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DEMONSTRATION OF FUEL CELLS TO RECOVER ENERGY FROM LANDFILL GAS

PHASE III. DEMONSTRATION TESTS, AND PHASE IV. GUIDELINES AND RECOMMENDATIONS

Volume 1. Technical Report

Prepared for

Cffice of Research and Development

Prepared by

National Risk Management
Research Laboratory
Research Triangle Park, NC 27711

FOREWORD

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DEMONSTRATION OF FUEL CELLS TO RECOVER ENERGY FROM LANDFILL GAS

PHASE III. DEMONSTRATION TESTS, AND PHASE IV. GUIDELINES AND RECOMMENDATIONS

Volume 1. Technical Report

by

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ABSTRACT

This report summarizes the results of a four-phase program with the U. S. Environmental Protection Agency under Contract 68-D1-0008, "Demonstration of Fuel Cells to Recover Energy from Landfill Gas." The environmental impact of widespread use of this concept would be a significant reduction of global warming gas emissions (methane and carbon dioxide). This work was conducted over the period from January 1991 through June 1995.

International Fuel Cells Corporation (IFC) conducted the four-phase program to demonstrate that fuel cell energy recovery using a commercial phosphoric acid fuel cell is both environmentally sound and commercially feasible. Phase I, a conceptual design and evaluation study, addressed the technical and economic issues associated with operation of the fuel cell energy recovery system of landfill gas. Phase II includes design, construction and testing of a landfill gas pretreatment unit (GPU) to remove critical fuel poisons such as sulfur and halides from the landfill gas, and to design fuel cell modifications to permit operation on low heating value landfill gas. Phase III was the demonstration test of the complete fuel cell energy recovery system. Phase IV described how the commercial fuel cell power plant could be further modified to achieve full rated power on low heating value landfill gas.

The demonstration test successfully demonstrated operation of the energy recovery system, including the GPU and commercial phosphoric acid fuel cell modified for operation on landfill gas. Demonstration output included operation up to 137 kW; 37.1 percent efficiency at 120 kW; exceptionally low secondary emissions (dry gas, 15% O_2) of 0.77 ppmV carbon monoxide, 0.12 ppmV nitrogen oxides, and undetectable sulfur dioxide; no forced outages with adjusted availability of 98.5 percent; and a total of 709 hours operation on landfill gas. The pretreatment (GPU) operated for a total of 2,297 hours, including the 709 hours with the fuel cell, and documented total sulfur and halide removal to much lower than specified <3 ppmV for the fuel cell. The GPU flare safely disposed of the removed landfill gas contaminants by achieving destruction efficiencies greater than 99 percent. An environmental and economic evaluation of a commercial fuel cell energy system concluded there is a large potential market for fuel cells in this application.

TABLE OF CONTENTS – VOLUME 1

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS – VOLUME 2

Section **Page**

LIST OF FIGURES

LIST OF TABLES

REFERENCES

1. Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines, EPA-450/3-90-011a (NTIS PB91-197061). March 1991, page 3-30.

2. Landfill Gas Utilization – Database of North American Projects, Susan A. Thomloe and John G. Pacey, presented at the Solid Waste Association of North America's 17th Annual International Landfill Gas Symposium, March 22–24, 1994, Long beach, CA.

3. Demonstration of Fuel Cells to Recover Energy from Landfill Gas, Phase I Final Report: Conceptual Study (Report EPA-600/R-92-007; NTIS PB92-137520). G. J. Sandelli, January 1992.

4. Solid Waste & Power, "Will Gas-To-Energy Work at Your Landfill?," Greg Maxwell, June 1990, p.44.

5. Air Emissions for Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines, EPA-450/3-90-011a (NTIS PB91-197061). March 1991, page 3-23.

6. Ibid, Table 3-6 pages 3-25 through 3-28.

7. "Recovery of VOC's Using Activated Carbon;" James R. Graham, and Mukuno Ramaratnam; Chemical Engineering, February 1993.

ABBREVIATIONS

EPA	United States Environmental Protection Agency
IFC	International Fuel Cells Corporation
ONSI	A Subsidiary of IFC (from On-Site Power)
MSW	Municipal Solid Waste
NMOC	Non Methane Organic Compound
SCR	Selective Catalytic Reduction
GPU	Gas Pretreatment Unit
QAPP	Quality Assurance Project Plan
SCAQMD	South Coast Air Quality Management District
LADWP	Los Angeles Department of Water and Power
LFG	Landfill Gas

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 (10^9 grams)	pounds	2,204,600
VOLUME			
SCMD	Standard cubic meters per day	SCFD (std cubic feet/ day)	35.3
SL/M	Standard liter per minute	SCFM (std cubic feet/ min)	0.0353
PRESSURE			
Pa	Pascal	PSI	1.45×10^{-4}
HEATING VALUE			
kcal/SL	Kilocalories per standard liter	Btu/SCF	112

1.0 EXECUTIVE SUMMARY

The US Environmental Protection Agency (EPA) has promulgated standards and guidelines for the control of air emissions from municipal solid waste (MSW) landfills. This Clean Air Act regulation will result in the control of up to 7 Tg/year of CH_4. The collection and disposal of waste methane, a significant contributor to the greenhouse effect, would result from the emission regulations. This EPA action provides an opportunity for energy recovery from the waste methane that could further benefit the environment. Energy produced from landfill gas could offset the use of foreign oil, and air emissions affecting global warming, acid rain, and other health and environmental issues.

International Fuel Cells Corporation (IFC) was awarded a contract by the US EPA to demonstrate energy recovery from landfill gas using a commercial phosphoric acid fuel cell. IFC conducted a three-phase program to show that fuel cell energy recovery is environmentally feasible in commercial operation. Work was initiated in January 1991. Phase I, a conceptual design and evaluation study, addressed the problems associated with landfill gas as the feedstock for fuel cell operation.

Phase II of the program included construction and testing of the landfill gas pretreatment module to be used in the demonstration. Its objective was to determine the effectiveness of the pretreatment system design to remove critical fuel cell catalyst poisons such as sulfur and halides.

Phase III of this program was a demonstration of the complete fuel cell energy recovery concept.

Phase IV prepared guidelines and recommendations describing how the PC25 ™ C power plant could be modified to achieve full-rated power of 200 kW on landfill gas, based upon the experience gained testing the PC25 A Model in this program.

Phase I

The MSW landfills in the US were evaluated to determine the potential power output which could be derived using a commercial 200 kW fuel cell. Each fuel cell would consume 2800 SCMD of landfill gas to generate 200 kW, assuming a heating value of 4.45 kcal/liter.

The potential power generation market available for fuel cell energy recovery was evaluated using an EPA estimate of methane emissions in the year 1992 [1]. An estimated 4370 MW of power could be generated from the 7480 existing and closed sites identified. The largest number of potential sites greater than 200 kW occurs in the 400 to 1000 kW range. This segment represents a market of 1700 sites or 1010 MW.

The Phase I assessment concluded that these sites are ideally suited to the fuel cell concept. The concept can provide a generating capacity tailored to the site because of the modular nature of the commercial fuel cell. The best competing options, Rankine and Brayton Cycles, are not as effective at these power ratings due to high emission and poor energy utilization..

As a result of the assessment, the conceptual design of the commercial concept was required to be modular (transportable from site-to-site) and sized to have the broadest impact on the market. The design is based on providing a modular, packaged, energy conversion system which can operate on landfill gases with a wide range of compositions as typically found the US. The complete system incorporates the landfill gas collection system, a fuel gas pretreatment system and a fuel cell energy conversion system. In the fuel gas pretreatment section, the raw landfill gas is treated to remove contaminants to a level suitable for the fuel cell energy conversion system. The fuel cell energy conversion system converts the treated gas to electricity and useful heat.

1. Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines, EPA-450/3-90-011a (NTIS PB91-197061). March 1991, page 3-30.

Landfill gas (LFG) is utilized in 110 MSW landfills in the US[2]. These systems have proven the effectiveness of the landfill gas collection systems. Therefore design and evaluation studies in Phase I were focused on the energy conversion concept utilizing fuel cells.

The commercial landfill gas to energy conversion system is illustrated in Figure 1-1. The fuel pretreatment system has provisions for handling a wide range of gas contaminants. Multiple pretreatment modules can be used to accommodate a wide range of landfill sizes. The wells and collection system collect the raw landfill gas and deliver it at approximately ambient pressure to the gas pretreatment system. In the gas pretreatment system the gas is treated to remove NMOCs including trace constituents which contain halogen and sulfur compounds.

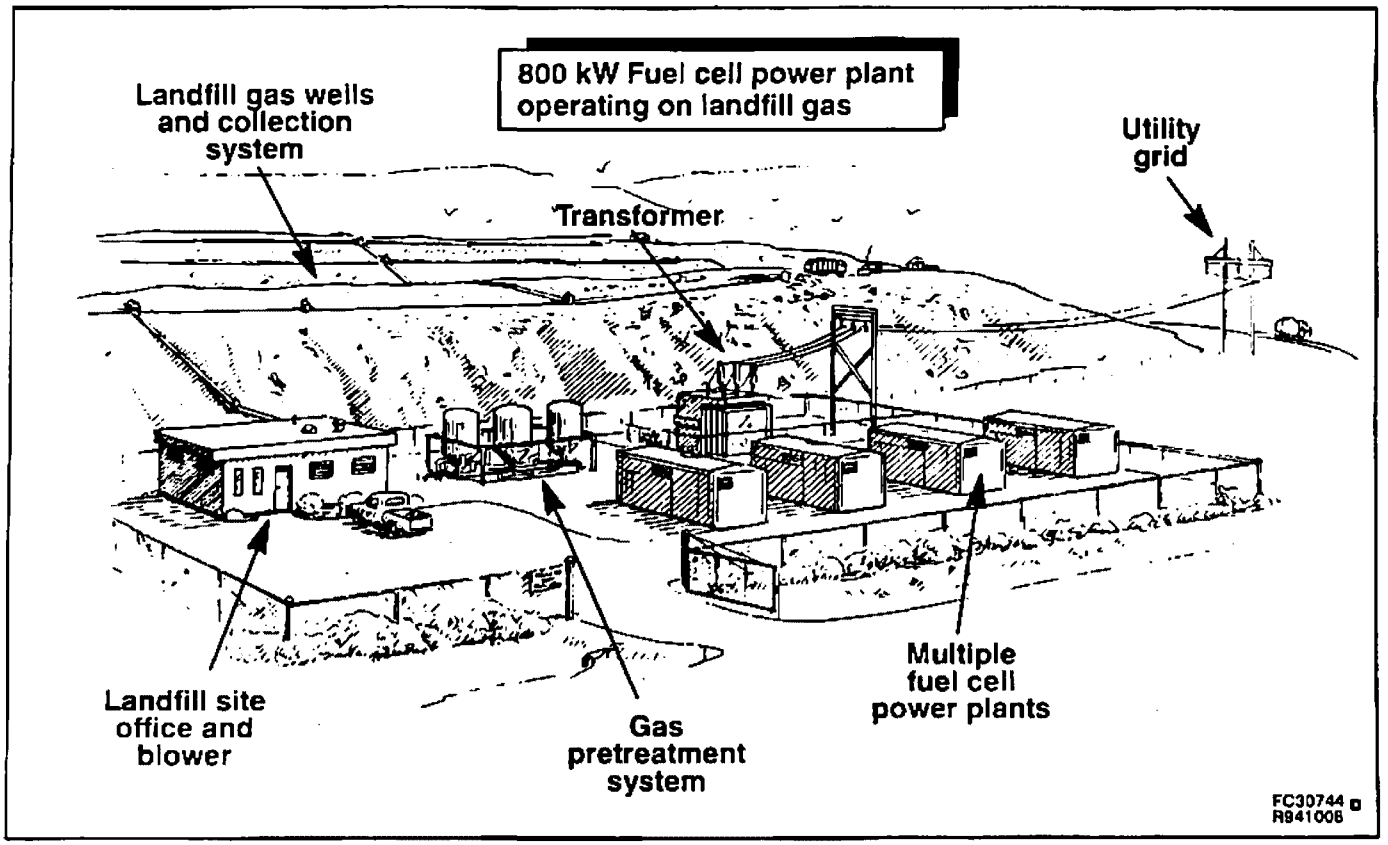


Figure 1-1. Fuel Cell Energy Conversion System Commercial Concept

The commercial energy conversion system shown in Figure 1-1 consists of four fuel cell power plants. These power plants are designed to provide 200 kW output when operating on landfill gas with a heating value of 4.45 kcal/liter and for accommodating higher contaminant concentrations. The output from the fuel cell is utility grade ac electric power. It can be transformed and put into the electric grid, used directly at nearby facilities, or used at the landfill itself. The power plants are capable of recovering co-generation heat for nearby use or rejecting it to air.

2. Landfill Gas Utilization – Database of North American Projects, Susan A. Thornloe and John G. Pacey, presented at the Solid Waste Association of North America's 17th Annual International Landfill Gas Symposium, March 22–24, 1994, Long beach, CA.

Phase II

The major element of Phase II was the construction and subsequent testing of a gas cleanup system at the Penrose Landfill site in Los Angeles (Sun Valley), California. Landfill gases consist primarily of carbon dioxide (CO_2), methane (CH_4), and nitrogen (N_2), plus trace amounts of hydrogen sulfide (H_2S), organic sulfur, organic halides and non-methane hydrocarbons. The specific contaminants in the landfill gas of concern to the fuel cell are sulfur and halides. Both of these ingredients can "poison" and therefore reduce the life of the fuel cell power plant's fuel processor. The fuel processor converts CH_4 in the landfill gas stream into hydrogen (H_2) and CO_2 in an endothermic reaction over a catalyst bed. The catalyst in this bed can react with the halides and sulfides and lose its activity; i.e., poison irreversibly.

The system designed to remove fuel cell contaminants is shown in Figure 1-2. This system is known as the Gas Pretreatment Unit (GPU). H_2S is first removed by adsorption on a packed bed. The material which performs this function is a specially treated carbon activated to catalyze the conversion of H_2S into elemental sulfur which is deposited on the bed. This conversion to sulfur is by the following reaction:

$$H_2S + 1/2\ O_2 \longrightarrow H_2O + S$$

This bed is not regenerable on site, but the carbon can be regenerated off site if desired.

