaining system issues diagnosed during the Groton test include: recurring high GPU pressure drop (corrected by adding two new coalescing filters and water traps to prevent LFG condensate from entering the small H_2S removal bed), and periodic freeze-ups of the refrigeration system (eliminated by adding an in-line dryer to the d-limonene refrigerant in addition to the d-limonene air vent dryer installed at Penrose). After these improvements were made, the GPU availability for the second half of the Groton test improved to 70 percent.

1.5.2 Fuel Cell Performance

Power Output and Efficiency

At Penrose, the fuel cell was operated at maximum power of 137 kW, which was 3 kW below the goal for operation on LFG. The lower power output was due to less than expected heating value of the inlet LFG stream. The power output at the Groton landfill improved to a peak value of 165 kW. This was due to a 31 percent increase in higher heating value of the Groton LFG.

Fuel cell efficiency was calculated by dividing the energy power output measured at the fuel cell outlet with the GPU exit gas flow rate and lower heating value (LHV). The electric power was measured using a utility grade meter calibrated by the Los Angeles Department of Water and Power. The GPU exit gas flow rate was measured using a Yokogawa calibrated gas flowmeter. The GPU exit gas heat content was determined by averaging the hourly on-line gas chromatograph (GC) samples collected at the GPU exit for the time periods corresponding to fuel cell efficiency measurement periods. These heat content measurements were based on ASTM Method D-3588 (ASTM 1991).

The heat content measurement results, reported on a dry gas basis at 60 ^{o}F and 14.696 psia, are summarized in Table 1-4. The average higher heating value (HHV) at Penrose (based on 7 measurements) was 445.8 Btu/scf versus 580.6 Btu/scf at Groton (based on 6 measurements). The most significant difference was the lower nitrogen content and higher methane content in the Groton gas. Both sites contained very little higher hydrocarbons, with Groton measuring none heavier than methane, and Penrose measuring about 0.02 percent ethane.

Table 1-4. GPU Exit Gas Heat Content Averages		
	Penrose	**Groton**
Average Composition (ASTM method D-1945)[1]		
Nitrogen (%)	17.31	1.16
Carbon Dioxide (%)	37.88	41.21
Methane (%)	44.11	57.30
Ethane (%)	0.02	< 0.01
Propane (%)	nd[2]	< 0.01
Butane (%)	nd	< 0.01
Pentane (%)	nd	< 0.01
Hexanes (%)	nd	< 0.01
> Hexanes (%)	nd	< 0.01
Higher Heating Value (Btu/scf)	445.8	580.6
Lower Heating Value (Btu/scf)	401.3	522.8

[1] Source: ASTM 1996
[2] nd = non-detected

Fuel cell efficiency at Groton was calculated over a nine-day period while the fuel cell was operating at a constant 140 kW. Efficiency during this period of continuous operation was 38.0 percent on a lower heating value basis (See Table 1-5). This calculated efficiency was higher than the 36.5 percent efficiency calculated over a continuous six-day period at 120 kW at the Penrose landfill.

Table 1-5. Fuel Cell Efficiency Results

	Period of Steady Power Output	Steady Power Output Achieved (kW)	Net Energy Output Per Electric Meter (kW)	Gas Flow Consumed (ft^3)	GPU Exit LHV by ASTM Method (BTU/scf)	Efficiency[3]
Penrose	1/24/95 to 1/30/95	120	16,800	3.92E+5	401.5[1]	37.1%
Groton	6/10/97 to 6/19/97	140	28,682	4.87E+5	529.6[2]	38.0%

[1] Average of on-line analyzer measurements taken during steady power output.
[2] Average of two measurements taken on 6/19/97.
[3] Represents efficiency for the fuel cell only. Based on lower heating value.

Fuel Cell Availability

Total operating time for the fuel cell was determined to be 4,020 hours which included 707 hours at Penrose and 3,313 hours at Groton. During the Penrose test, the fuel cell was operational at all times except a period of about 11 hours when the shutdown occurred due to a failed sensor module. The longest Groton run lasted for 825 hours, with one forced outage caused by the fuel cell.

At the Penrose landfill, the adjusted availability was determined to be 98.5 percent, which includes about 11 hours of down time caused by the fuel cell. The adjusted availability for the Groton test was determined to be 96.5 percent, with total downtime of 119 hours.

Fuel Cell Exhaust Emissions

Fuel cell exhaust emission measurements were not performed at the Groton landfill. The emissions for the Penrose site are summarized in Table 1-6. Also included are comparative data taken from other fuel cell units operated on natural gas (Trocciola and Preston, 1998a). Based on these emission levels, fuel cells can operate on LFG while maintaining low emissions, as experienced in natural gas applications.

Table 1-6. Fuel Cell Emissions Summary – Penrose Landfill

	Penrose Average	Average Based on 16 Units Operating on Natural Gas
Nitrogen Oxides (ppmv)	0.12	0.46
Sulfur Dioxide (ppmv)	< 0.23	negligible
Carbon Monoxide (ppmv)	0.77	1.1
Oxygen (%)	7.9	Not available
Carbon Dioxide (%)	12.5	Not available
Note: dry measurements, corrected to 15% oxygen		

1.6 DATA QUALITY ASSESSMENT

A QAPP was developed for the Penrose test, and data quality indicators were determined to address accuracy and precision of key performance parameters. A discussion of sampling procedures, calibration procedures, analytical procedures, and other QA requirements is provided in Section 4. A QAPP was not prepared for the Groton test. However, procedures outlined at Penrose for data handling, sampling, and analyses were continued to maintain data quality. Table 1-7 presents the quality assurance goals and test results for the GPU and the fuel cell.

The quality assurance measurement for accuracy of hydrogen sulfide and three of the four tested halogenated volatile organic compounds did not meet the 15 percent goal. Since the GPU removed all of these selected compounds to below the detection limit in the GPU exit gas, these errors are not significant to the conclusions regarding the overall effectiveness of the GPU for sulfur and halide removal.

The accuracy of the ASTM D-3588 method for calculating GPU exit gas heat content did not meet the 2 percent goal for all constituents, most notably methane at -3.5 percent. All other hydrocarbon species were negligible in these tests. The impact of the 3.5 percent error could be an overstatement of the apparent fuel cell efficiency by 3.5 percent (i.e., the reported 36.5 percent efficiency could be 35.3 percent). A comparative analysis between a series of measurements conducted using an on-line analyzer in the GPU inlet stream and the ASTM measurement results in the GPU exit stream revealed a close agreement (within 1 percent) between the two methods. This indicates that the real error is probably less than 3.5 percent.

The accuracy and precision goals and results for the fuel cell exhaust emissions are also presented in Table 1-7. The quality assurance tests of the emissions monitors showed that the SO_2, CO, CO_2, and O_2 measurements generally met or exceeded the QA goals. The NO_x emissions tests met the stated QA goals for accuracy and precision.

Table 1-7. Summary of Quality Assurance Goals and Test Results

		Precision		Accuracy		
Measurement	**Method**	**Goal**	**Results**	**Goal**	**Results**	**Effect On Data Conclusions**
GPU						
Sulfur Compounds[1] Hydrogen Sulfide	EPA 16 & 18	5%	0.6%	15%	30.7% [4]	H_2S was not detected at GPU exit during GPU performance test, so accuracy was not significant to conclusion regarding GPU effectiveness.
Volatile Organic Compounds[2] Vinyl Chloride Cis-1,2-dichlorethane 1,1 dichlorethane tertrachloroethene	EPA – TO14	15% 15% 15% 15%	19.0% 5.8% 6.9% 6.4%	15% 15% 15% 15%	54.5% 17.6% 13.2% 31.3%	These species were never detected at GPU exit, so effect of not meeting precision (vinyl chloride) or accuracy goal (vinyl chloride, cis-1, 2-dichloroethane, tetrachloroethene) was not significant to conclusion regarding GPU effectiveness.
GPU Input Gas Heat Content[3]	On-Line Analyzer	2%	N\A	2%	1.1%	Meets QA goal for accuracy
GPU Output Gas Heat Content	ASTM D-3588	2%	0.11%	2%	N_2, CO_2, C_3H_8 within 2% CH_4 – 3.5% C_3H_8, C_4H_{10} C_5H_{12} >10%	Accuracy does not meet QA goals for some species. Net effect on heat content is possibly 3 to 4%.
FUEL CELL						
SO_2 Emissions[1]	EPA-6C	5%	Zero drift = -2.1 to +0.9% Span drift = -1.2 to +1.3%	5%	-4.0%	Meets QA Goals
NO_x Emissions[1]	EPA-7E	10%	Zero drift = -28 to +35.2% Span drift = -32 to +21.5%	15%	-22.4% -20.7%	Low absolute NO_x values make higher uncertainty less significant
CO Emissions[1]	EPA-10	10%	Zero drift = 2.8 to +1.9% Span drift = -30 to +2.1%	10%	-5.4%	All but 1 span drift meets QA goals
CO_2 Emissions[1]	EPA-3A	5%		5%	1.3%	Meets QA goal
O_2 Emissions[1]	EPA-3A	5%		5%	0.8%	Meets QA goal

[1] Source: 60 CFR 40
[2] Source: Riggin 1988 and Winberry *et al.* 1988
[3] Source: ASTM 1991
[4] Determined from analysis of one hydrogen sulfide audit

1.7 TECHNOLOGY MODIFICATIONS TO ACHIEVE FULL POWER PRODUCTION

Based on the experience gained from the first application of fuel cells at landfills, the vendor anticipates that the PC25™ power plant can be modified to achieve full rated power when operating on LFG. The following paragraphs briefly discuss these recommendations.

The PC25™ power plant was designed to produced 200 kW of net power when operating on natural gas having a higher heating value range of 976.6 kcal/SL to 1196.2 kcal/sL. LFG with 50 percent methane and a higher heating value of 498.4 kcal/SL was projected to

produce 140 kW of net power. To increase the net power, higher flows of LFG would be required to obtain an equivalent natural gas fuel content and heating value.

One approach for achieving higher flows consists of increasing the fuel flows without producing unacceptable pressure drops. The PC25™ fuel delivery train to the hydro-desulfurizer contains two fuel isolation valves and a check valve having inside diameters (ID) of 2.54 cm and a fuel control valve having an ID of 1.27 cm. By increasing the ID of the isolation valves and the check valve to 3.81 cm, the ID of the fuel control valve to 2.54 cm, and the connecting plumbing to 3.81 cm, flow increases would be accommodated with acceptable pressure drops. The manufacturer expects that these changes would not require major modifications to the power plant.

The high flow rates of LFG would also increase the pressure drop across the fuel flow fields within the cell stack assembly (CSA), and would result in a corresponding increase in the fuel inlet operating pressure. This increased fuel side operating pressure affects the desired pressure differentials between the fuel and air sides of a cell. This differential is known as "reactant cross pressure". The increase in fuel inlet pressure by itself does not result in an unacceptable increase in fuel delivery system pressure drops, but the corresponding increase in reactant cross pressure exceeds established operating limits. One approach capable of lowering the fuel inlet pressure consists of adjusting the flow directors in the CSA fuel manifolds with a corresponding change in the size of the cathode exit flow orifice. This change would produce flows sufficient to generate 175 kW of power. For flows to produce 200 kW, the size of the cathode exit flow orifice would be reduced, and would result in the need for a larger cathode air blower. This approach has a minimum impact on CSA production costs and CSA height.

1.8 VENDOR SUPPLIED TECHNOLOGY COSTS

The equipment verified at the Penrose and Groton landfills represents a single 200 kW production capacity module. According to IFC Corporation, the installed cost for the GPU tested was about $2,450/kW for the Penrose test (labor plus material cost equals $490,000) and $1,655/kW for the Groton test. The cost for the PC25™ fuel cell was $3,000/kW. The operating and maintenance costs are 0.4¢/kW-hr for the GPU and 1.5¢/kW-hr for the fuel cell. These cost factors are based on estimates provided by the vendor, and were not independently verified by the Center.

IFC Corporation projects that a full-scale implementation of the energy conversion technology would incorporate at least four modules capable of generating 800 kW power. They expect the installed cost to be significantly reduced for both the GPU and fuel cell in the future. The GPU scale-up cost from a single 200 kW unit to four units may decrease to $264/kW with system simplifications, dedicated production in a manufacturing facility, and other cost reduction options. For the fuel cell, IFC estimates that a cost factor of $1,500/kW may be offered for the mature technology as routine and production scale quantities are manufactured. These costs have not been verified by the Center, and more accurate and current costs can be obtained from the vendor.

SECTION 2

INTRODUCTION TO LFG AND FUEL CELL TECHNOLOGY

2.1 METHANE CONTROL TECHNOLOGY CHALLENGE

Municipal solid waste landfills are one of the largest anthropogenic sources of methane in the United States, contributing approximately 36 to 40 percent of total U.S. methane emissions annually. The EPA estimates that in the absence of gas recovery and utilization projects, 10 to 14 million metric tons of methane will be emitted by landfills in the year 2000 (EPA 1993). Methane, which is produced by the anaerobic decay of organic material contained in buried solid waste, is a potent greenhouse gas with a global warming potential estimated at 21 times that of carbon dioxide (IPCC 1995). In addition, the explosive nature of methane poses a significant safety hazard from migrating LFG through the side slopes of landfills.

Methane is the major component of LFG produced in landfills. Typical LFG is composed of 35 to 60 percent methane and 40 to 55 percent carbon dioxide, with Non-Methane Organic Compounds (NMOCs), nitrogen and sulfur compounds, oxygen, moisture, and other trace compounds comprising the remaining 0 to 15 percent.

LFG generation is affected by a number of factors, including solid waste density, moisture content, pH, and temperature. Consistent LFG generation is generally achieved within several months of waste placement, and LFG production is a function of the amount of waste in place. Dry landfills typically have a lower annual generation rate than wet landfills. EPA modeling assumes that a typical solid waste landfill with a density of 44.44 lb/ft^3 will produce 2.0 cubic feet of methane per pound of compacted waste over time.