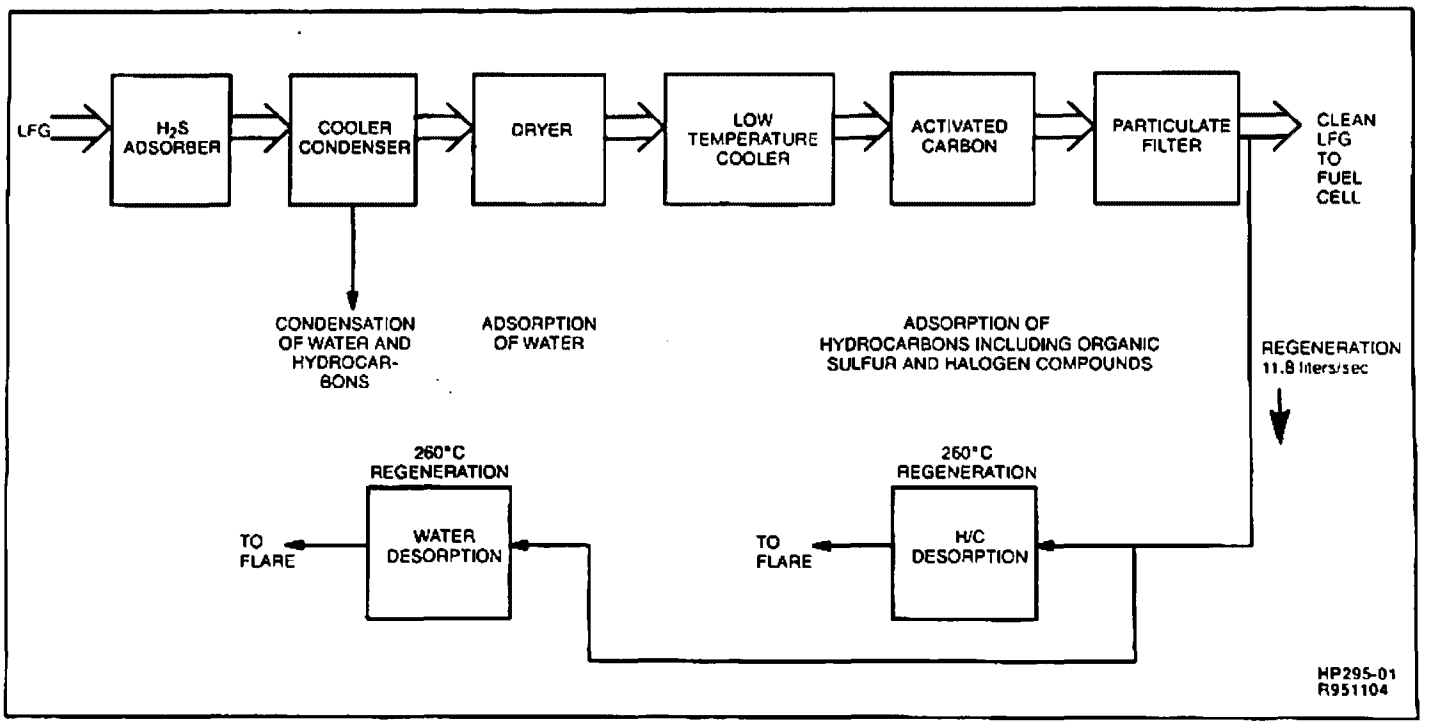


Figure 1-2. Landfill Gas Pretreatment Unit (GPU) System

The first stage cooler removes water, some heavy hydrocarbons, and sulfides which are discharged as condensate to the Penrose plant's existing water condensate pretreatment system. Since the demonstration landfill GPU operates on a small slipstream from the Penrose site compressor and gas cooler, some of the water and heavy hydrocarbon species are removed prior to the GPU. Most of the contaminant halogen and sulfur species are lighter and remain in the landfill gas to be treated in the gas pretreatment unit. All remaining water in the landfill gas, as well as some sulfur and halogen compounds, are removed in a regenerable dryer bed which has a high capacity for adsorbing the remaining water vapor in the landfill gas. There are two dryer beds so that one is always operational while the other is being regenerated. The dry landfill gas is then fed to the second stage cooler. This cooler can be operated as low as -32° C and potentially can condense out

additional hydrocarbons if present at high enough concentrations. In addition, the second stage cooler reduces the temperature of the carbon bed, therefore enhancing its adsorption performance. 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 the landfill gas. This unit consists of two beds of activated carbon so that one is always operational while the other is being regenerated. Both the regenerable dryer and hydrocarbon removal beds operate on a nominal 16 hour cycle of each set of beds operating in the adsorption mode for 8 hours and regeneration mode for 8 hours. The gas then passes through a particulate filter and is warmed indirectly by an ambient air finned tube heat exchanger to ensure a fuel inlet temperature above 0° C before being fed to the fuel cell unit.

The GPU was constructed by IFC at its facility in South Windsor, Connecticut. Construction of the unit was completed in February 1993. Upon completion of construction, the unit was evaluated at the South Windsor facility, using N_2 as the test gas. The unit successfully completed the 16 hour control test verifying that rated flows, pressure, and temperature were achieved. After the test, the unit was shipped to the landfill site located in Los Angeles, California, where it was installed in April 1993. Figure 1-3 is a photograph of the unit installed at the site.

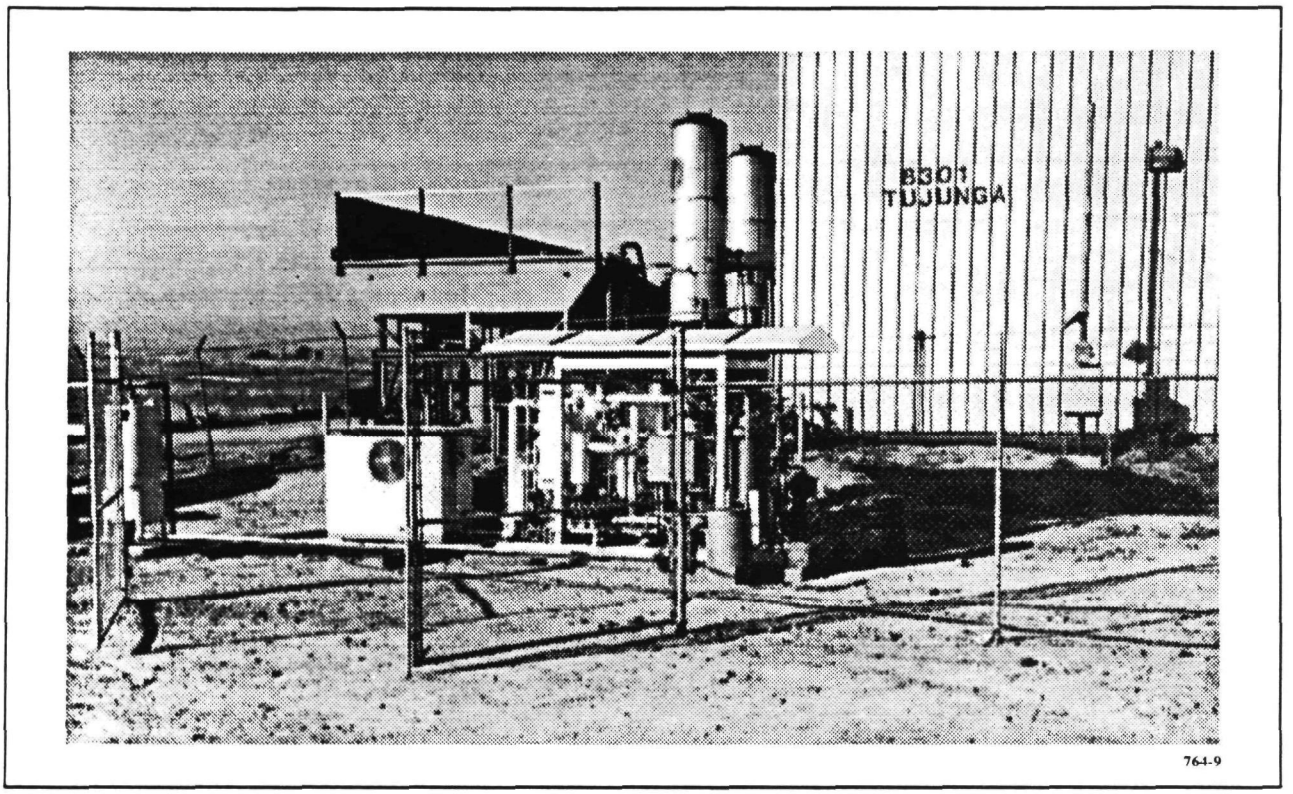


Figure 1-3. GPU Installation at Pacific Energy Landfill

The GPU was successfully tested at the Penrose landfill site in Los Angeles (Sun Valley), California. The GPU successfully removed the sulfur and halogen compounds contained in the landfill gas to a level significantly below the specified value for use with the phosphoric acid fuel cell and to date has operated for approximately 2300 hours.

Table 1-1 compares the measured sulfur and halide contents of the gas produced by the GPU to the specification value. The data verify that the GPU reduces the sulfur and halide contents of landfill gas to a concentration lower than required by the fuel cell power plant. The exceptionally low GPU exit contaminant levels indicate that the low temperature cooler is not essential, even thought the reduced temperature in the activated carbon bed increases capacity for sulfur and halogen compounds. For system simplification in the future, it may be beneficial to eliminate the low temperature cooler, and simplify the refrigeration system, in ex-

change for increasing the activated carbon bed volume slightly. Based on the favorable results of the GPU testing, the EPA directed IFC to proceed into Phase III of the program, which entails characterizing the performance; i.e., emissions, efficiency, and power output of the commercial phosphoric acid fuel cell power plant when operating on land fill gas which has been purified by the GPU.

Table 1-1.
GPU Sulfur and Halide Contaminant Removal Performance and Specification (ppmV)

	INLET	OUTLET	SPECIFICATION
Total Sulfur (as H_2S)[1] in ppmV	117	≤0.047	<3
Total Halides (as Chloride)[2] in ppmV	47	≤0.032	<3

[1] *Measured by Gas Chromatography/Flame Photometric Delineation by EPA Methods 15, 16, and 18*

[2] *Measured by Gas Chromatography/ by EPA Method TO-14*

The power plant utilized in this program is a commercial PC25 ™ 200 kW phosphoric acid fuel cell. The power plant was shipped and installed at the Penrose Landfill during 1994 (Figure 1-4). The unit was started on natural gas prior to its modification for operation on landfill gas. This testing was conducted to establish a baseline performance level. Upon completion of the natural gas testing, the unit was shut down, modified for low heating value gas, and subsequently connected to the GPU for testing on landfill gas. All power produced by the unit was fed into the electrical grid for sale to the local electrical utility, the Los Angeles Department of Water and Power (LADWP). This fuel cell is the first ever connected to the LADWP utility system grid. The revenue produced by the sale of this electricity was used to help offset program costs.

Emission testing of the power plant effluent was conducted by TRC Environmental Corporation during February 1995. Using EPA Methods 6c, 7e and 10 respectively, emission levels of sulfur dioxide (SO_2) were undetectable at a detection limit of 0.23 ppm, while nitrogen oxides (NO_x) averaged 0.12 ppm and carbon monoxide (CO) averaged 0.77 ppm. All the data are dry measurements corrected to 15% oxygen (O_2). These emission levels verify that fuel cells can operate on landfill gas while maintaining the low emission levels characteristic of this commercial fuel cell power plant.

An exciting dimension of the PC25 operating on landfill gas is that, unlike internal combustion engines and turbines, the unit has significant siting characteristics due to its demonstrated low levels of emissions, noise and vibration. It can be located remote from the landfill using gas piped from the site. In this way, its thermal energy, as well as its power, can be put to constructive use at a customer's building. In addition, by siting at the building, the economics improve significantly since the power plant displaces commercial electricity which has a much higher cost than the revenue which would be received if the fuel cell were sited at a landfill and received utilities' "avoided" cost. Utilizing the fuel cell's thermal energy can result in an overall efficiency [i.e., (Electrical Energy plus Thermal Energy)/Energy Content of Gas Consumed] of 80%. This high efficiency conserves natural resources and reduces the amount of CO_2 emitted to the atmosphere. It also improves the economics, since heat may be sold to the building owner.

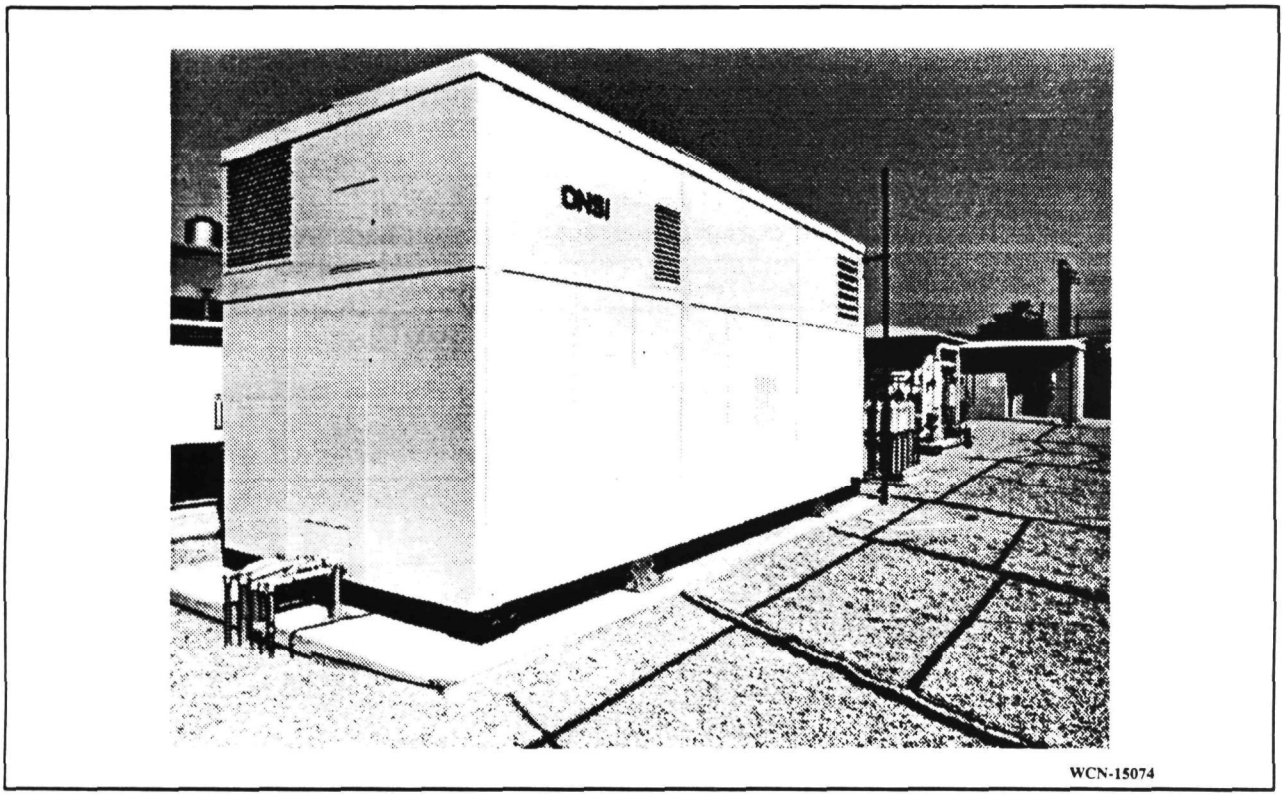


Figure 1-4. PC25 Power Plant Installation at California Landfill Site

2.0 INTRODUCTION

This report summarizes the results of a four-phase program with the U.S. Environmental Protection Agency under Contract 68-DI-0008, "Demonstration of Fuel Cells to Recover Energy from Landfill Gas." The environmental impact of widespread use of this concept would be a significant reduction in global warming gas emissions (methane and carbon dioxide). This work was conducted over the period from January 1991 through June 1995.

The results of the Phase I activity from January 1991 to August of 1992 are summarized in Section 3 of this report. In Phase I, a conceptual design of a commercial scale landfill-gas-to-energy concept utilizing a commercial phosphoric acid fuel cell is established.[3] This conceptual design is utilized to identify key issues associated with utilizing landfill gas as a feedstock for fuel cell operation, and to establish a conceptual design for the landfill-gas-to-energy demonstration utilizing a phosphoric acid fuel cell, conducted in Phase III of the program.

The Phase II activity for the period September 1992 through December 1993 is discussed in Section 4 and 5. The objective in Phase II is to address the two major technical issues impeding commercialization of the commercial concept: 1) Cleanup of the landfill gas to a level suitable for the fuel cell power plant; 2) Modification of the fuel cell power plant for operation on the dilute methane landfill gas fuel. These issues are addressed in a detail site specific process and engineering design of the system design, described in Section 4 of this report, and the construction and test of the gas pretreatment system which is described in Section 5 of this report.