Until recently, surface landfill emissions were not regulated at the Federal level. New Source Performance Standards (NSPS) and Emission Guideline regulations, promulgated in March 1996, require solid waste landfills with greater than 2.5 million metric tons of waste in place and emissions of over 50 metric tons of NMOCs annually to install LFG control systems. Collected LFG is to be treated at a minimum 98 percent destruction efficiency of NMOCs. These regulations, affecting those landfills that were open on or after November 8, 1987 (61 CFR 49, 9905, March 12, 1996), may drive the development of LFG flares and utilization projects because LFG collection is mandated.

At a minimum, the method for mitigating methane and NMOC from LFG is the installation of a gas collection and flare system. The fuel cell energy conversion system provides the opportunity for converting methane in LFG to useful energy. There are two significant differences between mitigation by flaring and mitigation with the fuel cell energy conversion system. First, the fuel cell energy conversion system produces electric energy and thermal energy which may be used to generate revenues from the LFG mitigation system. Secondly, the fuel cell efficiently converts methane to electricity, has lower emissions at the site, and can provide potential emission offsets due to the reduction in emissions from the electric utility which would otherwise be providing the energy.

Fuel cells are efficient converters of chemical energy to electrical energy. Up to 80 percent of energy available through the fuel supply can be converted into electrical and heat energy because the conversion process does not have an intermediate conversion step (i.e., the combustion step required by internal combustion engines). The efficiency of conventional fossil-fueled power plants is dependent on the load at which they operate. At non-peak loads, the efficiency of these commercial systems is significantly reduced. Fuel cells, on the other hand, operate at a relatively constant efficiency under varying loads. Because fuel cell power plants are modular, they can be pre-assembled and installed with relative ease. Based on natural gas

applications, low emission levels of nitrogen oxides, carbon monoxide, and sulfur dioxide can be achieved. In addition, low noise and vibration characteristics enable the units to be used in areas where such conditions must be met. Since LFG contains contaminants which affect fuel cell operation, a gas cleanup system is required to reduce impurities such as sulfur and halide compounds.

2.2 FUEL CELL POWER PLANT TECHNOLOGY DESCRIPTION

2.2.1 Gas Pretreatment Unit Process Description

A simplified schematic of the GPU and fuel cell system is shown in Figure 2-1. The GPU process consists of ambient temperature H_2S removal followed by cooling, condensation, drying, further cooling, hydrocarbon removal and final filtration. It is comprised on three primary subsystems: Clean gas production process, Regeneration process, and Refrigeration process.

Clean Gas Production Process

The clean gas production process operates on raw LFG which is regulated down to 1.52×10^5 Pascal (Pa) from the Penrose plant compressor. This process incorporates H_2S removal, refrigerated cooling, and condensation to remove water, adsorption drying, cooling, and hydrocarbon adsorption process units to remove contaminant from the LFG (see Figure 2-2).

The H_2S removal bed reacts H_2S with O_2 present in the LFG to produce elemental sulfur. This bed contains 119 liters (43 cm diameter by 81 cm deep) of activated carbon impregnated with potassium hydroxide, from Westates Carbon. It is not regenerated on-site, but it can be regenerated off-site if desired, and is replaced periodically. The first stage cooler condenser operates at approximately +2 ^oC and the 2nd stage cooler operates at –28 ^oC. The 1st stage cooler removes water, some heavy hydrocarbons, and sulfides which are discharged as condensate to the Penrose plant's existing gas condensate pretreatment system. Since the GPU operates on a small slip stream from the Penrose site compressor and gas cooler, some of the water and heavy hydrocarbons species are removed prior to the GPU. Most of the contaminant halogen and sulfur species are lighter and remain in the LFG to be treated in the GPU.

All remaining water in the LFG, as well as some sulfur and halogen compounds, are removed in a regenerable dryer bed which has a capacity for adsorbing the remaining water vapor in the LFG. The bed is 119 liters total volume (43 cm diameter by 81 cm deep) filled with 71 liters of Alcoa F200 alumina, followed by 48 liters of Davidson 3A mole sieve. There are two dryer beds so that one is always operational while the other is being regenerated.

The dry LFG is then fed to the second stage cooler. This cooler can be operated as low as –32 ^oC, and potentially can condense out heavy hydrocarbons if present at high levels. In addition, the second stage cooler reduces the temperature of the carbon bed which enhances its adsorption performance (Graham and Ramaratnam, 1993). The downstream hydrocarbon adsorption unit whose temperature is controlled by the second stage cooler, is conservatively sized to remove all heavy hydrocarbon, sulfur, and halogen contaminant species in LFG. The unit consists of two beds, each containing 119 liters of activated carbon (Barneby and Sutcliffe, type 209C). This way, one bed is always operational while the other bed is being regenerated. Both the regenerable dryer bed and hydrocarbon removal beds operate on a nominal 16 hour cycle with each set of beds operating in the adsorption mode for eight hours and regeneration

mode for eight hours. The gas then passes through a particulate filter and is warmed indirectly by an ambient air finned tube heat exchanger to insure a fuel inlet above 0 ^{o}C before being fed into the fuel cell. The GPU process operating pressure is nominally 1.38×10^5 Pa with minimal pressure loss across the equipment. A final regulator reduces the LFG pressure to the fuel cell, which operates at 1×10^3 to 3.5×10^3 Pa inlet pressure.

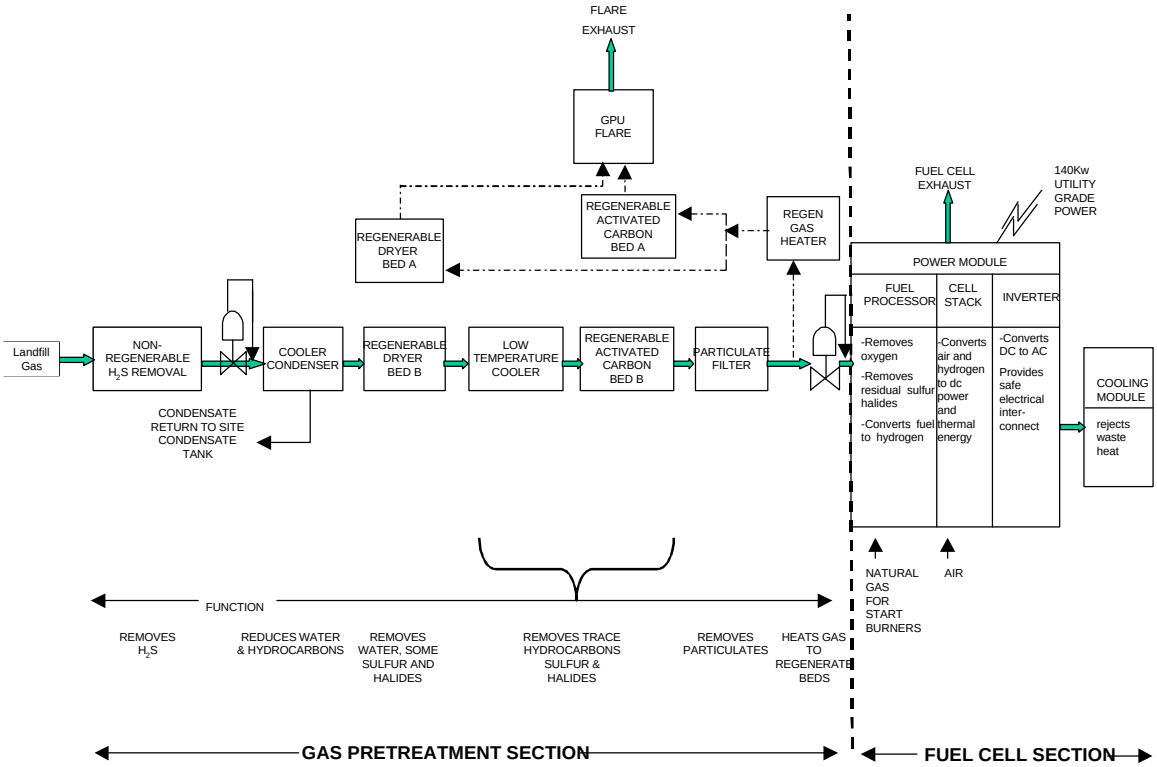

Figure 2-1 Flow Diagram of the GPU and Fuel Cell System

Regeneration Process

The regeneration process, shown in Figure 2-2, heats clean product LFG from the production process and regenerates the dryer and hydrocarbon adsorption beds in the reverse flow direction, and destroys the spent regenerant gas in an enclosed flare. An electric heater is used to heat the recycled clean LFG to 288 ^{o}C. This heated, regeneration gas is used first to regenerate the hydrocarbon adsorption bed, and then the dryer bed is regenerated. The regeneration gas heater is then bypassed and the dryer bed is cooled down with cold regeneration gas. Lastly, the hydrocarbon adsorption bed is cooled down. Each heating and cooling period lasts about two hours for a total regeneration cycle of eight hours. At all times, the regeneration gas flows to the enclosed flare ensuring continuous operation of the flare and continuous thermal destruction of the contaminants and regeneration gas prior to atmospheric dispersion.

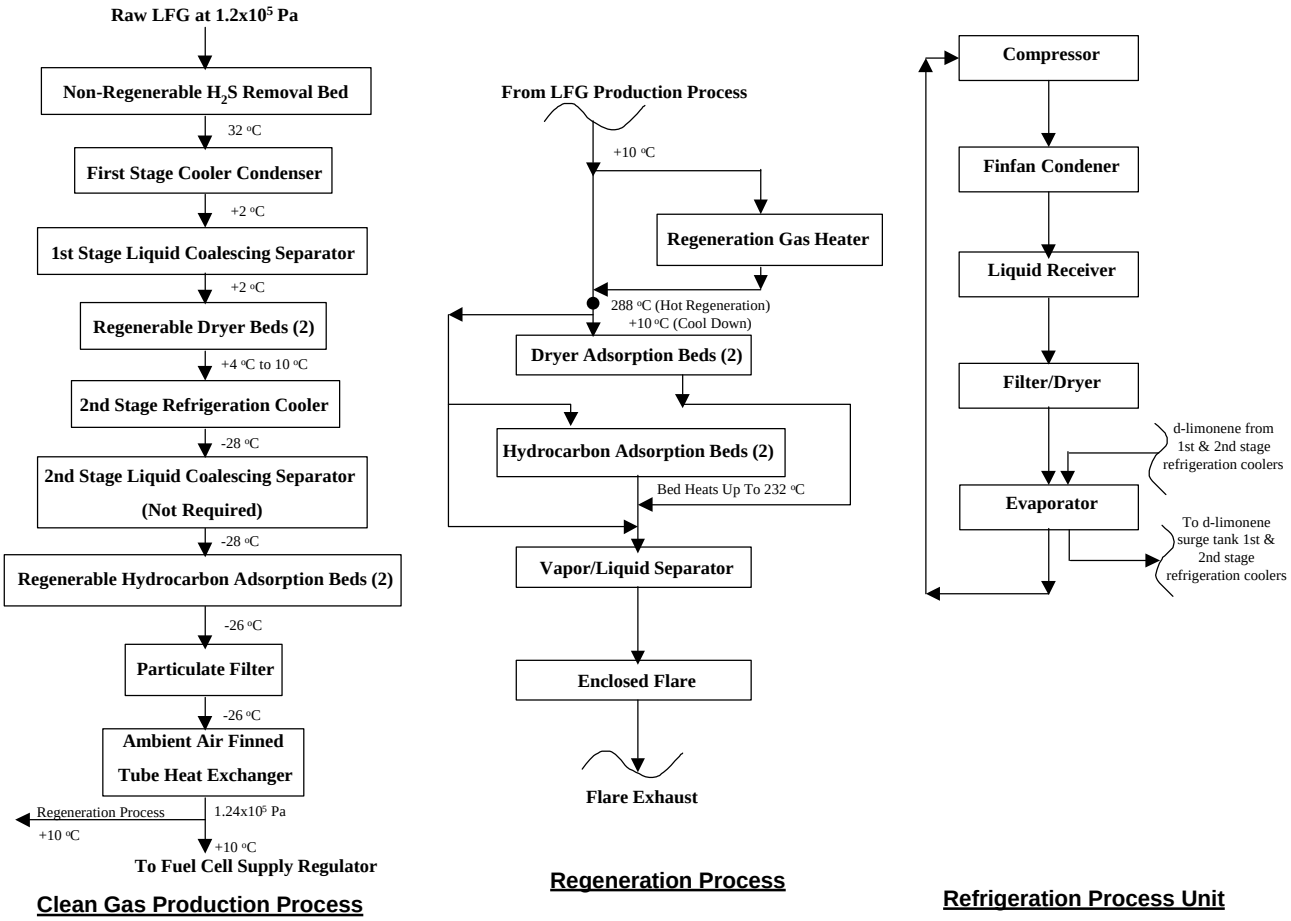

Figure 2-2. GPU Process Operation

Refrigeration Process

The refrigeration process uses R-22 refrigerant in the cycle which provides refrigerated d-limonene coolant at a nominal 2 °C to the first stage cooler and –28 °C to the second stage refrigeration cooler. The d-limonene refrigerant is accepted as an environmentally benign organic extracted from orange peels and pressed pulp. The refrigeration process incorporates a double-stage compressor and plate-type evaporator. The refrigeration cycle operates to maintain the d-limonene coolant temperature setting at its discharge from the evaporator. The compressor is driven by a 7.5 kW motor drive and operates continuously to recirculate R-22 refrigerant in the refrigeration process. The two refrigerants R-22 and d-limonene coolants are completely recycled and are not purged or vented from the process.

2.2.2 Fuel Cell System Process

The fuel cell system, normally used with natural gas, was slightly modified by IFC to accept LFG. It consists of three major components as shown in Figure 2-1: the fuel processor, the fuel cell stack, and a DC-to-AC inverter. The fuel processor converts methane from LFG into hydrogen by the steam reforming process. It also removes low levels of oxygen and sulfur in the LFG stream that may have remained following treatment in the GPU.

Fuel cells produce power and heat by combining hydrogen and oxygen electro-chemically. Natural gas or LFG is reformed within the power plant to provide the hydrogen fuel while ordinary air is used as the oxygen source. The fuel cell stack consists of two electrodes (cathode and anode), a phosphoric acid cell, and an external circuit for the conduction of electricity. Input hydrogen gas is oxidized at the anode to produce hydrogen ions and electrons. The electrons flow through an external circuit to the cathode. Hydrogen ions flow through the electrolyte to the cathode and react with the introduced oxygen in the presence of electrons to produce water and heat. The external direct current (DC) is then converted into 60-cycle alternating current (AC) by the inverter. This power could then be conducted through a transmission line via an interconnect point. Excess heat that is generated can be vented to the air through a cooling module. The fuel cell exhaust maintains low levels of NOx, SO_2, CO, and NMOCs, allowing the system to offer significant environmental benefits.

2.3 APPLICABILITY OF THE FUEL CELL TECHNOLOGY

To determine the potential power generation market available for fuel cell energy recovery, the current population of municipal solid waste landfills in the U.S. was examined. It was assumed that each fuel cell would consume 70 scfm of LFG with a heating value of 498 BTU/scf to generate 200 kW of power. The evaluation was based on using an EPA estimate of methane emissions in the year 1997, and an estimate of LFG production rate of 3.08 liters per Mg per year of refuse in place. As shown in Table 2-1, approximately 4,370 MW of power could be generated from the 7,480 existing and closed sites. The largest number of potential sites greater than 200 kW occurs in the 400 to 1,000 kW range, representing a market of 1,700 sites.

Table 2-1. Potential Power That Can Be Produced From Fuel Cells at U.S. Landfills
(Based on Landfill Size and Electric Power Output)

Individual Site Power Rating (kW)	Number Of Potential Landfill Sites	Total Estimated Power Output (MW)
< 200	3700	220
201-400	1100	330
401-1000	1700	1010
1001-1500	380	480
1501-2000	220	380
2001-2500	90	190
2501-3000	60	160
> 3000	230	1600
TOTAL	**7480**	**4370**

Based on Table 2-1, it can be assumed that fuel cell applications at landfills will likely require installations of more than one PC25-200 kW units (i.e., modular units can be installed to produce greater power).

To identify which landfills are candidates for application of this technology, several assumptions were made based on industry practice: (1) a typical U.S. landfill with 1 million tons of municipal waste in place generates about 400 scfm LFG, and (2) landfills smaller than 1 million tons of waste in place are less likely to have installed extensive LFG collection systems (due to depth and economic constraints). A query calculation in the EPA's Landfill Methane

Outreach Program Database (Profiles Database) suggests that an estimated 820 landfills, located in 30 states, are characterized by these assumptions (EPA 1997). This number is in approximate agreement with PC25-200 kW fuel cell manufacturer's estimate of 980 landfill sites. As a result, it is reasonable to assume that the fuel cell technology could be potentially applied at about 800 - 1,000 sites.

Potential applications of the fuel cell technology should also be adjusted to account for those locations where the technology is best suited from an economic and/or environmental standpoint. To this end, certain localities and/or regions of the country may be preferred where a developer can obtain a sales agreement for the generated power on the order of $0.08/kWh to $0.10/kWh (or more). Currently, sales agreements of this kind are difficult to obtain, in part, due to current pricing mechanisms for electrical power. However, favorable market conditions may exist in such areas as California, New York, and parts of New England, and may expand further as a result of deregulation.

Similarly, certain localities and/or regions of the country which are classified as non-attainment for ozone (i.e., NOx and VOCs) and where offsets are expensive or difficult to obtain, may be well suited for low/negligible emission technologies such as fuel cells. Generally, non-attainment areas include most major population centers and are where larger landfills are sited as well. Thus, a reasonable estimate of 70 percent of the applicable 1,000 landfills may be located within the non-attainment areas, and are likely to be candidates for implementing this technology.

For commercial operation, fuel cells will be required to produce full power on LFG (i.e., 200kW). Based on Table 2-1, the most favorable market appears to be sites which produced a total of 800 kW or 4 fuel cells. In addition, this market segment of landfills is unique because large gas turbines or internal combustion engines are likely not to be used at landfills that have the potential to produce greater than 1 MW power.

SECTION 3

VERIFICATION TEST DESIGN AND DESCRIPTION

3.1 BACKGROUND

The verification test described in this report is based on an evaluation of a landfill gas-to-energy test sponsored by the U.S. Environmental Protection Agency's Air Pollution Prevention and Control Division, "Demonstration of Fuel Cells to Recover Energy from Landfill Gas" (Trocciola and Preston, 1998a and 1998b; and Preston and Trocciola, 1998). It represents the first application of a commerical PC25™-200 kW fuel cell at two municipal solid waste landfills.

Technology verification testing was first conducted at the Penrose site in Los Angeles, CA from September 1993 to February 1995. The test was extended to the Groton landfill in Groton, CT to further test the performance of the LFG-to-energy conversion equipment under different conditions. This follow-on test started on June 1995, and was completed in July 1997. The equipment is currently in operation at the Groton landfill.

This section presents the performance verification goals and site characteristics of the Penrose and Groton landfills. Section 4 describes testing and quality control measurement methods, sampling techniques, and calibration procedures followed to ensure data quality. Section 5 presents results, and evaluates the performance of the GPU and the fuel cell system.

3.2 TECHNOLOGY PERFORMANCE VERIFICATION OBJECTIVES

Operational goals and objectives were established to confirm performance of the LFG-to-energy conversion technology through verification testing (see Table 3-1). In brief, the GPU verification objectives were to:

- Remove LFG contaminants to levels required to operate the fuel cell (<3 ppmv of total sulfur and halides);
- Demonstrate up to 500 total hours and 200 hours of continuous operation; and
- Measure emission levels and calculate destruction efficiencies of the GPU flare.

The fuel cell system performance goals included continuous operation to achieve 140 kW power output, estimate fuel cell efficiency, availability, and to measure fuel cell exhaust emission levels.

The verification tests were conducted under the direct management of EPA's Air Pollution Prevention and Control Division. IFC manufactured the GPU and the fuel cell equipment. The test team at Penrose landfill consisted of IFC, Pacific Energy, Southern California Gas, Los Angeles Department of Water and Power, and the TRC Environmental Corporation (TRC). IFC was responsible for coordination of participants, construction and start-up activities, plant operations, measurements and monitoring, and record-keeping. Pacific Energy provided the site, LFG supply and facilities, and staff to operate the GPU and monitor and document LFG quality and quantity. TRC conducted the emission tests, collected and analyzed GPU gas samples to estimate performance, and prepared the emission test report.

Additional laboratory analyses were conducted by Performance Analytical, Inc. and Texas Oiltech Laboratories, Inc.

Table 3-1. Verification Performance Goals

GPU Parameter	Performance Goal
Exit Total Sulfur Concentration	< 3 ppmv
Exit Total Halogen Concentration	< 3 ppmv
Total Duration of Operation on LFG	> 500 hours
Lowest Continuous Run on LFG	> 200 hours
Adjusted Availability	No Initial Goal (to be determined from test)
GPU Enclosed Flare Exhaust Emissions	No Initial Goal (to be determined from test)
Fuel Cell Parameter	Performance Goal
Maximum Power Output	140 kW or more
Stable Power Output	No Initial Goal (to be determined from test)
Energy Efficiency	No Initial Goal (to be determined from test)
Duration of Operation	No Initial Goal (to be determined from test)
Adjusted Availability	No Initial Goal (to be determined from test)
Exhaust Emissions	Equal to or less than those produced from fuel cells operating on natural gas SO_2 = negligible NO_x ∞ 0.5 ppmv CO ∞ 1.1 ppmv

The test team at the Groton landfill consisted of IFC, TRC, Performance Analytical, Inc., and Northeast Utilities operated the test equipment.

3.3 SITE SELECTION CRITERIA

The EPA and IFC sought candidate landfill sites to conduct the fuel cell verification. Several criteria were used to guide the selection of the initial test site (Penrose):

- The landfill site was to have an existing LFG collection system, stable gas flows and composition, available LFG blower capacity, available flare capacity, and excess LFG to operate the test equipment.

- The site was to have available space/facilities suitable for the verification tests. Ideally, the site(s) would have an available natural gas supply and contracts for electricity sales.

- Local codes and environmental regulations at the test site needed to be stringent enough (i.e., the South Coast Air Quality Management District) so that a successful verification would be readily accepted at most potential landfill sites in the U.S.

The Groton landfill also satisfied these conditions while providing different LFG test conditions, and a local utility agreed to host the verification test. As Table 3-2 shows, both test sites are representative of typical U.S. landfills based on size, composition, LFG flow, and moisture content.

Table 3-2. Landfill Gas Characteristics				
	Units	**Range For Most U.S. Landfills[1]**	**Penrose**	**Groton**
LFG Flow Conditions				
Total LFG Produced at Site	scfm	70-5000	3000	400
LFG Higher Heating Value	BTU/scf	349 to 598	446	585
Moisture	%	1 to 10	dry	wet
LFG Composition (by volume)				
Methane	%	35 to 58	44.0	57.0
Carbon Dioxide	%	40 to 55	38.0	41.0
Nitrogen	%	0 to 15	17.6	1.3
Oxygen	%	0 to 2.5	0.4	0.41
Total Halides (as Cl)	ppmv	not available	45 to 65	7 to 45
Total Sulfur (as H_2S)	ppmv	1 to 700	111	182
NMOCs (as methane)	ppmv	237 to 14,294	130 to 475	not available

[1] Source: EPA 1991; and Augenstein and Pacey, 1992

3.4 CHARACTERISTICS OF THE CANDIDATE SITES AND SELECTION

3.4.1 Initial Verification Test

All candidate landfill sites considered were in California, since they were located in a state which was expected to provide a significant portion of the total U.S. market for fuel cells. Landfill sites initially recommended by Pacific Lighting Energy Services included Oxnard Station, Penrose, Toyon Canyon, and Otay Station.

Oxnard and Otay landfills were eliminated from consideration primarily because they were located at a greater distance from Los Angeles than other sites (and thus, not under the purview of stringent regulations of the SCAQMD), and because natural gas service was not available onsite (as required for GPU and fuel cell tests). The Toyon Canyon site was dropped from consideration because of unstable LFG flows and composition, especially during the summer months.

The Penrose site was selected because: (1) it was representative of typical U.S. landfills based on size and LFG composition, (2) it was located within the SCAQMD region (3) an existing LFG system was available and well maintained; (4) natural gas supplies were accessible onsite; (5) contracts to sell electricity and purchase equipment were available; and (6) there was sufficient space for a verification test equipment to be installed. Contracts for electricity sale existed because of operation and subsequent power sales from IC engines operating on LFG at the site.

3.4.2 Follow-On Verification Test

The purpose of the follow-on test of the fuel cell power plant was to test the consistency of operation using LFG that differed from the initial test conditions. That is, LFG with higher heating value than Penrose was expected to be tested and operated for a year. The project was moved to the East Coast and narrowed down to a New England site since the Northeast Utilities Company agreed to provide significant financial contribution to become the host utility for the test. The Groton landfill site was chosen because it had recently been closed and

capped, had an active LFG collection system, and was supported by Groton town officials. The site also had access to a natural gas supply which was considered necessary for preliminary tests.

3.5 DESCRIPTION OF SELECTED SITES

3.5.1 Penrose Site

The Penrose site is located approximately 15 miles northwest of downtown Los Angeles, in Sun Valley, California. It is one mile west of the Golden State Freeway at Penrose Avenue. The Penrose site is actually a power station where the LFG from four different non-hazardous municipal waste landfills is brought, and processed to produce electricity with six reciprocating compressors.

The refuse is filled over an area of 72 acres with an average depth of 200 feet. The facility has been closed since 1983, and approximately 9 million tons of municipal solid waste is in place. Typical LFG collection rates at Penrose are greater than 3 million standard cubic feet per day. The collection system consists of 85 wells (55 are single pipe wells and 30 are double pipe wells). The wells are interconnected with above and below ground header systems. The LFG collected is conveyed to six 150-horsepower reciprocating compressors that compress the LFG to about 90 to 100 psig before delivery to six 2 kW Cooper Superior IC engines. The site typically generates 9.4 MW. The electricity is sold to the Southern California Edison Company under a 20-year contract. Labor resources for the power plant include a three-man crew to operate and maintain the facility.

3.5.2 Groton Landfill

The Groton landfill, located in Groton, Connecticut, is a 45-acre closed landfill, with approximately 2 million tons of waste in place. Prior to the selection of the site for the fuel cell verification test, LFG generated at the landfill was collected and burned in an open flare at an approximate rate of 400 scfm. On the basis of this flow, it was estimated that 1 MW of electric power could be generated on site. The fuel cell system currently uses a maximum flow of 80 scfm LFG; excess LFG is conveyed to the on-site flare.

3.5.3 Comparison of Gas Quality

LFG collected at Penrose landfill contained 44 percent methane compared with approximately 57 percent methane measured from the Groton landfill. The nitrogen content in Groton LFG was about 1.3 percent compared to a relatively high 17.6 percent nitrogen content at Penrose. The nitrogen content of the Penrose site is higher than the range (0 to 15 percent) expected from most U.S. landfills (with a typical value of 5 percent). Carbon dioxide and oxygen contents were comparable at the two sites. A concentration range for total halides is not available for U.S. landfills. However a typical value of 132 ppmv has been presented in Trocciola and Preston 1998a. Due to the lack of variability expected in halide levels, it can not be assessed whether the halide levels are representative of U.S. landfills. Additional comparison of LFG quality and composition is detailed in Table 3-2.

Based on differences in the LFG methane content, the net energy recoverable from a unit volume of Penrose LFG would be lower than that recoverable from a corresponding volume

of Groton LFG, (i.e., the heating value of Penrose LFG was lower than the heating value of LFG from the Groton landfill).

3.6 SITE-SPECIFIC ENGINEERING DESIGN AND LAYOUT

3.6.1 Penrose Landfill

The power plant layout for the Penrose landfill is shown in Figure 3-1. Located in the northern portion of the landfill site, the gas pre-treatment skid and refrigeration unit were sited in the middle of the test area. The fuel cell power plant and cooling module were located directly south of the gas pre-treatment unit. The fuel cell pad was made of reinforced concrete, approximately 3.35m by 7.62m, while the cooling pad was approximately 2.4m by 3.66m. The typical area required for such a project is about half an acre.