Section 4 of the report, titled Demonstration Test Design, describes the site specific process and engineering design of the gas pretreatment unit designed for this application, plus the PC25 ™ A, 200-kW phosphoric acid fuel cell power plant, and the landfill-gas-to-energy site which was selected in Phase I. The PC25 A fuel cell is uniquely suited to this application due to its low secondary emissions: typically 0.5 ppmV NO_x, 1.1 ppmV carbon monoxide; and 0.03 ppmV non-methane hydrocarbons (all measured at 15 percent oxygen on a dry gas basis using natural gas fuels). Section 4.1 describes the development of the gas pretreatment process from a conceptual design in Phase I, to a complete, detailed mechanical and process design including field modifications in Phase II. In Section 4.2 the PC25 A power plant design modifications to permit operation on landfill gas up to a nominal 140 kW rating are described. Section 4.3 describes the overall site specific process design for the demonstration including the gas pretreatment system and its integration to the fuel cell power plant system. Section 4.4, Site Specific Engineering Design, summarizes the details of the site location and construction for the demonstration equipment.

Section 5, Gas Pretreatment Unit Verification Test, summarizes all aspects of the verification testing of the gas pretreatment system during Phase II. Section 5.1 summarizes the Landfill Gas Pretreatment Module Test Plan and the test protocol used to direct all test activities, while Section 5.2 reviews permitting requirements including South Coast Air Quality Management District and City of Los Angeles Building and Safety Department. Section 5.3 reviews test result including factory testing, initial field checkout testing, and the field verification test.

The results of the Phase III demonstration test activities beginning on January 1994 and ending in June, 1995 are described in Section 6. During this third phase of the program, IFC developed a Test and Quality Assurance Project Plan, completed all permitting activities for the fuel cell with the City of Los Angeles, installed and checked out the fuel cell power plant at the site on natural gas, modified the fuel cell for operation on landfill gas, and then connected the fuel cell to the gas pretreatment unit and operated the demonstration test, including obtaining critical emissions and operating data. The demonstration operated at the existing Penrose Station landfill gas energy recovery facility owned by Pacific Energy in Sun Valley, California. Internal combustion engines presently generate up to 8.9 MW of electricity at this site with landfill gas from four separate

3. Demonstration of Fuel Cells to Recover Energy from Landfill Gas, Phase I Final Report: Conceptual Study (Report EPA-600/R-92-007; NTIS PB92-137520). G.J. Sandelli, January 1992.

landfills. Electricity produced by the fuel cell was sold to the Los Angeles Department of Water and Power electric utility grid.

The QAPP is described in Section 6.1 of this report. The field test preparation is described in Section 6.2, including permitting, site preparation, fuel cell installation and checkout on natural gas, fuel cell modification for landfill gas, and checkout of the GPU plus fuel cell operating together on landfill gas. Section 6.3 summarizes the field test results, including GPU and fuel cell performance, and fuel cell emissions.

The results of the Phase IV study to identify the lowest cost means to modify the latest model ONSI commercial phosphoric acid fuel cell, the PC25 C, for operation at a full rated 200 kW using landfill gas are summarized in Section 7.

The conclusions for the four-phase program are given in Section 8.

3.0 CONCEPTUAL DESIGN, COST AND EVALUATION STUDY RESULTS

3.1 Requirement for Landfill Gas Application

This section reviews the opportunities for using fuel cells for methane mitigation and energy conversion and describes the significant potential market for power generation using fuel cells. A list of requirements is developed for the conceptual design of a commercial fuel cell landfill gas to energy system. The results of the evaluation study form the basis for a conceptual design of a demonstrator fuel cell system for testing at a selected landfill gas site.

3.1.1 Landfill Gas Availability

The Municipal Solid Waste (MSW) landfills in the United States were evaluated to determine the potential power output which could be derived using a commercial 200-kW fuel cell. Each fuel cell would consume 2800 SCMD of landfill gas to generate 200 kW, assuming a heating value of 4.45 kcal/liter.

The potential power generation market available for fuel cell energy recovery was evaluated using an EPA estimate of methane emissions in the year 1997[1] and an estimate of landfill gas production rate of 3.08 liters per Mg per year of refuse in place[4]. An estimated 4370 MW of power could be generated from the 7480 existing and closed sites identified as shown in Table 3-1. The largest number of potential sites greater than 200 kW occurs in the 400 to 1000 kW range. This segment represents a market of 1700 sites or 1010 MW.

The assessment concluded that these sites are ideally suited to the fuel cell concept. The concept can provide a generating capacity tailored to the site because of the modular nature of the commercial fuel cell. The best competing options, Rankine and Brayton Cycles are not as effective at these power ratings due to high emissions and poor energy utilizations.

The result of our assessment is a requirement for the conceptual design of the commercial concept to be modular in nature and sized to have the broadest impact on the market.

Table 3-1. Size Distribution of Landfills and Potential Power Output

Site Power Rating (kW)	No. of Sites	Total Power Output (MW)
Less than 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 Sites	4370 MW

3.1.2 Landfill Gas Characteristics

The available information on landfill gas compositions was evaluated to determine the range of gas characteristics which a fuel cell landfill-gas-to-energy power plant will encounter. This information was used to set the requirements for the gas pretreatment and fuel cell power plant designed to operate on a wide range of available landfill gas compositions within the United States.

4. Solid Waste & Power, "Will Gas-To-Energy Work at Your Landfill?," Greg Maxwell, June 1990, p.44.

A summary of landfill gas characteristics is shown in Table 3-2. The heating value of the landfill gas varies from 3.12 to 5.34 kcal per liter with a typical value of 4.45 kcal per liter. The major non-methane constituent of landfill gas is carbon dioxide. The carbon dioxide ranges from 40 to 55 percent of the gas composition on a dry basis. Other diluent gases include nitrogen and oxygen, which are indicative of air incursion into the well (most frequently in perimeter wells). Nitrogen concentrations can range as high as 15 percent on a dry basis but typical values are five percent or less. Oxygen concentrations are monitored closely and held low for safety reasons. Pacific Energy has indicated that the landfill gas is typically saturated with water vapor at temperatures up to 49°C.

Table 3-2. Landfill Gas Characteristics

Characteristic	Range	Typical
Heating Value (HHV)	3.12-5.34 kcal/l	4.45 kcal/l
CH_4	35-58%	50%
CO_2	40-55%	45%
N_2	0-15%(1)	5%
O_2	0-2.5%(1)	<1% (for safety)
Sulfur as H_2S	1-700 ppmv	21 ppmv
Halides	N/A	132 ppmv
Non-Methane Organic Compounds (NMOCs)	237-14,294 ppmv (as hexane)	2700 ppmv (as hexane)

Note: (1) Highest values occur in perimeter wells

Landfill gas contains trace amounts of nonmethane organic compounds (NMOCs). A typical value of NMOC concentration of 2700 ppmv (expressed as hexane) was derived from data provided by EPA[5]. The NMOC concentration in the landfill gas is an important measure of the total capacity required in the gas pretreatment system, while the specific individual analyses provide a basis for gas pretreatment subcomponent sizing. The specific contaminants in the landfill gas, of interest to the fuel cell, are sulfur and halides (chiefly chlorides and fluorides). The sulfur level ranges from 1 to 700 ppmv, with a typical value on the order of 21 ppmv. Sufficient data were not available to assess the range of the halides, but a typical value of 132 ppmv was calculated for this contaminant[6]. The range of contaminant values varies not only from site to site, but also at any given site with time due to seasonal weather or moisture content. These characteristics require the pretreatment system design to be capable of handling these gas quality variations to avoid expensive site specific engineering of the pretreatment design which would affect the marketability and economics of the concept.

3.1.3 Emission Requirements

Existing U.S. regulations do not address methane emissions from landfills directly. Proposed new EPA regulations would control non-methane organic compounds from large landfills (150 Mg per year and up) and hence would indirectly control methane emissions.

Landfill gas emission requirements are primarily determined at the state and local level. State requirements are generally limited to controlling explosion hazards, typically limiting methane concentrations to below 25 percent of the lower explosion limit. An evaluation of state regulations revealed that collection and control requirements generally necessitate venting, or the use of a flare. However, Federal Clean Air Act requirements are driving the state and local air quality rules toward tighter controls, including secondary air emis-

5. Air Emissions for Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines, EPA-450/3-90-011a (NTIS PB91-197061). March 1991, page 3-23.
6. Ibid, Table 3-6 pages 3-25 through 3-28.

sions which would result from energy recovery processes. For instance, in non-attainment regions for ozone, strict requirements for secondary emissions including NO_x, carbon monoxide, and NMOCs may exist. The best known example of such strict local emission requirements is the South Coast Air Quality Management District (SCAQMD) in southern California.

3.1.4 Present Options for Methane Abatement from Landfill Gas

A number of landfill gas methane abatement options exist, each with its own particular characteristics and range of applicable economic landfill sizes or site characteristic for optimum use. Among these options the fuel cell is unique in that it produces electric power and recovers waste heat at higher efficiency and produces negligible secondary emissions. The fuel cell performance allows it to be used efficiently in small sites, while its modularity allows its use in larger sites covering a significant portion of the landfill gas market. The characteristic of modularity allows the fuel cell to match the landfill gas output of the site as production expands or is depleted. A review of the abatement options indicates that the fuel cell should be evaluated and compared competitively for small (< 1 MW) to medium (< 3 MW) capacity sites with the most common means of mitigating methane, the flare, and the lean-burn internal combustion engine. The internal combustion engine can be modified for cogeneration and/or secondary emission reduction with the addition of selective catalytic reduction (SCR) with ammonia and gas pretreatment to protect the emission catalyst from the contaminants in landfill gas. The fuel cell system was not compared to turbine technologies in this study because the characteristics of the fuel cell system are attractive to smaller sites and thus the economics cannot be fairly compared. Combustion turbines, however, are an effective abatement option for larger capacity sites (> 3 MW).

3.1.5 Requirements for Conceptual Design

A competitive fuel cell system for abating landfill gas methane can provide an attractive, low emission, flexible and cost effective alternative to present mitigation and energy conversion systems.

The conceptual design of a landfill gas fuel cell conversion system must incorporate those features which can provide this capability and be verified in a demonstration program. To meet this potential the conceptual design must incorporate those features which meet the following requirements:

- ***Application to a Large Number of Landfills*** – The conceptual design can accommodate a wide range of landfill sizes through the use of a basic building block or modularity and multiples of these modules.
- ***Accommodation to Variations in Landfill Gas Composition and Contaminant Level*** – The landfill gas pretreatment and fuel cell system is tolerant to variations in gas heating value and a wide range of contaminant compositions.
- ***Competitive Economics*** – Cost to mitigate methane and NMOC emissions from MSW landfills to proposed EPA regulations should be minimized.
- ***Low Emissions*** – The overall system air emissions, solid and liquid wastes are kept at a minimum.

3.2 Commercial Fuel Cell Landfill Gas to Energy System Conceptual Design

This section describes the commercial fuel cell landfill gas to energy system conceptual design. The conceptual design is based on providing a modular, packaged, energy conversion system which can operate on landfill gases with a wide range of compositions as typically found in the United States. The complete system incorporates the landfill gas collection system, a fuel gas pretreatment system and a fuel cell energy conversion system. In the fuel gas pretreatment section, the raw landfill gas is treated to remove contaminants to a level suitable for the fuel cell energy conversion system. The fuel cell energy conversion system converts the treated gas to electricity and useful heat.

Landfill gas collection systems are presently in use in over 100 MSW landfills in the United States. These systems have been proven effective for the collection of landfill gas. Therefore these design and evaluation studies were focused on the energy conversion concept.

3.2.1 Overall System Description

The commercial landfill gas to energy conversion system is illustrated in Figure 3-1. The fuel pretreatment system has provisions for handling a wide range of gas contaminants. Multiple pretreatment modules can be used to accommodate a wide range of landfill sizes. The wells and collection system collect the raw landfill gas and deliver it at approximately ambient pressure to the gas pretreatment system. In the gas pretreatment system the gas is treated to remove NMOCs including halogen and sulfur compounds. The pretreatment system for the conceptual design is based upon a commercial system design operating at a landfill site in Johnston, R.I. The system designed for this program has been modified to reflect the knowledge gained at that site.

The commercial energy conversion system shown in Figure 3-1 consists of four fuel cell power plants. These power plants are designed to provide 200 kW output when operating on landfill gas with a heating value of 4.45 kcal per standard liter (500 Btu per standard cubic feet) and for accommodating higher contaminant concentrations. The output from the fuel cell is utility grade ac electric power. It can be transformed and put into the electric grid, used directly at nearby facilities, or used at the landfill itself. The power plants are capable of recovering cogeneration heat for nearby use or rejecting it to air.

As configured in Figure 3-1, the commercial system can process approximately 504 standard cubic meters per hour of landfill gas (mitigate 253 SCMD of methane) with minimum environmental impact in terms of liquids, solids, or air pollution. Details of the individual sub-elements in the energy conversion system follow this discussion.

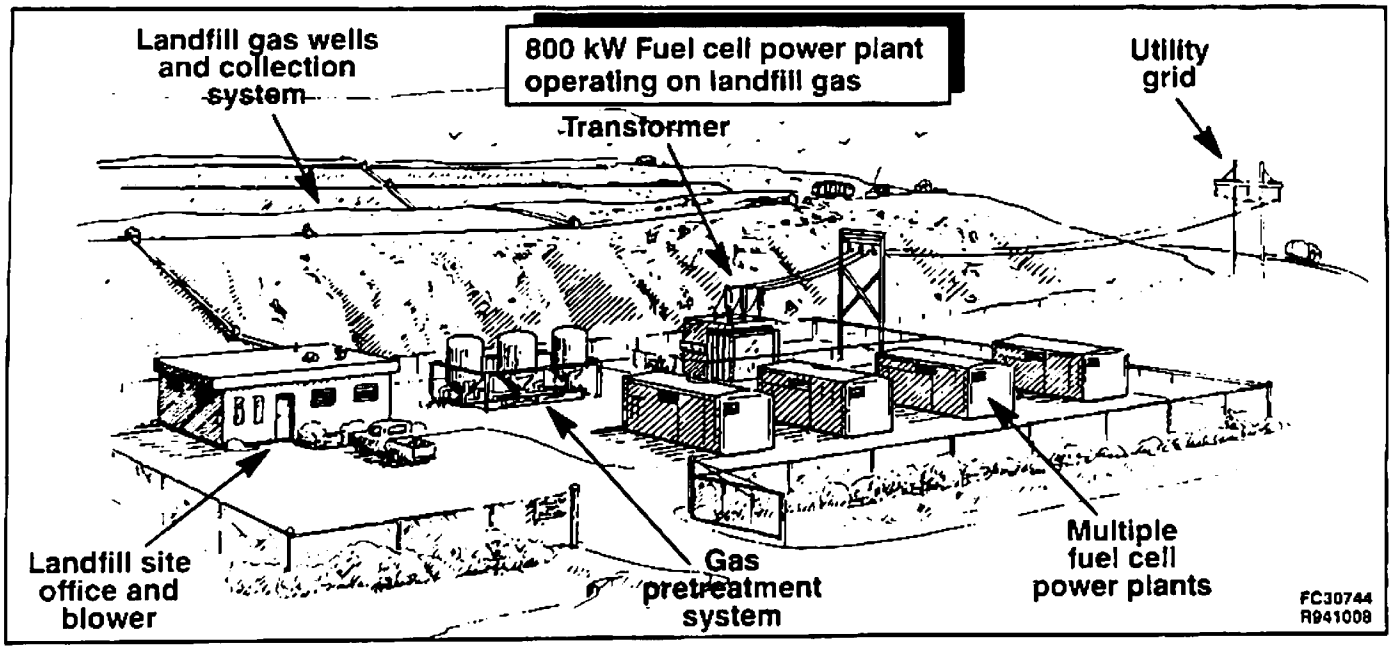


Figure 3-1. Commercial Fuel Cell Landfill-Gas-to-Energy Conversion Concept

Fuel Pretreatment System

A block diagram of the landfill gas pretreatment system for the conceptual study is shown in Figure 3-2. The fuel pretreatment system incorporates one non-regenerable step, plus two stages of refrigeration combined with two regenerable adsorbent steps. The use of staged refrigeration provides tolerance to varying landfill gas constituents. A non-regenerable carbon bed first removes hydrogen sulfide. The first stage condenser removes the water content to a uniform dew point of approximately 1 °C, and removes some heavier hydrocarbons from the landfill gas. The first stage condenser provides flexibility to accommodate the varying landfill characteristics by delivering a low dew point gas with a relatively narrow cut of hydrocarbons for the downstream beds in the pretreatment system. A regenerable dryer bed next reduces the dew point from 1 °C to less than -45°C, to prevent freezing in the second refrigeration step. The second refrigeration step enhances the effectiveness of the activated carbon bed, which removes the remaining volatile organic compounds in the landfill gas. This approach is more flexible than utilizing dry bed adsorbents alone and has built-in flexibility for the wide range of contaminant concentrations which can exist from site to site and even within the single site varying with time.