The control panel for the GPU was located in a utility building to the north, outside the testing area. To the right of this utility building was the flare for the gas pre-treatment system. The entire test area was enclosed by a chain-link fence. Electricity generated at the Penrose Landfill was sold to the Los Angeles Department of Water and Power.

3.6.2 Groton Landfill

The site layout for the fuel cell verification test at Groton is shown in Figure 3-2. The surface area required was about 13 m by 41m and was enclosed by a chain link fence. Since the potential for freezing was not a concern in Los Angeles, the GPU was not designed for cold weather operation. However, to account for cold temperatures of the northeast, an enclosed building was constructed to house the GPU at Groton. The housing was a pre-engineered, all-weather building with aluminum siding and insulated walls and roof. The building was heated to prevent potential freezing of LFG and LFG condensate. The area within the building was classified as a Class 1, Division 2 location, and associated electrical equipment and fixtures were built to be explosion proof.

The LFG moisture separator, hydrogen sulfide adsorber vessels, gas compressor, GPU, and refrigeration unit were sited in the gas pretreatment unit building. The building was equipped with a combustible gas detector to monitor the interior atmosphere and shut down the gas compressor if methane gas was detected. The existing LFG flare was located in the southern portion of the site along with an underground storage tank to collect condensate that comes from the LFG and the GPU. The GPU control room housed the GPU control panel, refrigeration unit purge air compressor, nitrogen bottles for activating the GPU pneumatic valves, and project documentation. A GPU flare was used to combust the regeneration gas.

Start-up burner fuel for the fuel cell and for the GPU flare was stored on a compressed natural gas bottle rack. The switchgear contained the distribution bus and breakers for the fuel cell and other site equipment. The step-up transformer took the 480-volt power from the fuel cell output and increased it to 13,800 volts for use on the utility grid. The equipment and site layout were designed for unmanned operation. The Groton landfill project sold the electricity generated to the Northeast Utilities system.

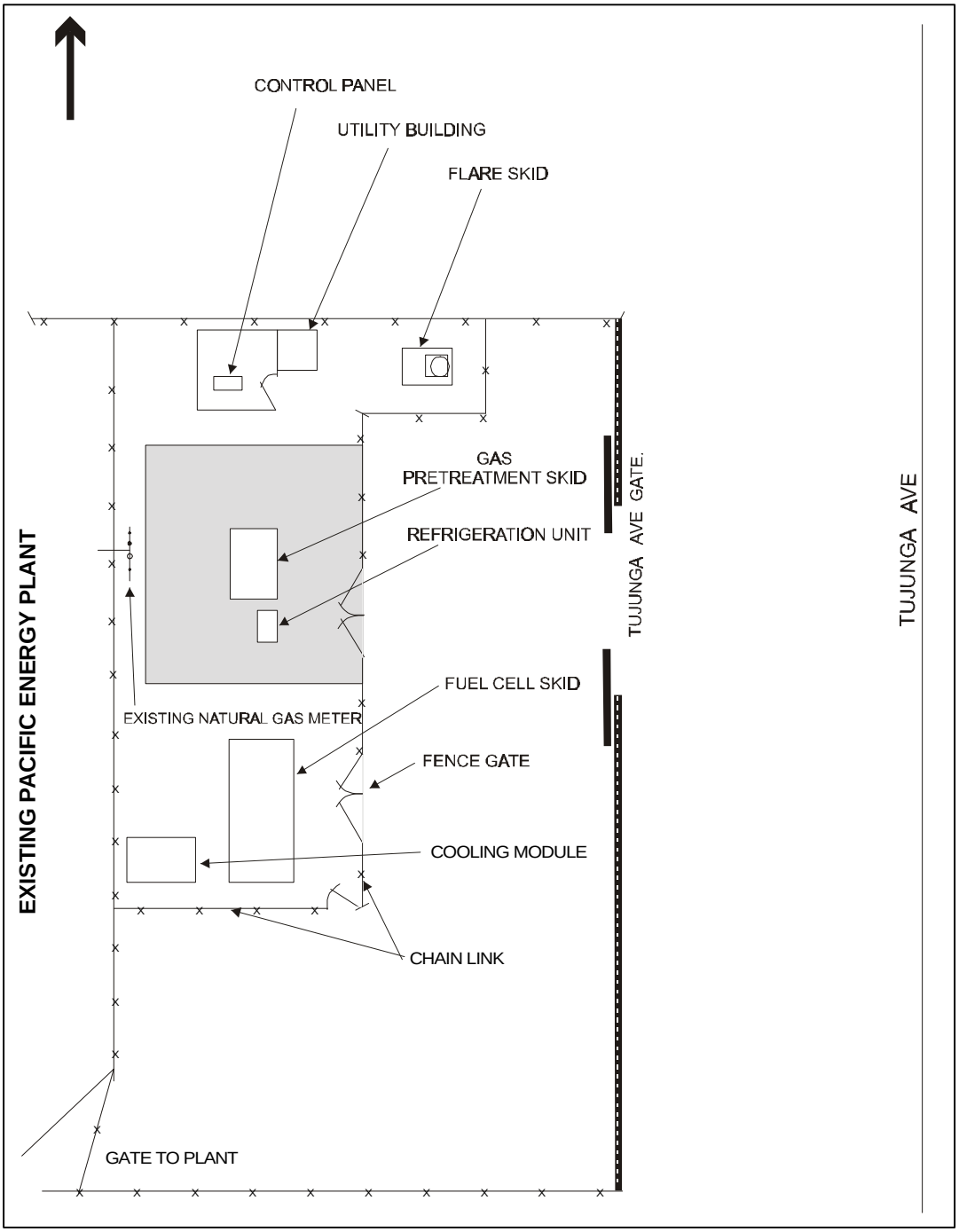

Figure 3-1. Penrose Landfill Test System Layout

The major modification for this test was the addition of a continuous duty LFG compressor to pressurize the gas to 40 psig, at a flow of 80 scfm. The GPU had been designed for LFG under high pressure due to the requirements of the original IC engine-based electricity generation system at Penrose. Since no such compression system existed at the Groton site, a new unit was installed to compress the LFG to levels suitable for GPU functioning.

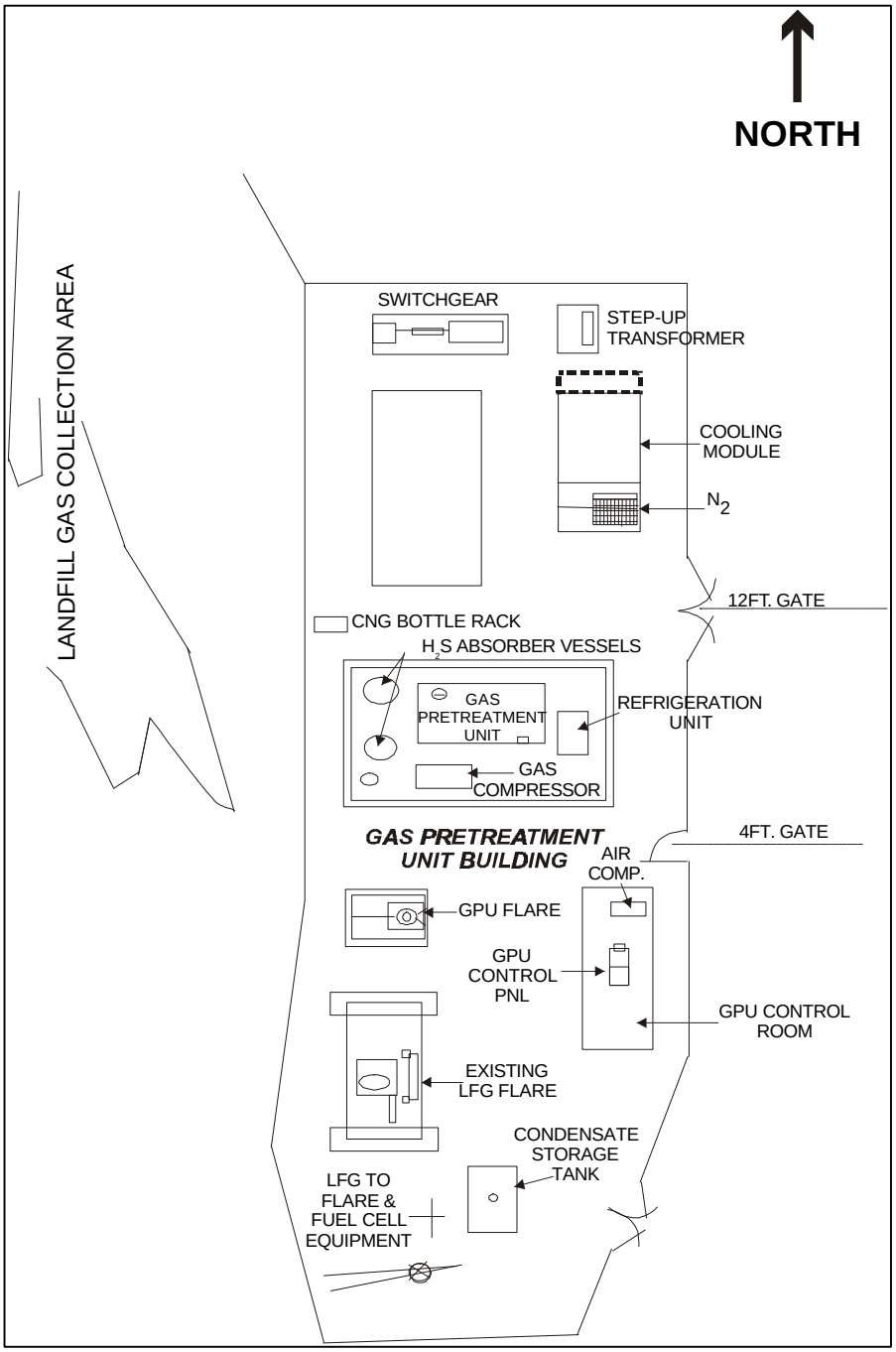

Figure 3-2. Groton Landfill Test System Layout

The capacity of the hydrogen sulfide removal beds was increased relative to the Penrose site, because initial data indicated significantly higher H_2S concentrations (500 ppmv) in Groton LFG. The last modification was the addition of compressed natural gas cylinders to the site to serve as start-up fuel for the reformer burners. This was necessitated since the site did not have a pre-existing natural gas supply.

3.7 SCHEDULE

The test at the Penrose landfill was conducted between September 1993 and February 1995. The Groton landfill test was performed from June 1995 to July 1997. The GPU shake-down archives were performed in the period of October 1993. During these start-up archives, the thermal, mechanical, and electrical performance of the GPU was confirmed on nitrogen gas at the IFC facility in Connecticut and then on LFG at Penrose landfill. The final tests involved the documenting GPU flare performance, and conducting LFG contaminant removal performance checks. The GPU was installed at Penrose landfill in April 1993 and tested for operational performance between September 1993 and December 1993. The complete fuel cell power plant was tested at Penrose landfill from December 7, 1994 to February 19, 1995.

The second test was conducted at Groton landfill beginning with initial set up in June 1995. After LFG quality tests and site preparations were conducted, the verification test was initiated in July 1996 and monitored through July 1997.

SECTION 4

QUALITY ASSURANCE AND QUALITY CONTROL MEASURES

4.1 OBJECTIVE AND ROAD MAP

The objective of Section 4 is to briefly present measurement methods and quality assurance measures for the two verification tests. For the Penrose test, a Quality Assurance Project Plan (QAPP) and Test Plan were developed to ensure that performance and emission measurements were conducted by qualified individuals using proper equipment and written procedures. The QAPP followed the guidelines presented in EPA's Quality Assurance Handbook for Air Pollution Measurement Systems (EPA 1979) for generating accurate and defensible data.

The plan at Groton was to continue the verification test that began at the Penrose site. The operating power output was to be increased to 140 kW if possible. Gas analyses were conducted per the quality assurance guidelines developed at Penrose to maintain a consistent data set. With the exception of the GPU flare and fuel cell exhaust emissions, all measurements conducted at Groton were identical to the data collected at Penrose. An EPA Quality Assurance Officer observed the sampling techniques to ensure measurements were conducting per QAPP guidelines.

Section 4.2 lists the measurements conducted, Section 4.3 discusses sampling techniques, sampling frequency, and analytical procedures, Section 4.4 discusses calibration techniques, and Section 4.4 discusses quality control checks, audits, and corrective actions. The final section summarizes data reduction, validation, and reporting procedures. Additional detail on the QA/QC requirements for each test may be found in Trocciola and Preston, 1998a and 1998b; and Preston and Trocciola, 1998.

4.2 LISTING OF MEASUREMENTS CONDUCTED

The following parameters were measured to verify the performance of the GPU and the fuel cell system at Penrose:

Performance Measurements (GPU and Fuel Cell)

GPU Exit Gas Composition and Removal Efficiency

- Analysis for sulfur and target list VOCs (see Table 4-1) including halides

Fuel Cell Efficiency, determined from the following measurements:

- GPU Inlet Heat Content (on-line method)
- GPU Exit Heat Content (manual method)
- GPU Output Gas Flowrate
- Fuel Cell Electrical Output

GPU and Fuel Cell Raw Availability and Adjusted Availability

Emission Measurements (Fuel Cell Exhaust and GPU Flare Exhaust)

Sulfur Dioxide (SO_2)
Nitrogen Oxides (NO_x)
Carbon Monoxide (CO)
Carbon Dioxide (CO_2)
Oxygen (O_2)
Flowrate
Moisture

4.3 SAMPLING AND ANALYTICAL PROCEDURES

4.3.1 GPU Exit Gas Composition

Samples were collected from the GPU exit to verify the GPU's ability to remove LFG contaminants. The sampling location was under 24 psig pressure which did not require sampling pumps. The sampling port was comprised of a gate valve with a ¼" tube Swagelok connector. The GPU exit and raw LFG sampling locations were in 1½" pipes.

It was expected that breakthrough of organic compounds would most likely occur at the end of an on-line cycle. Therefore, sampling was conducted at the end of the cycle to assess GPU performance. Samples were collected during the last hour of an eight-hour GPU bed "make" cycle (after seven hours of on-line operation; before regeneration commences at eight hours).