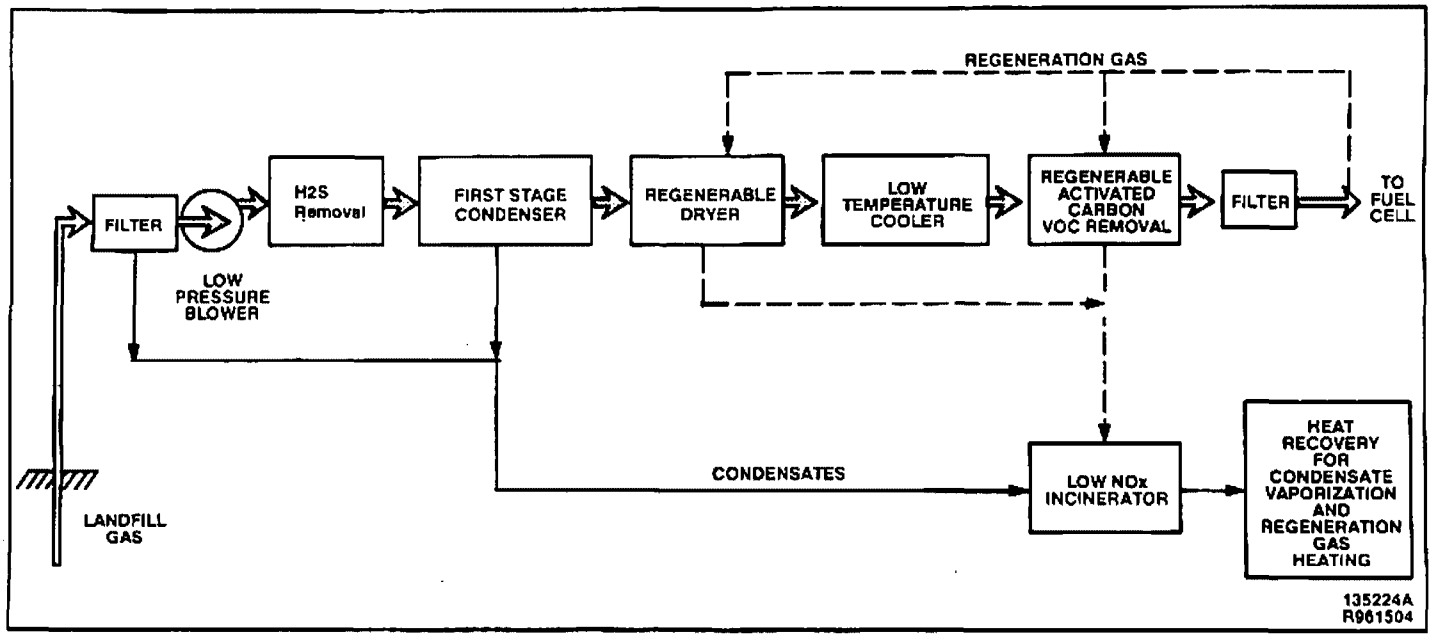


Figure 3-2. Simplified Block Diagram of Commercial LFG Pretreatment System

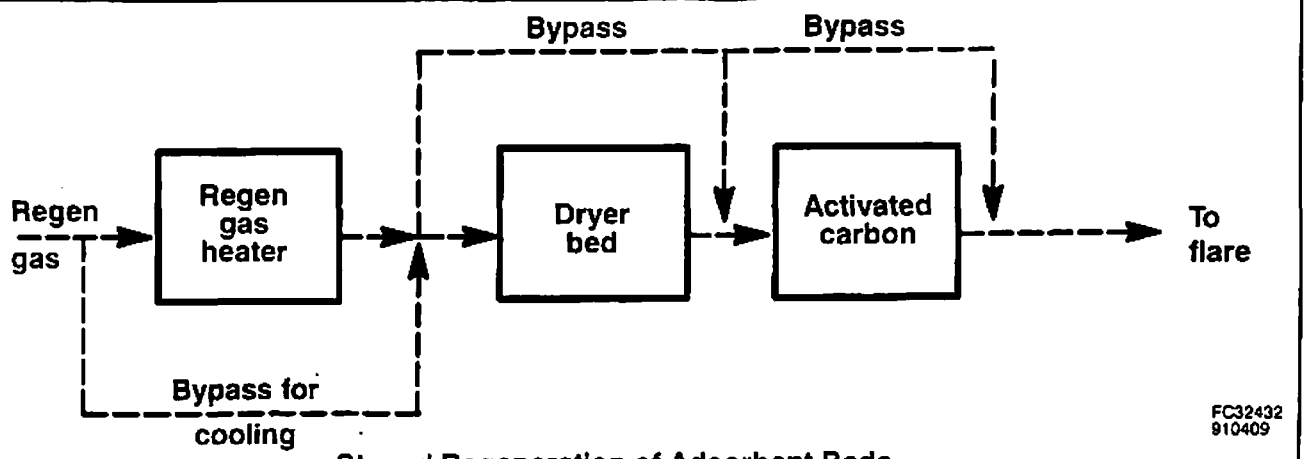
The two adsorbent beds are regenerated by using cleaned, heated gas from the process stream exit. Each adsorbent step consists of two beds in parallel. In operation, one bed is adsorbing while the parallel bed is being regenerated. The regeneration path and sequence are shown as dashed lines in Figure 3-2. A small portion of the treated landfill gas (approximately 8%) is heated by regeneration with the incinerator gases and then passed through the beds in the sequence shown. Figure 3-3 with its accompanying sample regeneration sequence shows the regeneration process in more detail. This system provides flexibility in the tailoring of the regeneration of each bed. The exact sequencing, regeneration gas flow, and timing would be based on experience gained in the Phase II and III demonstrations and final design (bed sizing and material optimizations) of the adsorbent beds for commercial applications. After exiting the final bed, the regeneration gas is fed into the low NO_x incinerator where it is combined with the vaporized condensates from the refrigeration processes and the mixture is combusted to provide greater than 98 percent destruction of the NMOC's from the raw landfill gas. The exhaust from the incinerator is essentially CO_2 and water. The pretreatment system design provides treated gas to the fuel power plant in an efficient, economic, and environmentally acceptable manner.

Key features of the design and the related product benefits are summarized in Table 3-3. The system design provides flexibility for operation on a wide range of landfill gas compositions, high thermal efficiency and

low parasite power requirements. While the pretreatment system is based upon modification of an existing system and it utilizes commercially available components, the process train and operating characteristics of this design need to be validated by demonstration. Key demonstrations required include: the achievement of the low total halide contaminant levels in the treated gas; effectiveness of the regeneration cycle as affected by regeneration time and temperature; durability of the regenerable beds; and low environmental emissions.

The pretreatment system was analyzed to estimate the overall thermal efficiency, and internal electric power requirements., and its maintenance characteristics. These characteristics are summarized in Table 3-4. The estimated thermal efficiency is 92 percent with the balance of the thermal energy used for regeneration, vaporization of condensates and incineration of the regeneration gases. Electric power is used for pumping the gases and the refrigeration and is accounted for as a parasite power characteristic of the system. Maintenance requirements consist of maintaining and adjusting controls and valves in the regeneration system replacement of filter elements, replacement of fully regenerated spent bed materials on an annual basis and replacement of the hydrogen sulfide removal bed on a periodic basis. The frequency is controlled by the hydrogen sulfide content of the gas.

The environmental impact of the gas treatment system was evaluated. The impact of air emissions, liquids, and solids disposal were considered. The incinerator is designed for greater than 98 percent destruction of all NMOC's, and NO_x emissions of less than 0.11 kg per 10^6 kcal of fuel consumed are expected. There is no liquid effluent from the system since all condensates are vaporized and subsequently incinerated. Solid disposal involves removing spent regenerable and non–regenerable bed materials at the factory and treatment by an EPA approved processor for reclamation. The bed materials are routinely handled and processed by qualified waste processors.



Staged Regeneration of Adsorbent Beds

8 Hour Sequencing					
Step	Duration (hrs)	Mode	Regen gas heater	Dryer bed	Activated carbon bed
1	0.5	Heating	On	Bypass	Regen
2	1.5	Heating	On	Regen	Regen
3	0.5	Heating	On	Bypass	Regen
4	1.5	Heating	On	Bypass	Bypass
5	2.0	Cooling	Bypass	Regen	Regen
6	1.0	Cooling	Bypass	Bypass	Regen
7	1.0	Cooling	Bypass	Bypass	Bypass

Figure 3-3. Staged Regeneration of Adsorbent Beds and Sample Regeneration Sequence

Table 3-3. Key Features of Commercial Pretreatment System Conceptual Design

Design Feature	Product Benefit
• 4.8×10^4 Pa nominal operating pressure	• Low pumping power
• Two refrigeration stages	• Handle wide range of landfill gases • Improve effectiveness of regenerable beds
• Vaporization and incineration of liquid condensates from refrigeration stages	• No contaminated liquid effluents for disposal
• Beds regenerated with heated clean fuel followed by low NO_x incineration	• No contaminated liquid effluent
• Recover heat from incineration for vaporization of refrigeration condensate and heating clean regeneration gas	• High thermal efficiency

Table 3-4. Gas Pretreatment System Projected Performance	
• Fuel pretreatment system efficiency (% of raw landfill gas delivered to fuel cell)	• 92%
• Parasite power requirement (% of fuel cell electric power)	• 2%

Fuel Cell Power Plant

The commercial landfill gas energy conversion conceptual design incorporates four 200-kW fuel cell power units. Since each of the four units in the concept is identical, this discussion will focus on the design issues for a single 200-kW power unit.

A simplified functional schematic of the fuel cell power unit is shown in Figure 3-4. Major sections of the system include the fuel processing system, fuel cell electrical conversion system and the thermal management system. In the fuel processing section treated landfill gas is converted to hydrogen and CO_2 for introduction into the fuel cell stack. The fuel treatment process includes a low temperature fuel preprocessor to remove 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 to provide additional hydrogen and CO_2.

In the fuel cell stacks hydrogen from the process fuel stream is combined electrochemically with oxygen from the air to produce dc electricity and byproduct water. The product water is recovered and used in the reformer. The heat generated in the cell stack is removed to an external heat rejection system. This energy can be either rejected to the ambient air or recovered for use by the customer. The dc power produced in a fuel cell stack is converted to ac power in a power conditioning package not shown on the process schematic.

A preliminary design of a fuel cell power plant was established to identify the design requirements which allow optimum operation on landfill gas. Three issues specific to landfill gas operation were identified which reflect a departure from a design optimized for operation on natural gas. A primary issue is to protect the fuel cell from sulfur and halide compounds not scrubbed from the gas in the fuel pretreatment system. An absorbent bed was incorporated into the fuel cell fuel preprocessor design which contains both sulfur and halide absorbent catalysts. A second issue is to provide mechanical components in the reactant gas supply systems to accommodate the larger flow rates that result from use of dilute methane fuel. The third issue is an increase in the heat rate of the power plant by approximately 10 percent above that anticipated from operation on natural gas. This is a result of the inefficiency of using the dilute methane fuel. The inefficiency results in an increase in heat recoverable from the power plant. Because the effective fuel cost is relatively low, this decrease in power plant efficiency will not have a significant impact on the overall power plant economics.

The landfill gas power plant design provides a packaged, truck transportable, self-contained fuel cell power plant with a continuous electrical rating of 200 kW. It is designed for automatic, unattended operation, and can be remotely monitored. It can power electrical loads either in parallel with the utility grid or isolated from the grid.

In summary, a landfill gas fueled power plant can be designed to provide 200 kW of electric output without need for technology developments. The design would require selected components to increase reactant flow rates with a minimum pressure drop. To implement the design would require non-recurring expenses for system and component design, verification testing of the new components, and system testing to verify the power plant performance and overall system integration. A thermodynamic analysis of the fuel cell power plant optimized for operating on landfill gas was completed. The resulting performance of the landfill gas power plant is compared to a power plant operating on natural gas in Table 3-5.