Tedlar bag samples were collected twice per week from the GPU exit during the one-month performance test period. The tedlar bags were collected over approximately five-minute periods using a stainless steel valve to regulate the flowrate. Integrated samples were collected and analyzed off-site by gas chromatography/mass spectrometry (GC/MS) and gas chromatography/flame photometric detector (GC/FPD). The target compound list is shown in Table 4-1.

The samples collected in tedlar bags were analyzed for seven sulfur compounds and total reduced sulfur as hydrogen sulfide utilizing a GC/FPD according to the procedures outlined in EPA Method 16 (60 CFR 40). An initial calibration curve with a minimum of three points was established using calibration gas standards containing the analytes of concern. The calibration curve spanned the expected concentration of the samples. The initial calibration was verified at least once at the beginning of each 24-hour period with the analysis of a mid-level Continuing Calibration standard. The percent difference of the continuing calibration response factors was within ±15% from the initial calibration mean response factor. One field sample per analytical sequence was analyzed in duplicate to demonstrate the precision of the analytical technique on the sample matrix.

The samples collected in tedlar bags were also analyzed by GC/MS for VOCs. The analyses were performed according to the methodology outlined in EPA Method TO-14 from the *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air* (Riggin, 1988). The method was modified for using Tedlar bags. The analyses were performed by GC/MS utilizing a direct cryogenic trapping technique.

Table 4-1. Typical Concentrations, Detection Limits, and Blank Samples for Targeted Compounds in the GPU Exit			
	Typical Value in Untreated Landfill Gas	**Detection Limit Objective**	**Blank Samples**
Sulfur Compounds (ppmv)			
H_2S	102.0	0.04	< 0.002
Methyl mercaptan	3.0	0.04	< 0.002
Ethyl mercaptan	0.5	0.04	< 0.002
Dimethyl sulfide	6.5	0.04	< 0.002
Dimethyl disulfide	< 0.07	0.02	< 0.002
Carbonyl sulfide	0.2	0.04	< 0.002
Carbon disulfide	< 0.07	0.02	< 0.002
Total sulfur as H_2S	109.0	0.28	< 0.002
Volatile Organic Compounds (ppmv)			
Dichlorodifluoromethane	0.3-0.9	0.009	< 0.001
1,1 dichloroethane	1.2-2.9	0.002	< 0.001
Benzene	1.1-1.7	0.002	< 0.001
Chlorobenzene	0.6-1.4	0.002	< 0.001
Ethylbenzene	4.5-12.0	0.002	< 0.001
Methylene chloride	4.0-11.0	0.003	< 0.001
Styrene	0.5-1.1	0.003	< 0.001
Trichloroethene	1.3-2.4	0.001	< 0.001
Trichlorofluoromethane	0-0.6	0.004	< 0.001
Toluene	28.0-47.0	0.002	< 0.001
Tetrachloroethene	2.4-4.8	0.002	< 0.001
Vinyl chloride	0.1-1.4	0.005	< 0.001
Xylene isomers	5.0-28.0	0.005	< 0.001
Cis-1.2-dichloroethene	3.9-5.9	0.003	< 0.001
Total halides as Cl	47.0-67.0	0.086	

4.3.2 GPU Flare and Fuel Cell Exhaust Emissions

The flare was used to control emissions from the GPU during bed regeneration periods. The flare stack was a 32-inch-diameter refractory lined stack with two sampling ports located 90° apart - one diameter upstream from the outlet and approximately three diameters downstream of the nearest flow disturbance. Flare tests at the GPU exhaust were conducted with sampling times correlating to specific events in the bed regeneration cycles. Flare inlet and outlet samples were collected during hot regeneration of the carbon bed and the dehydration bed, and cold regeneration of the dehydration bed (see Figure 4-1).

Triplicate 60-minute test runs were conducted for each compound listed in Table 4-2 for the flare inlet and outlet. These samples were collected during the first hour, the middle six hours, and the final hour of bed operation. The flare inlet gas flow was measured with an in-line process monitor which sends a signal to the control room chart recorder. The following paragraphs discuss individual measurement techniques.

Inlet and Outlet VOC Emission Concentration – Determined from the triplicate one-hour samples collected simultaneously at the inlet and outlet in Tedlar bags using the evacuated canister technique according to EPA Method 18 (60 CFR 40). The samples were analyzed by gas injections on a GC/MS according to EPA Method TO-14 (60 CFR 40). The samples

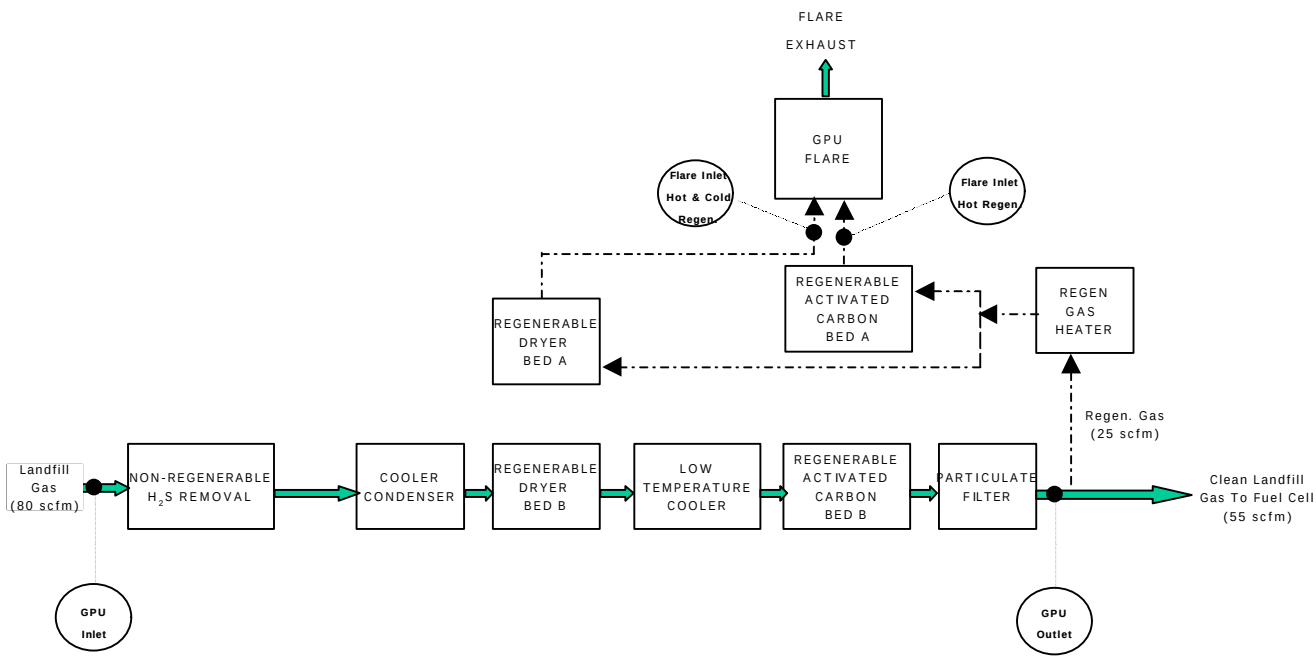

Figure 4-1 Flow Diagram of GPU Flare Test Locations

(Shown With "B" Beds on Line and "A" Beds Being Regenerated)

were concentrated with a cryogenic trap prior to analysis. Each compound was quantified by external calibration curves prepared from gas standards.

Inlet and Outlet Sulfur Compounds Concentration - The same flare inlet and outlet bag samples collected for VOCs were also analyzed by GC/FPD for seven target compounds (see Table 4-2). Samples were analyzed by gas injection on a Hewlet Packard 5890 GC/FPD with a 60 m by 0.53 mm ID capillary column (crossbonded 100 percent dimethyl polysiloxane). These analyses were conducted off-site by an approved, independent testing laboratory. A multilevel calibration was performed for each compound.

Outlet NO_x, CO_2, and O_2 Emission Concentrations - Triplicate one-hour tests were conducted according to EPA Methods 7E, 10, and 3A (60 CFR 40). The reference method analyzers were housed in a mobile CEM laboratory parked at the base of the stack. Sample gas was transported to the system through 50 feet of heated Teflon sample line to a sample gas conditioner in the laboratory. Calibrations were conducted with EPA Protocol I gases.

Outlet Particulate Emissions - Particulate emissions were measured according to EPA Methods 5 and 202 at the flare outlet (60 CFR 40). Triplicate one-hour tests were conducted using non-isokinetic sampling. Samples were collected non-isokinetically because the gas velocity in the stack was below the detection limit of the pitot tube/manometer and hot wire anemometer methods. Total particulate matter was determined as "front half" which included material collected in the probe wash and filter, and "back half" which included both inorganic and organic material collected in the impingers.

Table 4-2. GPU Flare Emission Test Target Compounds	
Flare Inlet	**Flare Outlet**
Methane Total Non-Methane Organics Hydrogen Sulfide C1 through C3 Sulfur Compounds Carbon Dioxide	Methane Total Non-Methane Organics Oxides of Nitrogen Carbon Monoxide Carbon Dioxide Total Particulates
Toxic Air Contaminants (Including but not limited to) Benzene Chlorobenzene 1,2 Dichloroethane Dichloromethane Tetrachloroethylene Tetrachloromethane Toluene 1,1,1 Trichloroethane Trichloroethylene Trichloromethane Vinyl Chloride Xylene	 Benzene Chlorobenzene 1,2 Dichloroethane Dichloromethane Tetrachloroethylene Tetrachloromethane Toluene 1,1,1 Trichloroethane Trichloroethylene Trichloromethane Vinyl Chloride Xylene
Oxygen Nitrogen	Oxygen Nitrogen
Moisture Content	Moisture Content
Temperature	Temperature
Flowrate	Flowrate

Emissions from the fuel cell exhaust were measured over one day. SO_2, NO_x, CO, CO_2, and O_2 and exhaust flowrate were monitored for six 1-hour periods on February 17, 1995. Pollutant measurements were conducted according to EPA Methods 6C, 7E, 10, and 3A (60 CFR 40). Exhaust flow rate was also measured according to EPA Methods 1 and 2 (60 CFR 40).

4.3.3 Heat Content Measurements

For the Penrose test, heat content measurements were conducted at the GPU exit and inlet. ASTM Method D-3588, which covers procedures for calculating heat content from compositional analyses of gas samples, was followed to determine the heat content of GPU exit gas (ASTM 1991). In addition, Pacific Energy operated a continuous fuel heat content analyzer (gas chromatograph) on the raw landfill gas (a sample was analyzed every four minutes). The continuous analyzer data were compared with the ASTM measurements to quantify the difference in the fuel heat content and to allow using on-line measurements when exit heat content data were not obtained.

For the ASTM method, samples were collected in steel canisters by purging the canisters with at least 12 volumes of sample gas. Compositional analyses of the samples were conducted using a gas chromatograph equipped with a thermal conductivity detector to measure the concentrations of N_2, O_2, CH_4, and CO_2, and a gas chromatograph equipped with a flame ionization detector to measure the concentrations of C1 through C6 hydrocarbons. For each gas chromatograph method, an initial calibration curve with a minimum of three points was analyzed using calibration gas standards containing the analytes of concern. The calibration curve spanned the expected concentration of the samples. The initial calibration was verified at least once at the beginning of each 24-hour period with the analysis of a mid-level Continuing

Calibration standard. The percent difference of the continuing calibration response factors was targeted to be within ±15 percent from the initial calibration mean response factor. The heat content of the samples was then calculated using the equations presented in ASTM Method D-3588 from the measured chemical composition.

The on-line analyzer was automatically calibrated daily using a certified gas. The calibration gas contained CO, O_2, N_2, and CH_4. The data system recorded the response factor of each compound, compared it to the certified reference, and reported a deviation.

Accuracy calculations for the ASTM method derived heat content values indicate that the methane concentration was 3.5 percent lower than the certified value. Nitrogen, carbon dioxide, and propane measured concentrations were within 2 percent of the certified values. The remaining compounds (propane, butanes, and pentanes) had a variation greater than 10 percent. The results of this audit indicated that performance was less than QAPP specifications. However, the net effect on heat content analyses was not significant. A comparison study between the on-line Pacific Energy analyzer and ASTM method measurements showed that the two methods were consistently within 2 percent.

4.3.4 Fuel Cell Power Output and Fuel Flow Rate

Fuel cell power output was measured continuously with a calibrated utility-grade digital electric meter. The meter was a digital-display-type meter (Transdata EMS, Model PMG 30018-15) calibrated according to the American National Standard Code for Electricity Metering (ANSI C12). It was installed at the outlet of the fuel cell, following DCDAC conversion equipment, and thus reflects energy loses at the connection into the electric grid.

Fuel cell fuel inlet flowrate was measured continuously with a temperature and pressure calibrated process monitor, a Yokogawa YFCT Flow Computing Totalizer (Style B). Calibration of the gas meter installed on the GPU exit was performed by the manufacturer.

4.3.5 GPU and Fuel Cell Availability

Fuel cell availability was determined by compensating for the times when the unit was not operating due to factors caused by other equipment or operating conditions. Factors which account for adjusted availability include: unforced outages not due to the power plant, shutdowns due to operator error, waiting time for replacement parts where parts were recommended the customer should have on hand, and periods of time when power plant could be worked but manpower was not available such as weekends or vacations. Adjusted availability was not calculated for the GPU. Instead, gross availability, without compensation for downtimes was reported.

4.4 CALIBRATION PROCEDURES

4.4.1 Manual Sampling Equipment

The sampling and measurement equipment, including continuous analyzers, recorders, pitot tubes, dry-gas meters, orifice meters, thermocouples, probes, nozzles, and any other pertinent apparatus was uniquely identified, underwent preventive maintenance, and was calibrated before and after each field measurement, following written procedures and acceptance criteria. Most calibrations were performed with standards traceable to the National Institute for Science and Technology (NIST). These standards include wet test meters, standard

pitot tubes, and NIST Standard Reference Materials. Records of all calibration data were maintained in files.