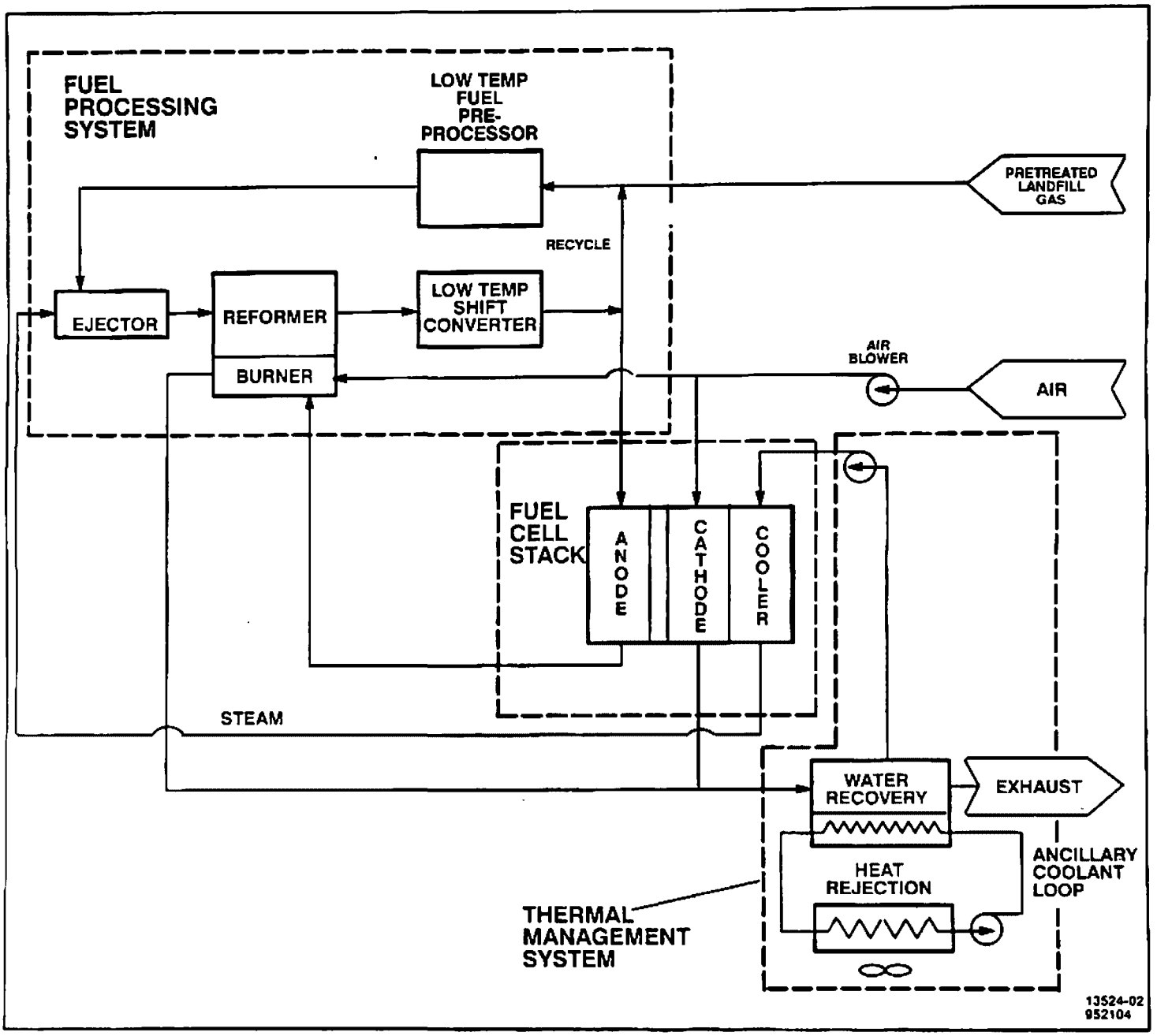


Figure 3-4. Functional Schematic Fuel Cell Landfill Gas Power Unit

Table 3-5. Performance Comparison for Nominal 200 kW Output

	NATURAL GAS POWER PLANT	LFG POWER PLANT
Fuel	Natural Gas	Landfill Gas
Electrical Efficiency (LHV) – %	40.0	36.4
Fuel Flow Rate (SL/M)	896	1960
Heat Rate (HHV) – kcal/kWhr	2,390	2,620
Available Heat – kcal/hr	192,000	208,000
Ambient Temperature for Fuel Water Recovery – °C	35	35
Startup Fuel	Natural Gas	Landfill Gas

The estimated air emissions of the fuel cell power plant is provided in Table 3-6. The fuel cell air emissions are low because gas contaminants which could become emissions are removed by the gas pretreater and fuel preprocessor. The air emissions are significantly lower than other landfill gas conversion devices giving the fuel cell power plant the potential for being the best available control technology for landfill gas methane mitigation. Verification of these emission estimates will be a key element of the demonstration program.

Table 3-6. Estimated Fuel Cell Air Emissions

	LFG FUEL CELL
Emissions – kg/10^6 kcal	
NO_x	0.04 - 0.07
SO_x	0.00005
Particulates	0.000005
Smoke	None
CO	0.07 - 0.14
Total Hydrocarbons	0.02 - 0.05

Overall System Performance

The commercial application of the concept to the market described previously was assessed. For the purpose of the evaluation, a site capable of supporting four fuel cell power modules was selected. The site characteristics assumed are the typical values discussed earlier. The site would produce approximately 12,200 standard cubic meters of landfill gas per day. The gas contains approximately 50 percent methane by volume with a heating value of 4.45 kcal/liter. The system is capable of supplying 784 kW of net electric power to the grid and has an available thermal energy of 0.84 million kcal per hour. Overall system performance is outlined in Figure 3-5.

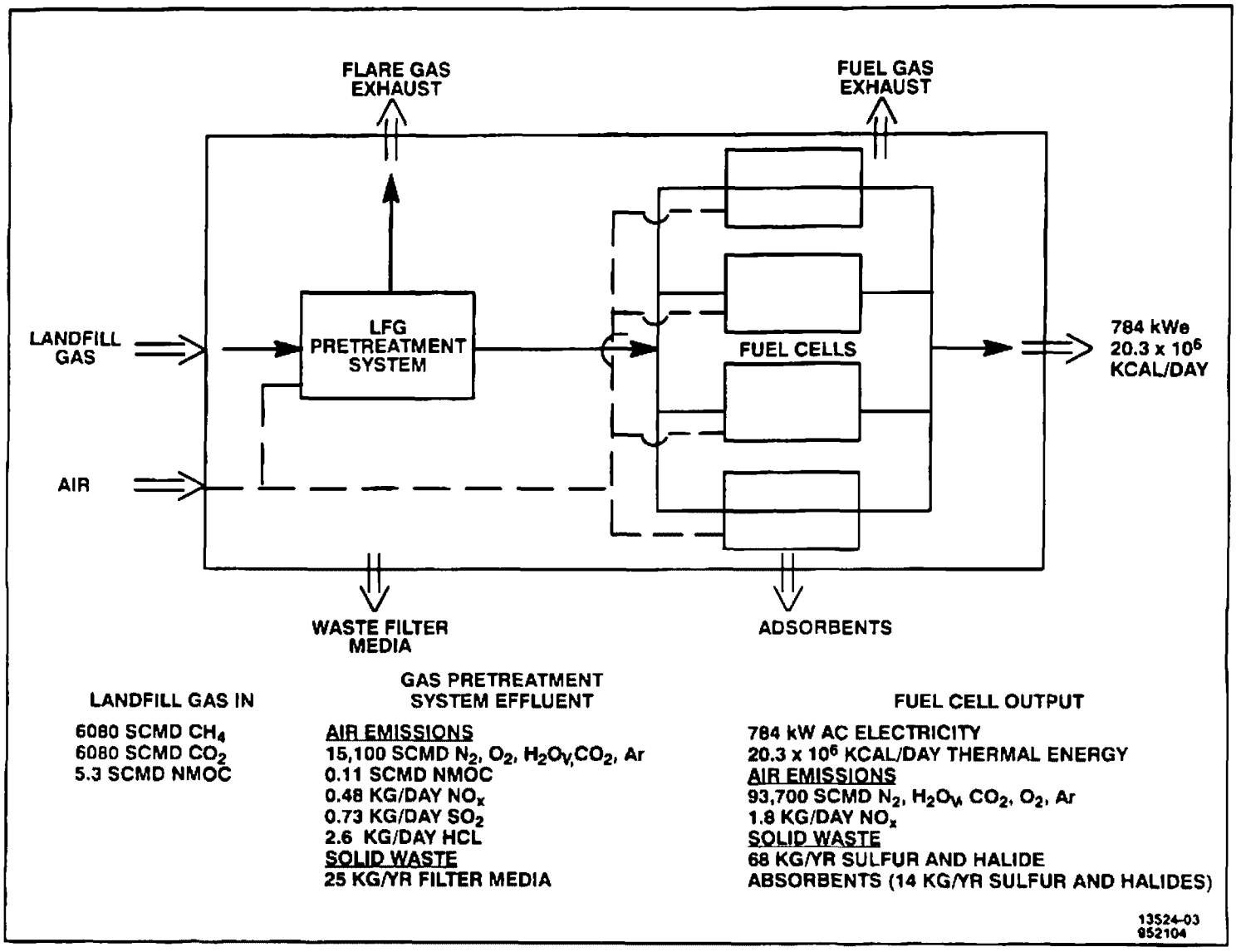


Figure 3-5 Overall System Schematic and Performance Estimate for Fuel Cell LFG-to-Energy Conversion System

Impact of Heating Value on System Performance

Heating value of the landfill gas can vary from site to site or at a given site with time The most significant variation is a reduction in heating value from air intrusion into the landfill during energetic withdrawal and collection of the gas. Although most of the oxygen in the air is consumed in the landfill, nitrogen content of the gas increases thereby lowering the heating value of the gas.

Figure 3-6 shows the impact of changing the landfill gas heating value from 3.56 to 5.34 kcal/SL (kcal per standard liter) on fuel cell power plant heat rate and power output. In general, the lower the heating value of the gas the lower the power plant thermal efficiency will be (or otherwise stated, the higher the power plant heat rate will be).

The power output of a fuel cell power plant optimized to operating on landfill gas with 50 percent methane is shown in Figure 3-6. A reduction in methane content or heating value below 4.54 kcal/SL results in a loss in energy input and power output. Above 4.54 kcal/SL the power plant automatic flow controls will self-adjust to maintain 200 kW output. Natural gas blending may be considered as a means to maintain the gas heating value above 4.54 kcal/SL at some sites.

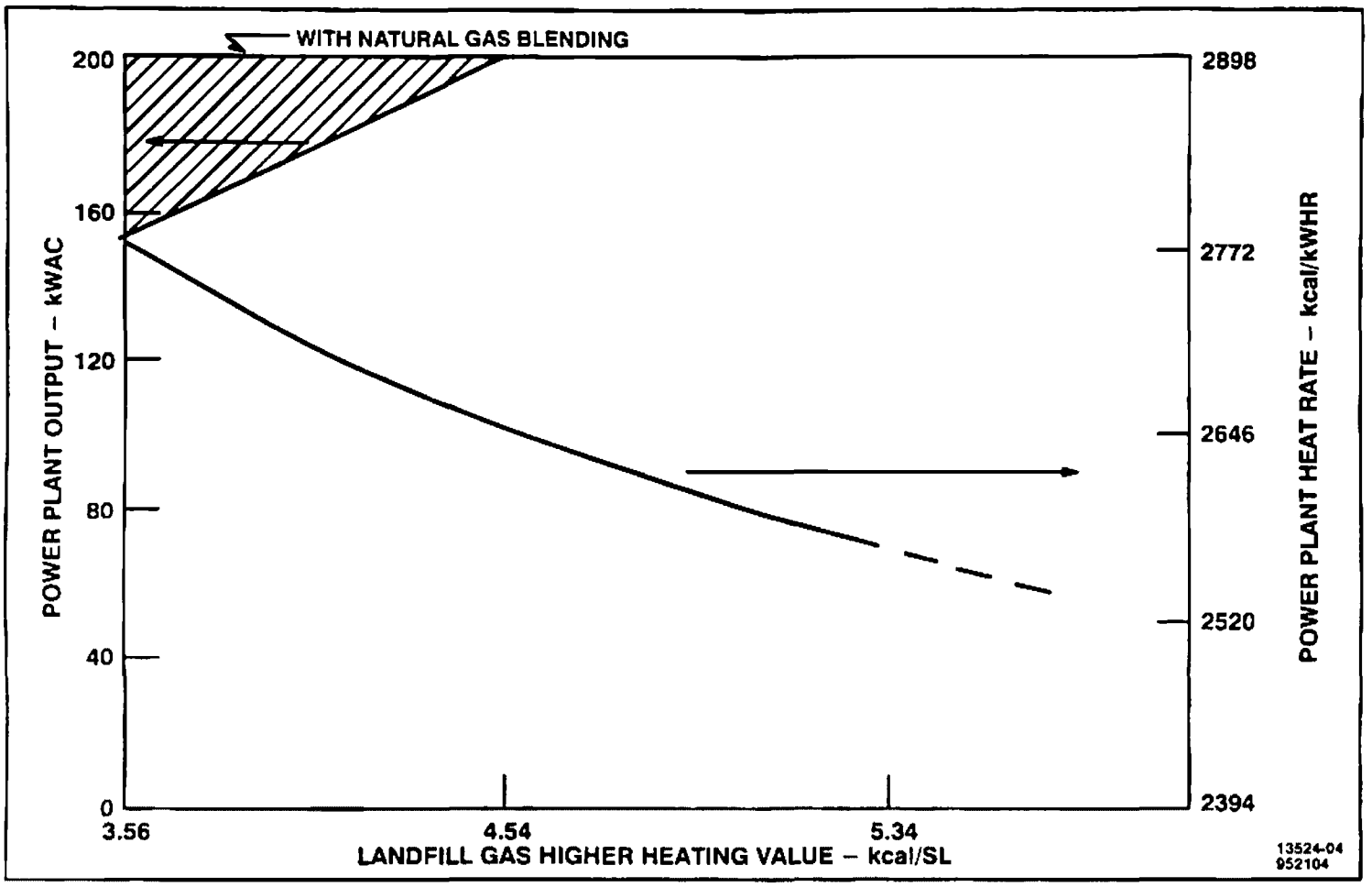


Figure 3-6. Impact of Landfill Gas Heating Value on Power Plant Power Output and Heat Rate

3.2.2 Environmental and Economic Assessment of the Fuel Cell Energy Conversion System

The commercial application of the energy recovery concept to the market described previously was assessed For the purpose of the evaluation, a site capable of supporting four fuel cell power plant units was selected The site assumed characteristics, shown in Table 3-7, are the typical values discussed earlier. The site would produce approximately 12,200 standard cubic meters of landfill gas per day. The gas contains approximately 50 percent methane and has a gas heating value of 4.54 kcal/SL.

At a minimum the method for mitigating the methane and NMOC from landfill gas is installation of a gas collection system and flaring of the gas. The fuel cell energy conversion system provides the opportunity for converting the methane in the landfill gas to useful energy. The baseline for the comparisons in this system are the conventional option with flaring.

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, thermal energy and emissions offsets which can be used to generate revenues from the landfill gas mitigation system. Secondly, since the fuel cell converts methane to electricity more efficiently, it has lower emissions at the site than competing options and provides significant emission offsets due to the reduction in emissions from the electric utility which would otherwise be providing the energy. These differences are the basis for the assessment of the energy conversion system discussed in this section. It should be noted that both the flare system and the fuel cell system essentially eliminate all methane emissions from the landfill site and have a 98 percent destruction of the non-methane organic compounds.

Table 3-7. Site Characteristics for Landfill Gas Assessment	
Landfill Gas Generation Rate	12,200 SCMD
Bulk Constituents (vol %, dry)	
• Methane	50
• CO_2 and Other Inerts	50
Contaminants (PPM_v)	
• Total Non-Methane Organic Hydrocarbons	2700
• Total Sulfur	21
• Total Halides	132
• Methyl Chloride	14
• Vinyl Chloride	7
Gas Heating Value ~ kcal/SL	4.54

Environmental Assessment

The analysis of the environmental impact shows that both the fuel cell and the flare system can be designed to eliminate the methane and the non-organic methane compounds from the landfill gas system. For the example site considered, the methane elimination is essentially complete for both systems and 98 percent of the NMOC are destroyed. Trace amounts of SO_x and NO_x will be emitted in each case. With the fuel cell system, however, significant reductions of NO_x and SO_x will be achieved due to the fuel cell energy generation. This analysis assumes an 80 percent capacity factor for the fuel cell and offsetting emissions from electric utility power generation using a coal-fired plant meeting New Source Performance Standards. For the example site, the fuel cell energy conversion system provides 5.6 million kWhr of electricity per year, with a net reduction of 32.0 Mg per year of NO_x and 15.2 Mg per year of SO_x from reduced coal use. These reductions can be used as environmental offsets, particularly in critical areas such as California or other locations with stringent environmental requirements.

The environmental impact of application of the fuel cell concept to the potential market is shown in Table 3-8. The data show that both the flare and the fuel cell mitigate methane and NMOC, under the proposed standards and guidelines[1]. However, the flare merely converts these emissions to CO_2, acid rain, and other unhealthy pollutants. The fuel cell can provide a net reduction in global pollution by offsetting energy production from coal.