4.4.2 Fuel Cell and GPU Flare Continuous Monitoring

The continuous measurement analyzers were calibrated before and after each test for zero and span drift according to EPA Methods 6C, 7E, 10, and 3A (60 CFR 40). EPA Protocol I gases were used. The calibration gas was introduced to the system at the probe outlet using a three-way tee. An excess flow of calibration gas was metered to the tee with the excess flowing into the stack through the probe. A calibration error test was also conducted once by initially conducting a zero and span calibration, followed by introducing a zero, high and mid point calibration gas to the system.

The exhaust emission monitors were calibrated before and after each one-hour test with EPA Protocol I gases and the drift performance specifications were within the method specifications for each parameter except for NO_x (the NO_x analyzer was operated at the 0-2.5 ppm range which was too low to meet the method drift specification).

In the analysis of VOCs, verification of the GC/MS was checked at the beginning of every 24-hour analytical sequence by the direct injection of 50 nanograms (ng) of bromofluorobenzene. The calibration range of the target compounds was determined by a three-point curve. Linearity was established over the range of the three-point curve if the percent relative standard deviation of the response factors was less than 30% for each analyte. A continuing calibration was considered to establish the same conditions of linearity and range as the initial calibration if the response factor for each analyte was within 20% of the average response factor for the initial calibration. A continuing calibration was performed at the beginning of each 24-hour period. A blank was analyzed following calibration as a sample to demonstrate that the analytical system was free from contamination.

4.4.3 Other Equipment

The calibration of the gas meter installed on the GPU Exit was performed by the manufacturer. The calibration for the electrical power measurements were conducted by the Los Angeles Department of Water and Power. The calibration reports for these equipment and the on-line heat content analyzer are provided in Trocciola and Preston, 1998b.

4.5 QUALITY CONTROL CHECKS, AUDITS, AND CORRECTIVE ACTIONS

Continuous emission monitoring quality control checks included zero and span drift tests, calibration error tests, system bias checks, and audits. All continuous monitoring zero and span gases were delivered to the probe outlet to challenge the entire sampling system. The QC data was recorded on a data logger chart. A brief discussion of the quality control checks is provided below:

Blanks for both sulfur and VOC analyses were conducted with each set of samples delivered to the analytical laboratory. The blank concentration of target sulfur compounds was less than 2 ppbv and the blank concentration of target VOCs was less than 1 ppbv.

Audit samples for this verification were purchased for target volatile compounds, sulfur compounds, and heat content analysis. The audits were used to determine the accuracy of the results determined from the tests.

Instrument calibration verifications for GC and GC/MS were performed for target volatile compounds, sulfur compounds, and heat content analysis.

Laboratory duplicates were performed for each analytical parameter for each analytical sequence. The percent difference determined was used to evaluate matrix effect on the precision of the analytical technique. The precision objective for laboratory duplicates is 10% relative percent difference.

4.6 DATA REDUCTION, VALIDATION, AND REPORTING

4.6.1 Calculations

Overall Calculations:

Pollutant Mass Emission Rate (SO_2, NO_x, and CO)

$$\frac{\text{grams}}{\text{hr}} = \text{C} \times \text{F} \times \text{MW} \times 0.0025$$

where:
C = Concentration, ppmvd
F = Flowrate, dscm/m
MW = Molecular Weight (SO_2 = 64, NO_x = 46, CO = 28)

GPU Performance (total sulfur and halides) - The performance limit was 3.0 ppmv of total sulfur and 3.0 ppmv of total halides. Total sulfur was computed by summing the products of each sulfur species times the number of sulfur atoms per mole. The results were plotted vs. operating hours. Total halides were computed by summing the products of each halide species times the number of halide atoms per mole of species (e.g., CCl_4 = 4). The results were plotted vs. operating hours.

Fuel Cell and Flare Emissions

$$Emissions(lb/kWh) = \frac{Mass\ Emission\ Rate(lb/hr)}{Power\ Output\ (kWh)}$$

Concentration and flowrate measurements were used to calculate a mass emission rate of NO_x, SO_2, CO, and CO_2 from the flare stack and power plant. Emissions from each source were summed and converted to mass emissions per energy output as follows:

Fuel Cell Efficiency (reference Figure 4-1 for measurement locations)

$$Efficiency = \frac{\text{kWh at } [\text{C}] \times 3413\ \text{BTU/kWh}}{\text{scf at } [\text{B}] \times \text{BTU/scf}}$$

where:

scf = measured GPU exit gas at position [B]; based on flow, temperature, and pressure

BTU/scf = hourly average heat content measured with Pacific Energy's on-line analyzer and a correction factor (1.01) developed from a comparison of six GPU exit ASTM measurements to six hourly averages from the Pacific Energy analyzer

Fuel Cell Availability (adjusted to compensate for outages which are not caused by the power plant system)

$$Adjusted\ Availability = \frac{Operating\ Hours}{(Elapsed\ Time - Adjustment)}$$

Calculation of Data Quality Indicators

Precision: Continuous Emission Monitoring - (determined before and after each test period using a zero and span calibration drift test). The drift was calculated as a percentage of instrument range as follows:

$$\%\,\text{drift} = \frac{\text{monitor value - certified concentration}}{\text{span value}} \times 100$$

Precision: Sulfur and Halide Compounds in the GPU Exit samples - (calculated for each detectable compound from a series of three samples collected simultaneously):

$$RSD = \frac{s}{x}$$

where:

RSD = relative standard deviation
s = standard deviation
x = mean value

Precision: GPU Exit Gas Heat Content Analysis - (calculated from the RSD of a series of three replicate samples per above defined equation).

Accuracy: Continuous Emission Monitoring - (determined by analyzing audit gases for each parameter). The audit cylinders were EPA Protocol I (±1%) or equivalent. Accuracy was calculated as follows:

$$Accuracy = \frac{\text{Cm - Ca}}{\text{Ca}} \times 100$$

where:

Cm = monitor response

Ca = certified audit concentration

Accuracy: Sulfur and Halide Compounds - Audit samples were prepared gravimetrically by a specialty gas manufacturer and certified for ±5% accuracy. The audits were analyzed with the first set of samples submitted to the laboratory. The sulfur audit gases contained hydrogen sulfide and the halide audit gases contained six target compounds. Accuracy was determined as previously described for continuous monitoring.

Accuracy: GPU Exit Heat Content Analysis - One BTU audit cylinder gas audit was purchased from a specialty gas manufacturer and analyzed with the heat content samples by the ASTM method.

4.6.2 Data Validation

Each one-hour period of continuous emission data was reduced on a separate Lotus worksheet file. Copies of the raw data logger charts and the worksheet printouts are provided in Trocciola and Preston, 1998b. Laboratory data were submitted to the designated laboratory personnel for QA evaluation. The QA specialist examined the data, checked the precision and accuracy of the results (duplicate analyses and audits), and reported the findings.

4.6.3 Identification and Treatment of Outliers

Continuously monitored parameters did not change significantly throughout the program. Responses for CEM monitors and Pacific Energy process monitors were evaluated during the emissions testing and no unusual activities were observed. Similarly, the analytical values for halide and sulfur compounds concentrations of the GPU exit gas were constant over the course of the program.

The heat content of the GPU exit sample collected on February 9 was unusually low and was considered to be caused by a sampling error. It was expected that the sampling bulb was not completely purged with sample gas.

SECTION 5

TECHNOLOGY RESULTS AND EVALUATION

5.1 SUMMARY OF VERIFICATION RESULTS

Table 5-1 presents performance measurements data obtained at the Penrose and Groton landfills. The GPU exceeded the stated performance goals. Total halogen and total sulfur levels were well below the minimum requirement. The GPU flare met all mechanical and operating requirements of the SCAQMD, and its performance was determined to be in compliance.

The GPU exceeded the performance goal of 200 hours of continuous operation, with a total of 6,465 hours logged at the two landfills. The longest continuous runs of 342 hours and 827 were recorded at Penrose and Groton, respectively. The gross availability at the Penrose site was about 87 percent. At Groton, several shutdowns of the GPU resulted in overall gross availability of 45 percent; about half of these shutdowns occurred in the first six months of the testing period, and were related to one-of-a kind mechanical failures of the GPU equipment parts which were corrected and did not reoccur because they were related to moving the equipment from California to Connecticut. Significant downtime was also caused by the compressor which was added to increase the LFG pressure as required for the GPU. Several of these failures required considerable trouble-shooting time to determine the root cause and to design a suitable solution to the problem, and then procure and install the appropriate fix. It is estimated that over one thousand hours were lost due to failed compressor valves. Once the mechanical failures were resolved, the GPU gross availability for the second half of the Groton test period improved to 70 percent.

The fuel cell met all performance goals, with the exception that the maximum power generated at Penrose was 3 kW less than expected. This was primarily because the LFG heating value was less than expected (methane composition was about 44 percent). At Groton, the fuel cell achieved higher power (165 kW) because of higher heating value gas (methane concentration was over 57 percent). The fuel cell demonstrated the LFG-to-energy conversion concept with energy efficiency values between 36.5 and 38.0 percent (based on lower heating values), adjusted availability of over 96 percent, and over 4,000 operating hours logged. The fuel cell exhaust emissions were consistent with those reported for natural gas applications. The remaining discussion in this section focuses on the measurement and evaluation of each verified parameter.

5.1.1 GPU Contaminant Removal

The GPU removed contaminants in the LFG by a factor of about 64 times below the 3 ppmv performance goal for total sulfur, and by a factor of about 94 times below the 3 ppmv performance goal for total halides.

Figure 5-1 illustrates time series results for samples collected throughout the GPU operation. The concentration data represent measurement results obtained from tedlar bag samples collected at the GPU exit. With the exception of pre-test check out testing, simultaneous samples were not collected at the GPU inlet (i.e., during actual Penrose and Groton testing). Therefore, average concentration measurements produced from pre-test sampling were used to estimate removal efficiency.

Table 5-1. Summary of Performance at the Penrose and Groton Landfills

	Units	Goal	Penrose	Groton
GPU				
Exit Total Sulfur (as H_2S)	ppmv	<3	0.047	0.022
Exit Total Halides (as Cl)	ppmv	<3	0.032	0.014
GPU Flare Emissions[1]				
NO_x	ppmv	No Initial Goal	7.5 to 14.9	
CO	ppmv	No Initial Goal	1.6 to 5.8	
NMOC	ppmv	No Initial Goal	6.8 to 11.7	
Destruction Efficiency of Sulfur Compounds	%	No Initial Goal	>99	[A]
Destruction Efficiency of VOCs	%	No Initial Goal	>99	
Particulate Matter	grains/dscf	No Initial Goal	0.013	
Total Duration of Operation On LFG	hours	>500	2,297	4,168
Lowest Continuous Run On LFG	hours	>200	342	827
Adjusted Availability	%	No Initial Goal	87.3	45 (total) 70 (last 6 months)
Fuel Cell				
Maximum Power Output	kW	>140 kW	137	165
Stable Power Output	kW	No Initial Goal	120	140
Efficiency at Stable Output[2]	%	No Initial Goal	36.5	38.0
Total Duration of Operation on LFG	hours	No Initial Goal	707	3,313
Adjusted Availability	%	No Initial Goal	98.5	96.5
Exhaust Emissions				
SO_2	ppmv	negligible	<0.23	[A]
NO_x	ppmv	0.5	0.12	
CO	ppmv	1.1	0.77	

[A] Performance measurement was not required at this site.
[1] Results represent emission measurements conducted during hot bed regeneration (worst case conditions) and cold bed regeneration.
[2] Calculated at lower heating values.

During the GPU pre-start check out testing at Penrose, four samples showed no detectable halides while one sample detected 0.008 ppmv and another detected 0.032 ppmv. These outlet concentrations reflect greater than 99 percent removal efficiency (based on simultaneous measurement of 60 ppmv total halogens at the GPU inlet). The removal efficiency for total sulfur was also greater than 99 percent (based on measured inlet concentration of 113 ppmv). Total NMOC (as methane) showed a reduction from 5,700 ppmv at the inlet to 13.8 ppmv at the GPU outlet, for an overall removal efficiency of 99.8 percent.

During the Penrose test, the sample at 1,685 hours detected 0.009 ppmv total halides. All six remaining samples collected through 2,235 hours of operation showed no detectable

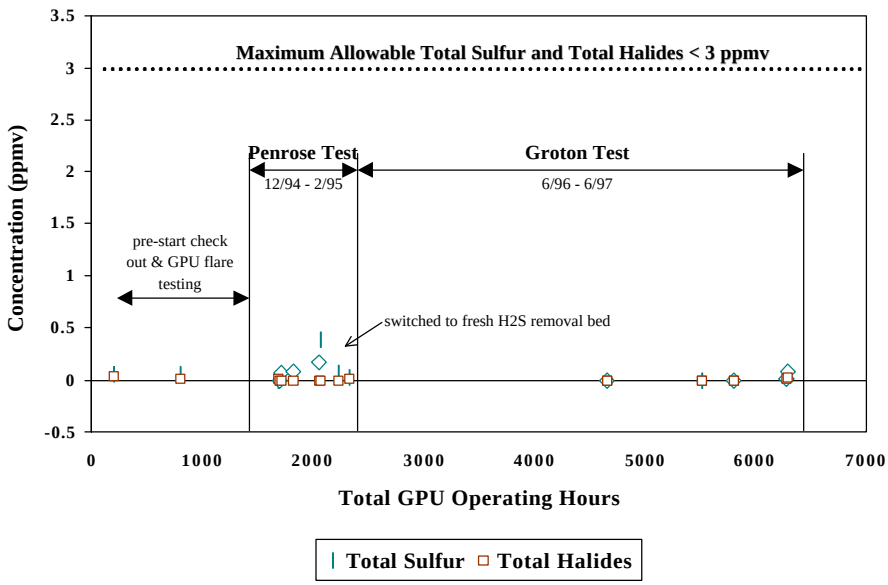

Figure 5-1. GPU Exit Contaminant Concentration Vs. Time

halides. Because of this degree of halide removal, IFC was able to eliminate a halide guard bed initially planned for integration into the PC25™ power plant. A direct calculation of removal efficiency could not be conducted because simultaneous concentration measurements were not taken at the GPU inlet. However, if it is assumed that the GPU inlet total halide concentration was about 60 ppmv, as measured in the initial pre-test analysis, the removal efficiency is greater than 99.98 percent. Table 5-2 presents the data for individual samples collected at Penrose.