Table 3-8. Emissions Impact of Fuel Cell Energy Recovery from Landfill Gas

Abatement Technology	Global Warming			Acid Rain and Health		
	Methane (Mg/Yr)	NMOC (Mg/Yr)	CO_2 (Mg/Yr)	SO_2 (Mg/Yr)	NO_x (Mg/Yr)	CO (Mg/Yr)
Venting Only	1.8×10^7	510,000	—	—	—	—
Flare	0	10,200	4.94×10^7	2,972	29,720	14,860
Fuel Cell	0	10,200	-6.45×10^7	-535,000	-259,000	-8,620

Economically the fuel cell energy system has the potential for deriving revenues from electric sales, thermal sales, and emission offsets credits. These revenues can be used to offset the investment cost associated with gas collection, gas pretreatment, and fuel cell power units. The level of these revenues depends upon the value of the electricity, the amount and value of the heat used, and the value of the emissions offsets.

Economic Assessment Results

The fuel cell energy system has the potential for deriving revenues from electric sales, thermal sales and emission offsets credits. These revenues can be used to offset the investment cost associated with the gas collection, gas pretreatment and the fuel cell power units. The level of these revenues depends upon the value of the electricity, the amount and value of the heat used and the value of the emissions offsets.

Electric rates vary considerably with geographic location and the purchaser of the electric energy. Commercial rates are applicable where the electricity can be used at the landfill or in nearby commercial facilities. Commercial rates vary from a high of 13.68 cents per kWhr to a low 2.71 cents per kWhr. The median rate in the United States is approximately 7 cents per kWhr. The rates charged to industry are generally lower and are closer to the fully burdened avoided cost for the utility. These rates range from 10.0 cents per kWhr to a low of 1.64 cents per kWhr with the mean value of approximately 5 cents per kWhr. In general, both the commercial and industrial rates are higher in locations with high population density and/or with air emissions problems. These locations are ideal for the use of the fuel cell energy conversion system with its favorable environmental impact. Since the rates vary considerably, the analysis in this section is done on a parametric basis for a wide range of electric rates.

The fuel cell energy conversion system was evaluated to establish the net revenues or costs for processing landfill gas to mitigate methane emissions. For the purposes of the analysis it was assumed that the fuel cell energy conversion system and the flare system would have an overall annual capacity factor of 80 percent. For this analysis, two levels of fuel cell installed cost were considered. The lower level, $1500/kW represents a fully mature cost when the power plant has been accepted into the marketplace and is routinely produced in large quantities. The upper level, $3000/kW installed, represents a price level when the power plant is being introduced into the marketplace, and is produced on a moderate and continuous basis. In addition to the fuel cell costs, a GPU installed cost of $190/kW and gas collection system cost of $310/kW are included in the overall system cost. Operating and maintenance costs are 0.4¢/kWHr for the GPU and 1.5¢/kWHr for the fuel cell.

The results of the analysis shown in Figure 3-7 describes the net revenues from the fuel cell energy system as a function of the value received for the electricity produced in the fuel cell energy conversion system. The case shown in Figure 3-7 assumes that 50 percent of the heat is recovered and that there is an emissions offset credit. The value of the heat recovered corresponds to the industrial value for natural gas adjusted for the combustion efficiency to produce the thermal energy at $11.59 per million kcal ($2.92 per million Btu's). The value for the emission offset is $1100/Mg for both NOx and SOx reductions. The net revenue shown on the figure represents the income to the energy conversion system owner after all investment and operating costs have been recovered. When the value of the net revenue is less than zero, this would represent a cost incurred for mitigating the methane from the landfill. For comparison purposes the cost for mitigating with the flare option are also shown in Figure 3-7. For the flare options,the costs include the cost of collecting and delivering the gas to the flare, the cost of the flare and the operating cost for this system. For the electricity values where the fuel cell revenues are greater than the flare option, the fuel cell would be the favored economic option. The cost for methane mitigation with a flare system is approximately $13,400 per million standard cubic meters processed per year.

Based on the range of industrial and commercial electric rates in the United States, the fuel cell would be the economic option in most locations at $1500/kW and would be the choice in those areas with average or higher electric rates at $3000/kW. This indicates that there could be substantial opportunity for efficient low emissions methane mitigation with the fuel cell power plant at product entry prices.

Figure 3-8 shows the fuel cell revenues for situations without heat recovery. Although the net revenues are somewhat decreased, the results and areas of competitiveness are similar to those noted for Figure 3-7.

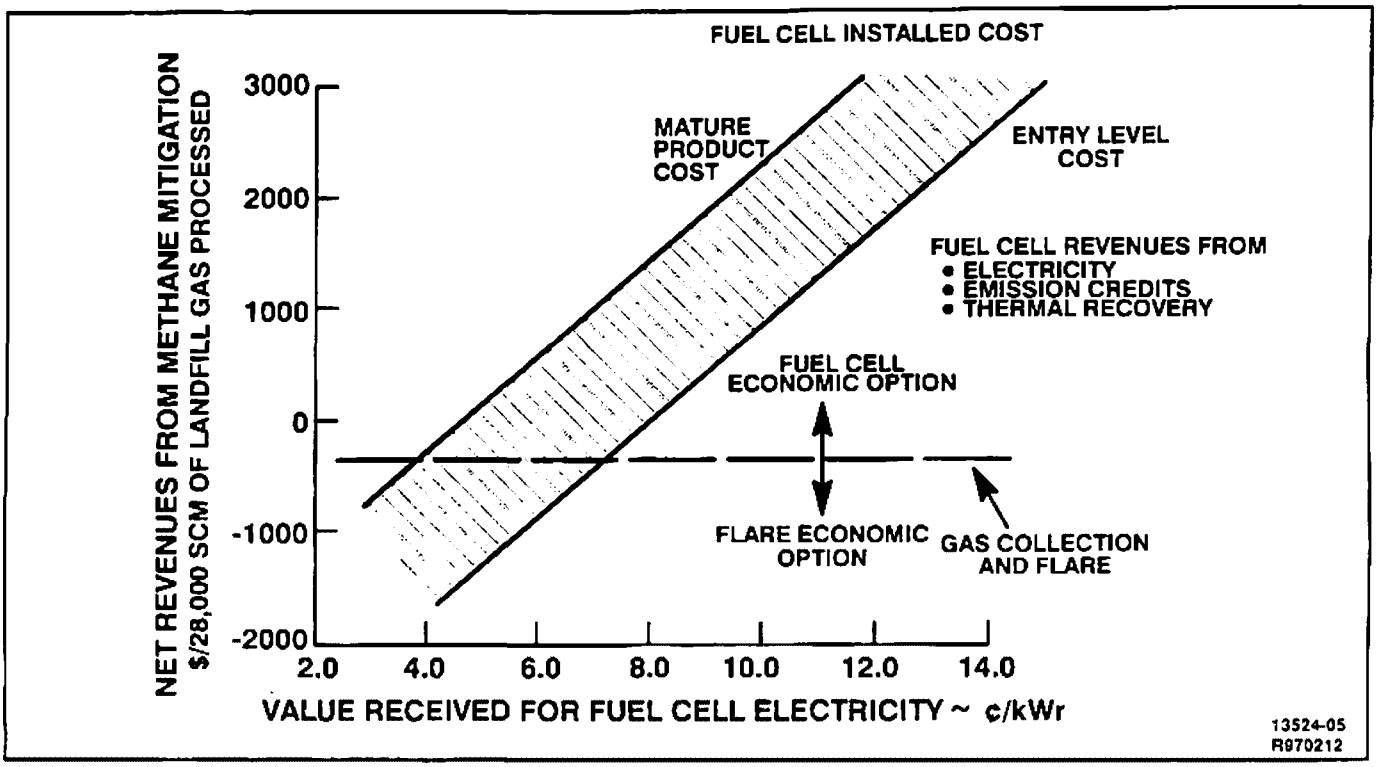


Figure 3-7. Comparison of Fuel Cell to Flare for Methane Mitigation Assuming Electric Revenues, Emission Credits and Thermal Recovery

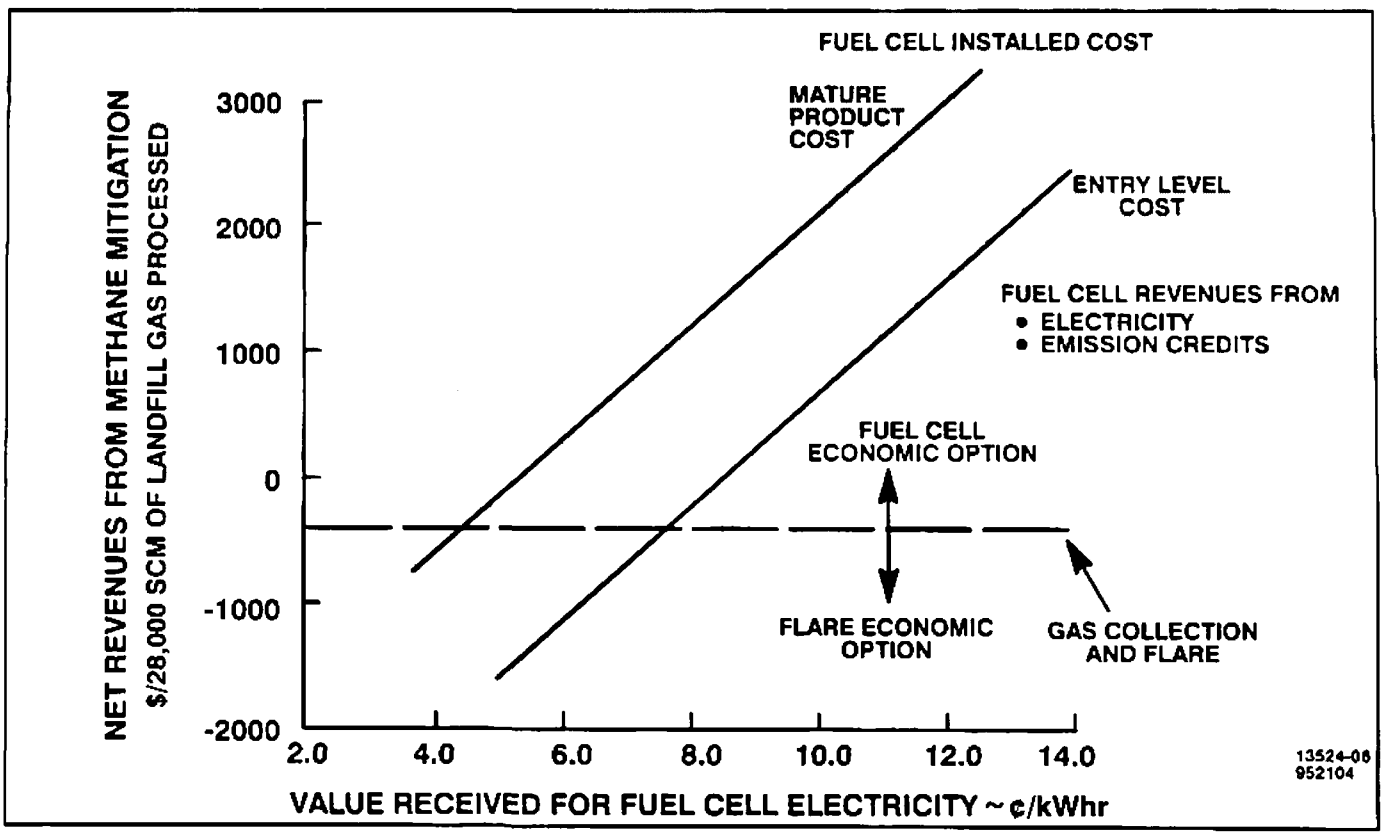


Figure 3-8. Comparison of Fuel Cell to Flare for Methane Mitigation Assuming Electric Revenues and Emission Credits

Figure 3-9 shows the fuel cell revenues for the most stringent application situation. In this case, the fuel cell receives revenues only from the sale of electricity. Although the emissions are lower from the fuel cell, no specific credit or value is attached to them for this example. Under these conditions the fuel cell is still the economic choice for most locations at $1500/kW. At $3000/kW it is still economical in those areas where the value of electricity is nine cents per kWhr or higher. This would primarily be areas such as California, New York, and parts of New England.

This analysis indicates that there is substantial market opportunity for the fuel cell energy conversion system. At market introduction prices, the power plant would be applicable in locations with high electric rates and situations where air emissions are quite severe. There are many areas of the country which have these characteristics and they are increasing with time, thus indicating an ever increasing market opportunity for the fuel cell power plants. These options were evaluated against the flare option which does not produce any useful energy. There are other energy conversion systems which could produce electric and/or thermal energies. Comparisons to these options are discussed in the following section.

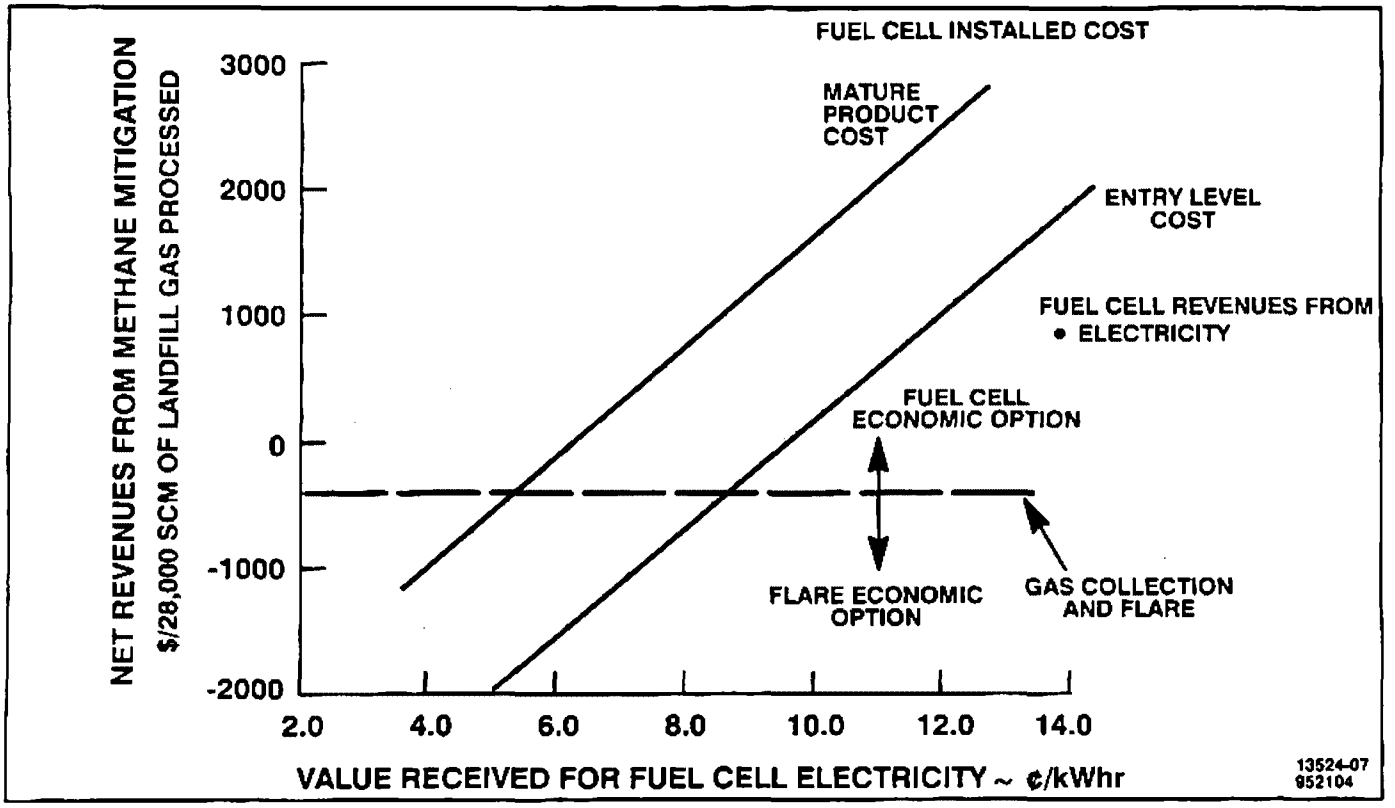


Figure 3-9. Comparison of Fuel Cell to Flare for Methane Mitigation Assuming Electric Revenues Only

Comparison With Other Energy Conversion Options

The internal combustion engine and the gas turbine engine have been suggested as competing options for methane mitigation at landfill sites. For the landfill size selected for this analysis, the internal combustion engine is more effective than the gas turbine option for clean-up. This is used as the basis for the comparisons in this section. The internal combustion engine can provide both heat and electric energy while consuming the methane at the landfill gas site. With the present state-of-the-art technology, however a lean-burn internal combustion engine has higher levels of NOx unless special precautions are taken to clean-up the exhaust. For this analysis, two cases are considered. The first case assumes there is no clean-up of the exhaust from the lean-burn internal combustion engine and the second assumes that the exhaust is cleaned with selective catalytic reduction (SCR). Since the SCR employs catalyst in the clean-up system, the landfill gas will have to be pretreated in a manner similar to the fuel cell system. For those cases with the SCR clean-up system, a pretreatment system has also been included as part of the total system cost.

Figure 3-10 shows the results of the economic analysis for the fuel cell system and the internal combustion engine system. Since both can provide electricity, the comparison between the systems are based on the cost of electricity generated from the energy conversion system with appropriate credit for thermal sales and/or emission offsets. For the case where the SCR is employed to clean-up the engine exhaust, the fuel cell power plant is competitive with installed prices on the order of $3000/kW. If no exhaust clean-up is required for the internal combustion engines, then the fuel cell is competitive at the fully mature price of $1500/kW. In this latter case, however, the operation of the internal combustion engine at the landfill site would be quite dirty and significant amounts of NOx would be added to the ambient air. For many locations where the fuel cell would be considered, such as California or other high emissions areas, the no exhaust clean-up option may not be available. Consequently, the fuel cell option would be fully competitive with the internal combustion engine option for most cases where on-site clean-up of the internal combustion engine is required.

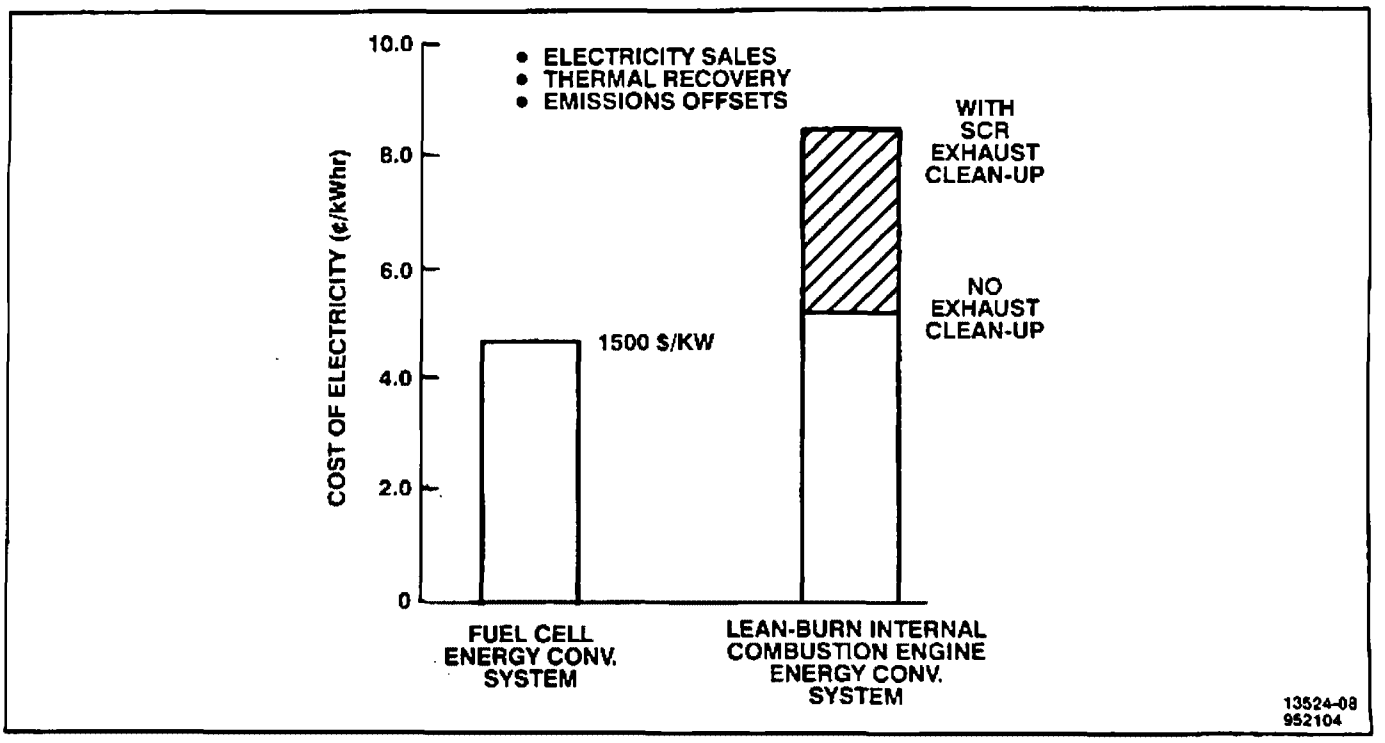


Figure 3-10. Comparison of Fuel Cell to Internal Combustion Engine Energy Conversion System

Based on the analysis of the flare and other energy conversion options, the fuel cell power plant is fully competitive in all situations in the mature production situation. For initial power plant applications with limited lot production, the fuel cell power plant is competitive in areas with high electric rates and/or severe emissions restrictions at the local landfill site.

Conclusions

Based on the environmental and economic evaluation of the commercial fuel cell energy system, the following conclusions can be made:

- The fuel cell landfill gas to energy conversion system provides net reduction in total emissions while simultaneously mitigating the methane from the landfill gas.
- With the initial product prices, fuel cells will be competitive in landfill sites located in high electric cost areas in sites with average commercial rates; where heat can be utilized or where there is a credit for the environmental reductions from the fuel cell energy conversion system.
- When the projected mature product price is achieved, fuel cells will be competitive for most application scenarios. In many situations, fuel cells will provide net revenues to the owners of the operating landfills. This could, in the long term, result in methane mitigation without additional cost of any sort to the ultimate consumer.

3.2.3 Critical Issues

This section summarizes the key marketing and technical issues that must be resolved to verify the commercial feasibility of the fuel cell landfill gas to energy conversion concept. Resolution of some of these issues will come with the recognition of the long term economic value of the fuel cell in mitigating landfill methane and NMOC emissions while significantly lowering secondary emissions and offsetting the air emissions from electric utility generators. Resolution of other issues will be achieved with the design and successful demonstration of the pretreatment system and fuel cell on landfill gas. The following marketing and technical issues need to be resolved:

Marketing Issues

- Market Entry at Initial Product Capital Cost – Market acceptance of the fuel cell energy recovery concept must be achieved by entry into markets with the highest electric rates or strictest emission controls. Federal incentives such as; low cost financing, emission credits, etc. can hasten acceptance of the concept.
- Limited Electric Revenues – Electric utility avoided cost rates are impeding energy recovery from sources such as landfill gas. Allowing revenues based upon the local commercial or industrial rates, or fully burdened avoided costs would encourage energy recovery and thus achieve the desired environmental impact.
- Available Uses of Thermal Energy – Fuel cell revenues increase with the sale of thermal energy. Identification of thermal loads near landfills or arrangements to locate the fuel cell at cogeneration sites near landfills (with gas pretreatment located at landfill) would improve fuel cell market competitiveness.

Technical Issues

- Verification of an Effective Pretreatment System – The pretreatment system design must economically treat landfill gas to meet the long term sulfur and halide limits required by the fuel cell. This demonstration program will verify the key process elements and steps of the commercial system. The system and its elements must be optimized to produce a cost effective commercial pretreatment system.
- Demonstration of Low Emissions – The demonstrator design and actual demonstration will verify the low emission capability of the commercial fuel cell landfill-gas-to-energy concept. This includes air emissions from both the fuel cell and pretreatment system as well as solid and liquid effluents projected for the commercial system.
- Demonstrate Overall System Operability, Durability and Reliability – A successful demonstration will allow projection of a low operating cost component of the methane mitigation life cycle cost for the commercial system. This includes trouble-free unattended operation and minimal degradation (durability) of the regenerable beds.

4.0 DEMONSTRATION TEST DESIGN

This section describes the site specific process and engineering design of the gas pretreatment unit designed for the landfill gas application, plus the PC25 A, 200-kW phosphoric acid fuel cell power plant, and the landfill-gas-to-energy site which was selected in Phase I. The PC25 A fuel cell is uniquely suited to this application due to its low secondary emissions: typically 0.5 ppmV NO_x, 1.1 ppmV carbon monoxide; and 0.03 ppmV non-methane hydrocarbons (all measured at 15 percent oxygen on a dry gas basis using natural gas fuels). Section 4.1 describes the development of the gas pretreatment process from a conceptual design in Phase I, to a complete, detailed mechanical and process design including field modifications in Phase II. In Section 4.2 the PC25 A power plant design modifications to permit operation on landfill gas up to a nominal 140 kW rating are described. Section 4.3 describes the overall site specific process design for the demonstration including the gas pretreatment system and its integration to the fuel cell power plant system. Section 4.4, Site Specific Engineering Design, summarizes the details of the site location and construction for the demonstration equipment.

4.1 Select Landfill Site

The objective of the site selection effort was to select the best available site for demonstrating the recovery of energy from landfills using fuel cells. The approach was to establish site selection criteria from the conceptual design of the commercial product; apply these criteria to potential landfill sites identified by Pacific Energy, and then downselect and rank these sites according to the criteria. Based on this evaluation, Pacific Energy's Penrose Power Station in Sun Valley, California, was selected as the site for the demonstration.

4.1.1 Site Selection Criteria

Two major site selection criteria were established for selecting the demonstration site. These criteria are:

(1) That the site be representative of U.S. landfills, so that the demonstration will be relevant to a large portion of the U.S. market; and

(2) That the site be suitable, with existing and reliable gas supplies and facilities available.

The first selection criterion, that the site be representative, requires that the landfill gas available at this site be typical of the majority of sites across the United States in major gas composition, heating value and contaminants. Equally important, is that the local codes and regulations be sufficiently demanding that a successful siting and demonstration at the selected site would be readily accepted at most if at not all potential sites across the United States.

The suitability criterion relates to the practicality and expense of conducting the demonstration at a candidate site. Specifically, a suitable site should have all required facilities in place including a proven landfill gas collection system, natural gas supply, permits, contracts for equipment and sale of electricity, and plenty of space available for the demonstration. Most importantly, the selected site should have an excess supply of landfill gas available for the demonstration during the proposed period of the demonstration gas pretreatment test in 1993 and the fuel cell demonstration in 1994 and 1995.

4.1.2 Characteristics of Candidate Sites and Selection

The candidate site selection was based upon the twelve active projects which Pacific Energy currently manages, as shown in Table 4-1. A preliminary assessment conducted by Pacific Energy identified four of these sites as potential candidates for the EPA demonstration. These sites are: the Oxnard Station in Oxnard, California; the Penrose Station in Sun Valley, California; the Toyon Station in Los Angeles, California; and the Otay Station in San Diego, California. Tables 4-2 and 4-3 show how these four candidate sites were assessed against the detailed sub-criteria which were developed in the program. The two leading candidate sites that emerged were Penrose and the Toyon Canyon site because of their

close proximity to the Pacific Energy and Southern California Gas facilities, and their location within the South Coast Air Quality Management District. Oxnard and Otay are less attractive due to their greater distance from Los Angeles, and lack of natural gas service.

The Toyon site was eliminated when it was determined that there was insufficient excess landfill gas available year-round for the demonstration, particularly during the summer months. This left the Penrose site as the best site for the demonstration.

The Penrose site is representative of U.S. landfills. Landfill gas is provided from four separate landfills with typical levels of contaminants and gas heating value. This site is also regulated by the South Coast Air Quality Management District which is nationally recognized for strict environmental regulations, so that a successful demonstration in this area is likely to be accepted by other localities within the United States.

The Penrose site is entirely suitable for the demonstration. All required facilities are already in place including: a proven landfill gas collection system, natural gas supply permits, contracts for equipment and saleable electricity, and more than adequate space available for the demonstration. With the recent tie-in to a fourth landfill, there is an excess of landfill gas available to provide the 2350 SL/M required for the demonstration. The site is readily accessible within a half-hour of the main facilities of the Pacific Energy and Southern California Gas. Support facilities and personnel are already in place.

Table 4-1. Pacific Energy Landfill Gas Sites

Landfill Gas Projects	Location		Type	MWe	Power Purchaser
Upland Pwr Sta.	Upland	CA	Elec. Pwr.	0.6	SCE
Oxnard Pwr. Sta.	Oxnard	CA	Elec. Pwr.	3.7	SCE
Penrose Pwr. Sta.	Sun Valley	CA	Elec. Pwr.	9.3	SCE
Toyon Pwr. Sta.	Los Angeles	CA	Elec. Pwr.	9.3	SCE
Gude Pwr. Sta.	Rockville	MD	Elec. Pwr.	3.0	PEPCO
Bakersfield Pwr. Sta.	Bakersfield	CA	Elec. Pwr.	1.8	PG&E
Stockton Pwr. Sta.	Stockton	CA	Elec. Pwr.	0.8	PG&E
Lompoc Pwr. Sta.	Lompoc	CA	Elec. Pwr.	0.6	PG&E
Crazy Horse Pwr. Sta.	Salinas	CA	Elec. Pwr.	1.4	PG&E
Santa Clara Pwr. Sta.	Santa Clara	CA	Elec. Pwr.	1.5	PG&E
Otay Pwr. Sta.	San Diego	CA	Elec. Pwr.	1.9	SDG&E
Bonsall Pwr. Sta.	San Diego	CA	Elec. Pwr.	1.5	SDG&E
				35.4	