Table 5-2. GPU Exit Contaminant Levels – Penrose Landfill
December 1994 – February 1995

GPU Operating Time (Hours)	1685	1701	1710	1826	2046	2069	2235
Hydrogen Sulfide	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Methyl Mercaptan	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Ethyl Mercaptan	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Dimethyl Sulfide	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Dimethyl Disulfide	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Carbonyl Sulfide	<0.004	<0.002	0.071	0.077	0.173	0.385	0.061
Carbon Disulfide	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Total Sulfur (as H_2S)	**nd**	**nd**	**0.071**	**0.077**	**0.173**	**0.385**	**0.061**
Dichlorodifluoromethane	<0.02	<0.02	<0.001	<0.001	<0.02	<0.02	<0.02
1,1-dichloroethane	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0012	<0.001
Benzene	0.001	<0.002	<0.002	<0.002	<0.002	<0.0016	<0.002
Chlorobenzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0011	<0.001
Ethyl Benzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0012	<0.001
Methylene Chloride	0.005	<0.002	<0.002	<0.002	<0.002	<0.0015	<0.002
Styrene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0012	<0.001
Trichloroethene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0009	<0.001
Toluene	<0.002	0.003	0.002	0.001	0.004	0.0041	0.002
Tetrachloroethene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.007	<0.001
Vinyl Chloride	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Xylene Isomers	0.001	0.003	0.001	<0.001	<0.002	0.0042	0.004
cis 1-2-dichloroethene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.0013	<0.001
Total Halides (as Cl)	**0.009**	**nd**	**nd**	**nd**	**nd**	**nd**	**nd**

nd – non-detected.
All GPU exit samples were collected during the last hour before regeneration.

Total sulfur concentrations in the GPU exit ranged between non-detectable to 0.385 ppmv. The elevated level of 0.385 ppmv represents an atypical condition resulting from a break-through occurring in the non-regenerable H_2S removal bed. The increased concentration results from carbonyl sulfide being formed in the dryer bed according to the following chemical reaction: $H_2S + CO_2 = COS + H_2O$. The low temperature carbon bed does not remove carbonyl sulfide. As shown in Figure 5-1, the exit H_2S levels returned to non-detectable after a fresh non-regenerable H_2S bed was installed,. This experience at Penrose established an operating procedure which required switching the non-regenerable H_2S removal bed to a fresh bed when GPU exit total sulfur concentrations increases. Carbonyl sulfide levels measured shortly after this switch decreased from 0.385 ppmv to 0.061 ppmv. In conclusion, the GPU consistently maintained total sulfur levels well below the goal under normal operating conditions.

Based on the experience with elevated total sulfur concentrations, the useable life of the H_2S removal bed was estimated at 21 days. This yields an apparent capacity of 0.12 grams of sulfur per gram of carbon in the bed. The 119 liter bed volume of the two beds used in the test was too small. Future installations would incorporate larger tanks designed for low cost, ease of servicing, and longer changeout times.

At Groton, GPU exit gas samples were taken from both parallel sets of beds in the GPU (dryer bed and carbon bed). Total halide results also showed no detectable levels for most samples, with the exception of those collected in the last month (see Table 5-3). The concentration for these samples ranged from 0.012 ppmv to 0.019 ppmv because of a change in GPU operating conditions. Similar to the Penrose test, simultaneous GPU inlet gas samples were not collected at Groton. Assuming the inlet total halide concentration is 7 to 45 ppmv, as measured from initial LFG analysis, the removal efficiency is estimated to be greater than 99 percent.

Total sulfur remained below detection limits when measured with summa canisters. However, duplicate analyses from Tedlar bags indicated 0.017 ppmv carbon disulfide (0.033 ppmv total sulfur as H_2S) at 5,803 hours, and 0.014 ppmv carbon disulfide (0.027 ppmv total sulfur as H_2S) at 5,805 hours. These data suggest that low levels of carbon disulfide may have adsorbed onto the summa canister walls. Although adsorption of carbonyl disulfide is a concern, the fuel cell preprocessor has the capability to remove organic sulfur, provided the concentration is less than 30 ppmv.

5.1.2 GPU Flare Emissions

The flare was tested during regeneration of Bed A. Samples were collected during hot regeneration of the carbon bed and the dryer bed, and cold regeneration of the dryer bed. The highest concentrations of VOCs and sulfur compounds were measured during the hot regeneration of the dryer bed. The data demonstrated that the flare reduced total NMOC levels from 21,100 ppmv to 11.5 ppmv during the worst-case hot dehydration bed regeneration (see Table 5-4).

Table 5-3. GPU Exit Contaminant Levels – Groton Landfill
June 1996 – July 1997

GPU Operating Time (hr)	2320	4645	4651	5514	5518	5803	5805	6286[4]	6287[4]
SULFUR COMPOUNDS (ppmv)									
Hydrogen Sulfide	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Methyl Mercaptan	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Ethyl Mercaptan	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Dimethyl Sulfide	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Dimethyl Disulfide	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Carbonyl Sulfide	0.022	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	0.010	0.080
Carbon Disulfide	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Total Sulfur (as H_2S)	**0.022**	**nd**	**nd**	**nd**	**nd**	**nd[1]**	**nd[1]**	**0.010**	**0.080**
VOLATILE ORGANIC COMPOUNDS (ppmv)									
Dichlorodifluoromethane	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1,1-dichloroethane	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Benzene	<0.003	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.001	0.00042
Chlorobenzene	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Ethyl Benzene	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Styrene	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0001
Trichloroethene	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	0.007	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.00039
Tetrachloroethene	<0.002	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Vinyl Chloride	<0.004	<0.001	<0.002	<0.002	<0.002	<0.002	<0.002	<0.001	0.0022
Xylene Isomers	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001
Cis 1-2-dichloroethene	<0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.00015
Total Halides (as Cl)	**0.014**	**nd**	**nd**	**nd**	**nd**	**nd**	**nd**	**0.012[2]**	**0.019[3]**

nd = non-detected.
N.A. = data not available.
[1] Carbon disulfide was not detected in Summa Canister sample, but was detected in a tedlar bag sample at 0.017 ppmv (0.033 ppmv totalsulfur) at 5803 hours, and at 0.014 ppmv (0.027 ppmv total sulfur) at 5805 hours.
[2] Chloromethane detected at 0.012 ppmv and Bromomethane at 0.00044 ppmv.
[3] Also detected (ppmv): Chloromethane = 0.013, Bromomethane = 0.00046, Chloroethane = 0.0016, and Trichlorofluoromethane = 0.00033.
[4] Data taken with final carbon beds operating warmer than normal, as part of testing for reduced cost GPU.

In order to calculate flare destruction efficiencies, volumetric gas flow rate at the flare exhaust was required. Although an exit gas flow rate measurement was conducted according to EPA Method 2, the rate was determined to be below the method's detection limit. As a result, destruction efficiency had to be estimated. It was estimated based on the sum of the methane and non-methane gas entering the flare, the stoichiometric combustion air required to oxidize the methane entering the flare, and a measured excess air factor of 2.3 based on oxygen content of the flare exhaust (60 CFR 40). The calculated flare exhaust flowrate was 368 scfm based on 25 scfm total gas flow entering the flare at 44.8 percent methane concentration, the stoichiometric air, and the excess air. Based on these calculations, there was a 14.7 times more gas flow at the outlet sampling location than there was at the inlet sampling location; a factor of 14.7 was used to calculate destruction efficiency. Based on this estimation method, the destruction efficiencies during hot regeneration of the dryer bed was calculated to be greater than 99 percent: dichloromethane at >99.98 percent, tetrachloroethylene at >99.85 percent, dimethyl sulfide at >99.2 percent, and total nonmethane organics at about 99.2 percent. Flare test data for these individual compounds are summarized in Table 5-4, and discussions of the data are provided below.

Table 5-4. GPU Flare Emission Levels (ppmv)
Penrose Landfill (October 23, 1993)

Equipment Tested	GPU		Flare		Flare		Flare	
Time	1000 – 1700		1030 - 1130		1230 - 1330		1730 - 1830	
Process Activity	Bed B: on-line, Bed A: on-regeneration		Carbon Bed A Regeneration (Hot)		Dryer Bed A Regeneration (Hot)		Dryer Bed A Regeneration (Cold)	
Sample Location	GPU Inlet	GPU Outlet	Flare Inlet	Flare Outlet	Flare Inlet	Flare Outlet	Flare Inlet	Flare Outlet
Methane	472,000	483,000	440,000	<1	448,000	<1	463,000	<1
Total Non-Methane Organics	5,700	13.8	1,860	11.7	21,000	11.5	250	6.8
Oxides of Nitrogen[4]	NR [1]	NR	NR	7.5	NR	8.9	NR	14.9
Carbon monoxide[4]	NR	NR	NR	5.8	NR	1.7	NR	1.6
Hydrogen Sulfide	106	<0.004	<0.004	NR	<0.016	NR	<0.004	NR
Carbon dioxide (%)	[2]	[2]	[2]	6.3[6]	[2]	6.2[6]	[2]	7.7[6]
Oxygen (%)	[2]	[2]	[2]	14.9	[2]	15.03	[2]	13.5
Nitrogen (%)	[2]	[2]	[2]	78.8[6]	[2]	78.8[6]	[2]	78.8[6]
C1 through C3 Sulfur CPDS (Total As H_2S)	117	0.017	0.254	NR	80.4	NR	0.05	NR
Carbonyl Sulfide	0.16	0.017	0.061	NR	<0.016	NR	0.014	NR
Methyl Mercaptan	2.79	<0.004	<0.004	NR	0.087	NR	<0.004	NR
Ethyl Mercaptan	0.44	<0.004	<0.004	NR	0.016	NR	<0.004	NR
Dimethyl Sulfide	6.57	<0.004	0.042	NR	73.9	NR	0.031	NR
Carbon Disulfide	<0.04	<0.002	0.146	NR	<0.008	NR	<0.002	NR
Dimethyl Disulfide	<0.04	<0.002	<0.002	NR	0.908	NR	0.005	NR
Toxic Air Contaminants								
Benzene	1.7	<0.002	0.03	<0.002	16	<0.002	<0.04	<0.002
Chlorobenzene	1.4	<0.002	<0.02	<0.002	3.8	<0.002	0.07	<0.002
1,2 Dichloroethane	<0.35	<0.002	<0.02	<0.002	<2.5	<0.002	<0.04	<0.002
Dichloromethane (Methylene chloride)	4.1	<0.002	0.28	<0.002	110	<0.002	0.07	<0.002
Tetrachloroethylene (tetrachloroethene)	4.8	<0.002	0.17	<0.002	19	<0.002	0.1	<0.002
Tetrachloromethane	<0.23	<0.001	<0.02	<0.001	<1.6	<0.001	<0.03	<0.001
Toluene	47	<0.002	1.2	0.007	230	<0.004	0.83	0.0025
1,1,1 Trichloroethane	<0.26	<0.001	<0.02	<0.001	<1.9	<0.001	<0.03	<0.001
Trichloroethylene	2.4	<0.002	0.02	<0.002	17	<0.002	<0.03	<0.002
Trichloromethane	<0.29	<0.001	<0.02	<0.001	<2.1	<0.001	<0.03	<0.001
Vinyl Chloride	1.4	<0.002	1.5	<0.002	<3.9	<0.002	<0.05	<0.002
Xylene	28.2	<0.002	0.04	<0.002	43.8	<0.002	1.8	<0.002
Additional Contaminants								
Dichlorodifluoromethane	0.26	<0.002	3.6	<0.002	<2.0	<0.002	<0.03	<0.002
Cis – 1,2 – Dichloroethene	5.8	<0.002	<0.02	<0.002	62	<0.002	<0.04	<0.002
1,1 – Dichloroethane	2.8	<0.002	<0.02	<0.002	32	<0.002	<0.04	<0.002
Ethyl Benzene	12	<0.002	0.04	<0.002	25	<0.002	0.76	<0.002
Styrene	1.1	<0.002	<0.02	<0.002	<2.4	<0.002	<0.03	<0.002
Acetone	15	<0.005	<0.07	<0.005	150	0.065	<0.12	0.02
2 – Butanone	3.7	<0.004	<0.06	<0.004	28	<0.004	<0.99	<0.004
Ethyl Acetate	10.8	<0.002	<0.04	<0.002	5.4	<0.002	<0.04	<0.002
Ethyl Butyrate	8.4	<0.002	<0.04	<0.002	2.1	<0.002	<0.04	<0.002
Alpha – Pinene	18	<0.002	0.05	<0.002	3.6	<0.002	1.8	<0.002
d-Limonene	18	<0.002	0.07	<0.002	1.4	<0.002	3.6	<0.002
Tetrahydrofuran	2	<0.002	<0.04	<0.002	0.99	<0.002	<0.04	<0.002
Total Particulates ($\mu g/m^3$)[5]	NR	NR	NR	41,900	NR	41,000	NR	20,300
Front Half	NR	NR	NR	0.0069	NR	0.0135	NR	0.0072
Back Half (Organic)	NR	NR	NR	0.0005	NR	0.0010	NR	0.0011
Back Half (Inorganic)	NR	NR	NR	0.0108	NR	0.0033	NR	0.0005
Moisture (%)		<0.01	<0.1	9.2	<0.1	9.1	<0.1	8.6
Temperature (^oF)			80	1186	80	929	79	990
Flowrate (slpm)	2260	1560	700	11,240[3]	700	11,440[3]	700	9170[3]

NOTES
[1] NR = Not Required
[2] Typical landfill gas values are: 43.9% CH_4, 40.1% CO_2, 15.6% N_2, 0.4% O_2
[3] Calculated based on the sum of the methane and non-methane gas entering the flare, the stoichiometric combustion of air to oxidize the methane entering the flare, and the excess air based on O_2 content of the flare exhaust.
[4] Ambient air concentration <1.0 PPMV
[5] 8-hour ambient air sample collected within 20 feet of flare measured 267 $\mu g/m^3$ (equivalent to 0.000116 gr/dscf)
[6] Calculated based on the flare inlet CO_2 plus complete combustion of organics in flare to CO_2. Percent nitrogen calculated as 100% minus sum of O_2 and CO_2.

Flare Destruction of VOCs

The highest VOC concentration entering the flare occurred during hot regeneration of the dryer bed. One-hour samples were collected in Tedlar bags simultaneously at the inlet and outlet during each phase of regeneration. The samples were analyzed for target compounds by GC/MS according to EPA Method TO-14 (60 CFR 40).

Toluene and acetone were the highest concentration VOCs entering the flare, at 230 ppmv and 150 ppmv, respectively. Inlet halide concentrations were also significant, with methylene chloride at 110 ppmv; cis-1,2-dichloroethane at 62 ppmv; 1,1-dichloroethane at 32 ppmv; trichloroethane at 17 ppmv; tetrachloroethane at 19 ppmv; and chlorobenzene at 3.8

ppmv. Flare outlet concentrations of these compounds were below the GC/MS detection limit of 0.002 ppmv.

The destruction efficiency of methylene chloride was greater than 99.97 percent based on a calculated flare exhaust flow of 368 scfm and inlet flow of 25 scfm. The destruction efficiency of tetrachloroethene, which is relatively difficult to oxidize, was greater than 99.85 percent.

Flare Destruction of Total Non-Methane Organics

The highest concentration of NMOCs was also measured during hot regeneration of the dehydration bed. Inlet concentration was 21,100 ppmv (as carbon) and the outlet concentration was 11.5 ppmv. Based on a 14.7-fold increase in air flow at the outlet, the destruction efficiency was 99.2 percent.

Flare Outlet Concentration of NO_x, CO_2, and Particulate Matter

The nitrogen oxides (NO_x) and carbon monoxide (CO) concentrations at the flare outlet averaged 10.4 ppmv and 3.0 ppmv, respectively, over the three test periods. Particulate matter, based on the front-half catch, averaged 0.009 grains/dscf over the three test runs. Particulate matter, based on front-half and back-half catches, averaged 0.013 grains/dscf.

The ambient concentrations of NO_x and CO were below the detection limits of the analyzers. Detection limits were 1.0 ppmv for each compound. Particulate matter was measured with one eight-hour sample collected within 20 feet of the flare on the day of the flare emission testing. The particulate matter concentration was 267 micrograms per cubic meter (ug/m^3).

Condensate Analyses

One condensate sample was collected from the first cooler condenser during the first hour of each cycle for a total of three samples. There was no condensate in the second condenser; as a result, no sample could be collected. Each sample was analyzed for the target sulfur compounds by GC/FPD and the target VOCs by GC/MS.

The highest concentration of VOCs were measured for acetone and 2-butanone, which were detected in each sample. The average concentrations were 16.7 mg/l of acetone and 12.7 mg/l of 2-butanone. The highest concentration of a target sulfur compound was 1.7 mg/l of dimethyl sulfide. However, an unknown sulfur compound was also detected in each sample which increased the average total sulfur concentration to 33.0 mg/l.

5.1.3 GPU Operation and Availability

A summary of GPU operation at the Penrose and Groton landfills is provided in Table 5-5. At the Penrose landfill, the GPU exceeded the performance goal of 200 hours of continuous operation with the longest continuous run of 342 hours. It also exceeded the goal of 500 total hours of operation with 1,782 hours logged with the fuel cell operating and a total operation of 2,297 hours, which includes initial GPU shakedown periods. The shutdowns at Penrose landfill were caused by a loss of the flare UV flame sensor, loss of temperature in the cooling process

for moisture elimination, condensate tank overflow due to high condensate influx at the site, electronic lock-up of control valves, and loss of LFG pressure to the GPU. Modifications were made to prevent such occurrences in the future.

Table 5-5. GPU Operation Summary During Fuel Cell Operating Periods

Landfill Test Site	Test Period	Total Hours	Total Adjusted Hours	Total Operational Hours	Total Shutdown Hours	Gross Availability
Penrose	12/7/94 - 2/19/95	1782	810	707	103	87.3%
Groton	6/17/96 - 7/14/97	9408	9262	4168	5094	45.0% 70% (last 6 months)

The gross availability of the GPU for the entire Groton test was 45 percent. Of the 21 GPU related shutdowns, about half were due to one-of-a-kind mechanical failures which were corrected and did not reoccur. Other shutdowns were due to three major system issues: high pressure drop across the GPU, periodic freeze-ups of the refrigeration system, and an under performing LFG compressor exhaust valve. Recall, the compressor was added at Groton to pressurize the incoming LFG. An estimated down time of approximately 1,050 hours was experienced as a result of malfunctioning compressor valves.

Since the compressor was not a component of the overall GPU system design, it can be generalized that shutdowns resulting from compressor are not representative of GPU's performance. When these downtimes are removed, the gross availability improves from 45 percent to 56 percent. After the remaining mechanical failures were corrected, the gross availability increased to 70 percent over the second half of the demonstration period. The longest operating period recorded was 827 hours.

5.1.4 GPU Exit Heat Content

Heat content measurements of the GPU exit gas were conducted to provide a basis for determining fuel cell efficiency. Table 5-6 and Table 5-7 summarize the data for the Penrose and Groton landfills. The average higher heating value at Penrose was 445.8 Btu/scf, versus 580.6 Btu/scf at Groton. The most significant difference was the lower nitrogen content and higher methane content in the Groton gas. Both sites contained low levels of higher hydrocarbons.

Table 5-6. GPU Exit Heat Content Measurements – Penrose Landfill

Sampling date	1/19/95	1/20/95	1/25/95	1/26/95	2/9/95	2/10/95	2/17/95	Averag
Sampling time	16:44	09:27	16:09	08:31	10:37	09:26	13:33	
GPU Exit Gas Composition (Measured by ASTM Method)								
Nitrogen (%)	16.27	17.25	16.24	16.34	23.89	17.66	20.10	**17.31**
Carbon dioxide (%)	35.54	38.90	39.56	39.53	36.04	38.86	34.91	**37.88**
Methane (%)	44.17	43.81	44.14	44.09	40.07	43.48	45.00	**44.11**
Ethane (%)	0.024	0.029	0.049	0.037	nd[1]	nd	nd	**0.02**
Propane (%)	nd	nd	nd	nd	nd	nd	nd	**nd**
Hexanes	nd	nd	nd	nd	nd	nd	nd	**nd**
> Hexanes	nd	nd	nd	nd	nd	nd	nd	**nd**
Higher Heating Value (BTU/scf)	450.5	447.4	451.5	450.5	409.1	443.4	458.4	**445.8**
Lower Heating Value (BTU/scf)	406.0	403.0	406.0	405.0	367.6	398.0	413.1	**401.3**

nd = non-detected.

Table 5-7. GPU Exit Heat Content Measurements – Groton Landfill

Sampling date	3/20/97	5/19/97	5/19/97	6/19/97	6/19/97	7/9/97	
Sampling time	14:30	10:15	14:53	10:15	12:30	14:15	***Average***
GPU Exit Gas Composition (Measured by ASTM Method)							
Nitrogen (%)	0.07	1.68	1.68	0.93	1.45	1.42	**1.16**
Carbon dioxide (%)	42.14	41.24	41.00	41.46	39.19	40.19	**41.21**
Methane (%)	57.78	56.59	56.86	57.32	58.70	57.97	**57.30**
Ethane (%)	nd	nd	Nd	nd	nd	nd	**nd**
Propane (%)	nd	nd	Nd	nd	nd	nd	**nd**
Hexanes	nd	nd	Nd	nd	nd	nd	**nd**
Higher Heating Value (BTU/scf)	585.5	573.4	576.0	580.9	595.5	587.4	**580.6**
Lower Heating Value (BTU/scf)	527.2	516.3	518.7	523.0	536.2	528.9	**522.8**

nd = non–detected.
Standard conditions at 60 ^{o}F and 14.7 psia.

5.1.5 Fuel Cell Power Output and Efficiency

The fuel cell did not deliver the 140 kW power expected at the Penrose landfill. This was attributed to the lower heat content LFG measured than initially expected. The Groton test results indicate a maximum power production of 165 kW, with 140 kW of steady production. The increase in power is due to about a 10 percent increase in the LFG heating value.

Table 5-8. Fuel Cell Power Output Results				
Landfill Test Site	**Fuel Cell Capacity**	**Fuel Cell Performance Goal**	**Maximum Power Output Achieved**	**Steady Power Output Achieved**
Penrose	200 kW	140 kW	137 kW	120 kW
Groton	200 kW	140 kW	165 kW	140 kW

Fuel cell efficiency was calculated using lower heating values (LHV) measured at the GPU exit per ASTM method (ASTM 1991 and 1996). The efficiency for the two tests ranged between 37.1 and 38.0 percent (see Table 5-9). They were derived by using the average LHV measurements corresponding to the days when steady state power production occurred.

Table 5-9. Fuel Cell Efficiency Results

	Period of Steady Power Output	**Net Energy Output Per Electric Meter (kW)**	**Gas Flow Consumed (ft^3)**	**GPU Exit LHV by ASTM Method (BTU/scf)**	**Efficiency[3]**
Penrose	1/24/95 to 1/30/95	16,800	3.92E+5	401.5[1]	37.1%
Groton	6/10/97 to 6/19/97	28,682	4.87E+5	529.6[2]	38.0%

[1] Average of two measurements taken on 1/25/95 and 1/26/95.
[2] Average of two measurements taken on 6/19/97.
[3] Based on lower heating value.

5.1.6 Fuel Cell Availability

A summary of the fuel cell availability for the two test periods is presented in Table 5-10. As with the GPU, adjusted availability discounts shutdown periods that were not directly attributable to the fuel cell. At both tests, the adjusted availability was determined to range between 96 and 98 percent.

Table 5-10. Summary of Fuel Cell Operation During Test Periods						
	Test Period	**Total Hours**	**Total Adjusted Hours**	**Total Operational Hours**	**Total Shutdown Hours**	**Adjusted Availability**
Penrose	12/7/94 - 2/19/95	1782	718	707	11	98.5%
Groton	7/15/96 - 7/14/97	8760	3432	3313	5328	96.5%

During the Penrose test, a single shutdown due to a bad sensor module in the fuel cell control system was experienced. A single shutdown due to the fuel cell also occurred at Groton. The cause of this shutdown was due to a mechanical failure within the fuel cell power plant resulting from the failure of several electrical space heating elements inside the unit. This

in turn damaged a pump, valve, and flow switch due to freezing of the parts. The mechanical components and heaters were replaced and normal operation was resumed.

5.1.7 Fuel Cell Emissions

The fuel cell emissions data were based on six, one-hour continuous monitor measurements conducted at the Penrose landfill. It was anticipated that the results of the emission testing conducted during this period would be representative of longer term continuous emissions. This is because the fuel cell power plant controller continuously adjusts the fuel and air mixture to maintain constant temperature inside the reformer burner where carbon monoxide and NO_x are generated.

Table 5-11 summarizes the measurements data, reported as actual dry concentrations in ppmv. The power plant SO_2 emissions (0.23 ppmv) were below the method detection limit. NO_x emissions averaged 0.12 ppmv, and CO emissions were near the detection limit, averaging 0.77 ppmv.

Table 5-11. Fuel Cell Emissions Summary – Penrose Landfill
February 17, 1995

	Fuel Cell Operating Time (Hours)						
	660-661	**662-663**	**664-665**	**666-667**	**667-668**	**669-670**	**Average**
Concentration (dry measurements)							
Nitrogen oxides (ppmv)	0.3	0.17	0.31	0.17	0.41	0.18	**0.26**
Sulfur dioxide (ppmv)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	**<0.50**
Carbon monoxide (ppmv)	1.5	1.8	2.1	2.3	0.6	1.9	**1.70**
Oxygen (%)	7.96	8.01	7.88	7.8	8.03	7.91	**7.93**
Carbon dioxide (%)	12.5	12.6	12.7	12.3	12.4	12.5	**12.50**
Concentration (dry measurements, corrected to 15% oxygen)							
Nitrogen oxides (ppmv)	0.14	0.08	0.14	0.08	0.19	0.08	**0.12**
Sulfur dioxide (ppmv)	<0.23	<0.23	<0.23	<0.23	<0.23	<0.23	**<0.23**
Carbon monoxide (ppmv)	0.68	0.82	0.95	1.04	0.28	0.86	**0.77**
Volumetric Flow Rate (dscm/m) [1]	10.1	10.1	9.4	9.4	9.7	9.7	**9.7**
Stack Temperature (^oC)	56.7	56.7	43.3	43.3	42.8	42.8	**48**
Mass Emission Rate (g/hr)							
Nitrogen oxides	0.35	0.20	0.33	0.18	0.46	0.20	**0.29**
Sulfur dioxide	<0.80	<0.80	<0.75	<0.75	<0.78	<0.78	**<0.78**
Carbon monoxide	1.06	1.27	1.37	1.51	0.41	1.29	**1.15**
Mass Emission Rate (g/kW-hr)							
Nitrogen oxides	0.0029	0.0016	0.0028	0.0015	0.0038	0.0017	**0.0024**
Sulfur dioxide	<0.0067	<0.0067	<0.0062	<0.0062	<0.0065	<0.0065	**<0.0065**
Carbon monoxide	0.0088	0.0106	0.0115	0.0125	0.0034	0.0107	**0.0096**

[1] dscm/m = dry standard cubic meters per minute 20 ^oC

The LFG fuel cell results agree well with other emissions data measured from natural gas fuel cells. Average emissions for 16 fuel cell power plants tested at IFC's manufacturing facility using natural gas fuel are: 0.46 ppmv NO_x and 1.1 ppmv CO. Emission tests were also conducted on a fuel cell unit operating at the SCAQMD Headquarters building in Diamond Bar, CA. The results showed 0.45 ppmv NO_x and 1.1 ppmv CO. The Diamond Bar site results were confirmed by two independent laboratories, and were used by SCAQMD as the basis for a blanket exemption from air permit requirements for fuel cells in the Los Angeles basin.

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