Table 4-2. Assessment of Candidate Sites vs. Evaluation Criteria

	Typical USA	Penrose	Toyon	Oxnard	Otay
1. Select site representative of U. S. Landfills so demonstration will be relevant to a large portion of the U. S. Market (compare landfill to range for U.S. Landfills.					
• Gas Heat Content (Btu/Ft^3 HHV)	500 Btu/Ft^3	440	470 – 550	550 – 570	550
• CH_4	50%	44	47 – 54	54	54
• Gas Diluents					
• $\%O_2$	< 1%	< 1%	< 1%	< 1%	0.2%
• $\%N_2$	< 2%	4%	7%	6%	3%
• $\%CO_2$	50%	54%	39%	39%	43%
• Gas Contaminants					
• Total NMOC (ppm)	274	130 – 474	36 – 130	36 – 50	Not available
• Total Sulfur (ppm)	21	150	14 – 24	Not available	27 – 63
• Total Halides (ppm)	132	78 – 95	7 – 58	Not available	Not available
• Local codes and regulators – to demonstration at this site likely to be accepted at other localities (yes/no)		Yes	Yes	Yes	Yes
• Name of local regulatory agency		SCAQMD	SCAQMD	Ventura APCD	San Diego APCD
• Geographic/market potential – is demonstrated located in area likely to support commercial fuel cell LFG-to-energy (yes/no)		Yes	Yes	Yes	Yes
• Size of existing Landfill Power Plant		8.9 MW	8.9 MW	3.7 MW	1.9 MW
2. Suitability of site for demonstration test					
• Multiple landfill gas sources		Yes	No	Yes	No
• Site, setup for LFG-to-energy		Yes	Yes	Yes	Yes
• Collection system-in-place (yes/no)		Yes	Yes	Yes	Yes
• Gas contracted (yes/no)		Yes	Yes	Yes	Yes
• Permit in place (yes/no)		Yes	Yes	Yes	Yes
• Power contracted in place (yes/no)		Yes	Yes	Yes	Yes
• Space available for demonstration (yes/no)		Yes	No	Yes	Yes
• Excess gas availability for demonstration (at least 84 SCFM)		Yes	No	Yes	Yes
• Natural gas service available		Yes	Yes	No	Yes
• Opportunity to demonstrate thermal utilization (Note: Little potential use at any site)		1. Plant Office	1. Plant Office	1. Plant Office 2. Hotel 3. Club House	1. Plant Office
• Accessibility for workers and visitors (Ex/Good/Poor)		Excellent	Excellent	Excellent	Poor
• Support facilities					
• Maintenance		Yes	Yes	Yes	Yes
• Phone/Office		Yes	Yes	Yes	Yes
• Sanitary		Yes	Yes	Yes	(Portable Only)
• Support personnel available (number) at site		5	5	2	1
• Site Ownership		Private Industrial Area	City of L.A. Dept. of Parks & Rec. (Griffith Park)	City of Oakland	County of San Diego
• Site Aesthetics		Fair	Excellent	Excellent	Good
• Landfill Status		3 Closed 1 Open	1 Closed	2 Closed 1 Open	1 Open

Table 4-3. Supplemental Landfill Data for Candidate Sites

	Penrose	Toyon	Oxnard	Otay
• Number of landfills serving site/names	1. Penrose 2. Shelton Arleta 3. Bradley 4. Tuxford	1. Toyon	1. Santa Clara 2. Ventura Coastal 3. Ballard	1. Otay
• Ownership of Landfills	1. Private 2. City of L.A. 3. Private 4. Private	1. City of L.A.	1. City of Oxnard 2. Sanitation Dist. 3. Private	1. County of San Diego
• Distance from Downtown Los Angeles	15 miles (northwest) Sun Valley/Burbank	7 miles (northwest) Griffith Park	70 miles (west) City of Oxnard	100 miles (south) City of Chula Vista
• Site Description	Old Industrial	Woods – View of Mountains	River, New Hotel, Golf Clubhouse, Homes	Hills, Light Industrial
• Ownership of Proposed Fuel Cell Site	1. Private Industrial 2. Pacific Energy	1. City of L.A. Dept. of Parks (Griffith)	1. City of Oxnard 2. Ventura County	1. City of San Diego
• Status of Landfills – Open (O)/Closed (C)	1. Penrose (C) 2. Shelton-Arleta (C) 3. Bradley (C) 4. Tuxford (C)	1. Toyon (C)	1. Santa Clara (C) 2. Ventura (C) 3. Bailard (O)	1. Otay (O)

4.1.3 Description of Selected Site

A detailed description of the selected site is given in Figures 4-1 and 4-2. These figures, provided by Pacific Energy, describe the location and description of the existing landfill gas to energy conversion equipment which consists of five 9.375 megawatt internal combustion engine generator sets. This site presently produces 8.9 megawatts of net power to the electrical grid.

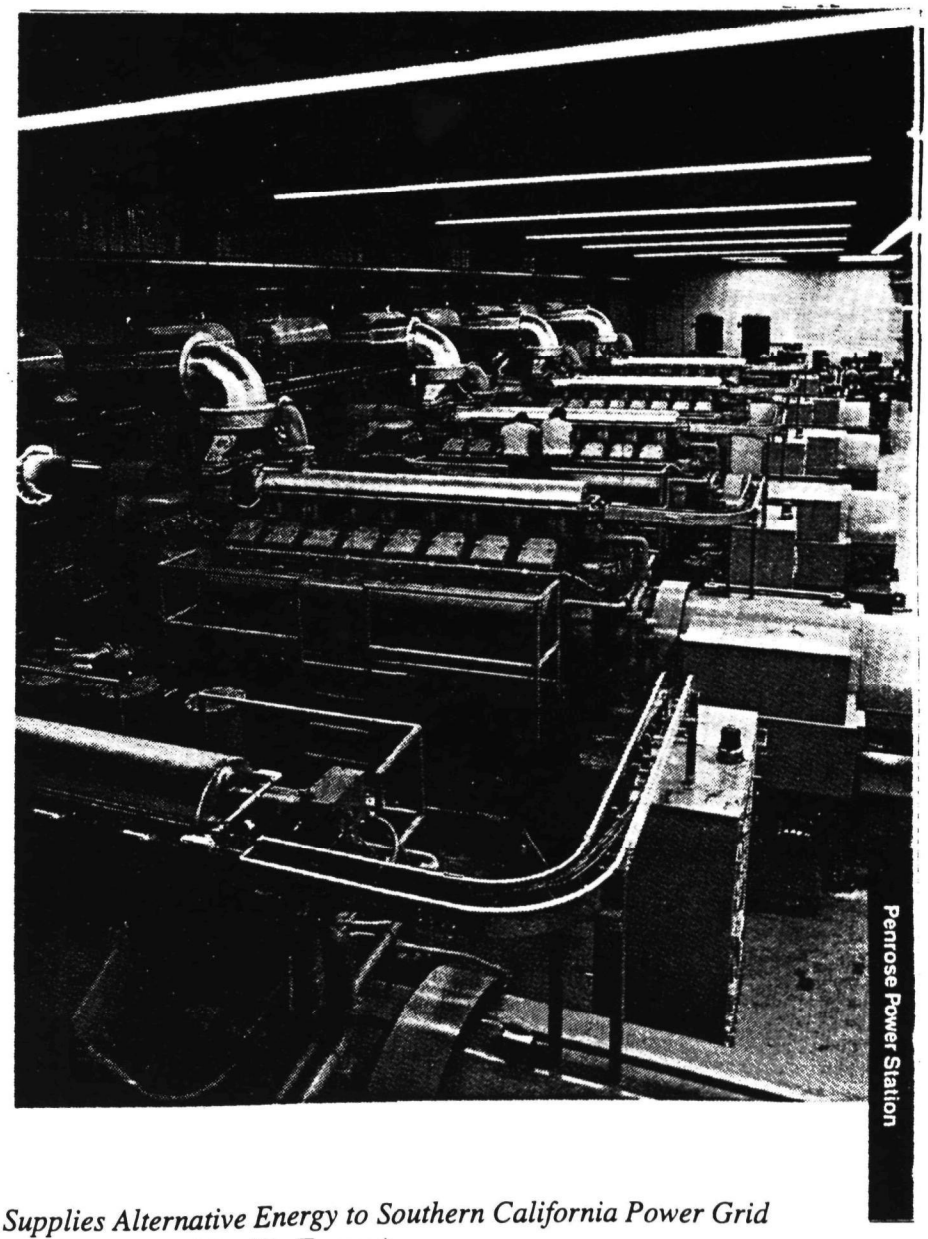
Figure 4-3 shows an aerial photograph of the Penrose Station which is located off Tujunga Avenue along the edge of the Penrose landfill. Site potential locations for the demonstration are identified on the aerial photograph. Site location number two was selected based upon its close proximity to the existing power plant station, ease of access to Tujunga Avenue, plus availability of virgin soil for laying foundations for the gas pretreatment and fuel cell equipment.

PACIFIC LIGHTING ENERGY SYSTEMS

LANDFILL GAS TO ELECTRIC POWER

Penrose Power Station

Penrose Plant Supplies Alternative Energy to Southern California Power Grid



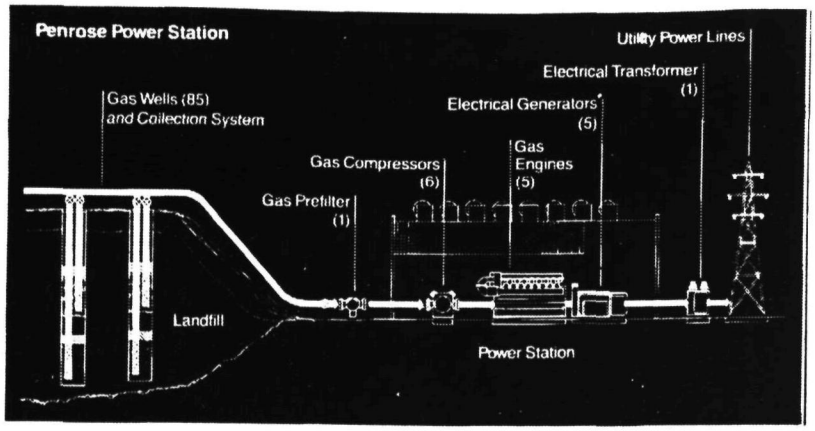
Situated in Sun Valley, an industrial/residential area in Los Angeles' San Fernando Valley, the Penrose power station, like its twin at Toyon Canyon, began operation in 1985 as one of the world's largest landfill gas-to-electric power plants. The gas from this relatively deep landfill fuels five "Clean Burn" internal combustion engines to produce a maximum 8.9 megawatts (MW) of electrical power which is sold to Southern California Edison. This alternative energy resource can serve the electrical needs of an estimated 8,900 homes and help conserve our natural energy resources by saving the equivalent of up to 115,000 barrels of oil per year. In addition, the project produces risk-free revenue for the city, pays local, state and federal taxes and provides environmental and safety benefits by reducing gas migration and surface gas emissions.

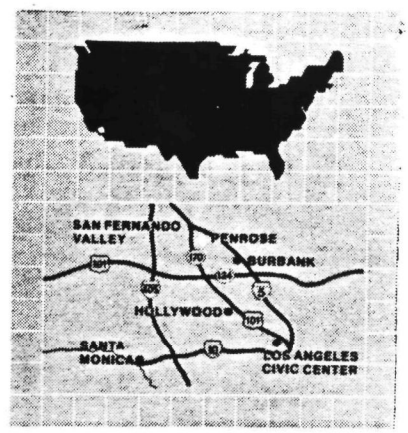
Landfill Description

The Penrose sanitary landfill, owned by Los Angeles By-Products, Inc., contains an estimated 9 million tons of non-hazardous municipal waste. The landfill opened in

Figure 4-1. Penrose Plant Supplies Alternative Energy to Southern California Power Grid
(Courtesy of Pacific Energy)

Landfill Gas to Electric Power





1960 and closed in 1983. It covers 72 acres and has an average depth of 200 feet, making it one of the deepest of Pacific Lighting Energy Systems (PLES) landfill projects. The landfill is located about fifteen miles northwest of downtown Los Angeles in Sun Valley and one mile west of the Golden State freeway (Route 5) at Penrose Avenue.

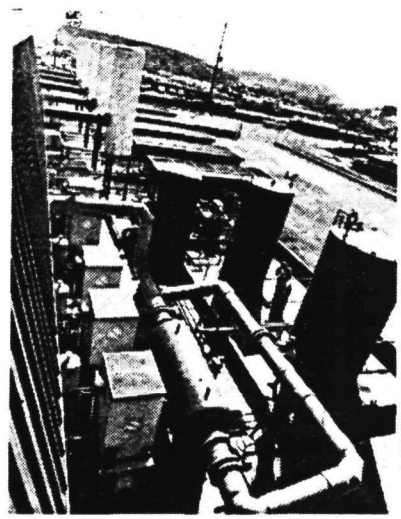
Power Station Description

The power station and gas collection systems were designed and developed, syndicated, and are operated by PLES. Construction work was completed in 10 months and start up began in December 1985.

The gas collection system consists of 85 wells, of which 55 are single pipe wells and 30 are duplex wells containing two pipes. The duplex wells recover gas from the midpoint and bottom of the landfill. Each well pipe (4" or 6" pvc) is slotted on the bottom third to recover the gas produced and has a butterfly valve installed on top to control gas flow. The wells are interconnected by a surface and subsurface pipeline system which fuels the power station located in the northeast corner of the site.

Within the station, six 150 horsepower motor-driven reciprocating compressors draw the gas from the landfill and through a two-stage oil bath prefilter at 20" to 40" vacuum. The gas from the compressors at 90 - 100 psig passes through a pulsation dampener and two coalescing filters, and is delivered to five 2,650 horsepower, Cooper Superior "Clean Burn," low NOx internal combustion engines. Each engine drives an 1,875 kW, 4,160 volt, synchronous generator. Together the five generators produce a maximum 9.4 MW of power of which about 5 to 10 percent is used internally with the remaining power fed to a 4,160 volt - 34,500 volt step-up transformer. The power produced is sold to Southern California Edison under a 20-year contract.

A three-man crew operates and maintains the station during the day and an automatic control system operates and monitors the station at night. A computer system registers any operating shutdown and signals the station's off-duty operating crew via a dial-up system.



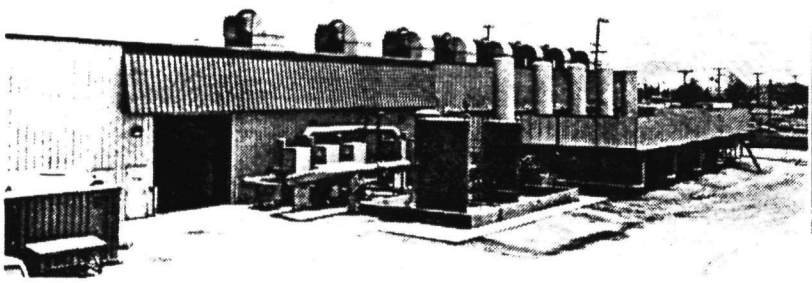
Key Project Data

Project Location	Sun Valley, City of Los Angeles
Landfill Name	Penrose Sanitary Landfill
Landfill Owner	Los Angeles By-Products, Inc.
Landfill Size	72 acres
Landfill Depth	150 to 200 feet (average)
Tons in Place (Refuse)	9 million
Number of Gas Wells	85
Number of Engine-Generators	5
Type of Engines	Gas-fired, internal combustion
Engine Size	2,650 hp
Gross Horsepower (5 engines)	13,250 hp
Type of Generators	4,160 volts, synchronous
Generator Size	1,875 kW
Gross kW (5 Generators)	9,375 kW
On-site kW use	5% to 10%
Net kW to Grid	8,900 kW (maximum)
Power Purchaser	Southern California Edison
Equivalent Homes Served	8,900 (maximum)
Barrels of Oil Saved, Yr	115,000 (maximum)
Estimated Project Life	20 years

Corporate Background

PLES develops and operates energy projects throughout the United States including district heating and cooling plants and plants which produce electric power using alternative energy resources such as landfill gas, wastewood, geothermal hot water, and hydropower.

PLES is a wholly-owned subsidiary of Pacific Lighting Corporation (NYSE), a multi-billion dollar a year holding company whose principal subsidiary is Southern California Gas Company. PLES continues a 100-year corporate heritage of energy service.



For additional information contact:

Pacific Lighting Energy Systems
6055 E. Washington Boulevard
Commerce, California 90040
(213) 725-1139

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952104

Figure 4-2. Landfill Gas to Electric Power
(Courtesy of Pacific Energy)

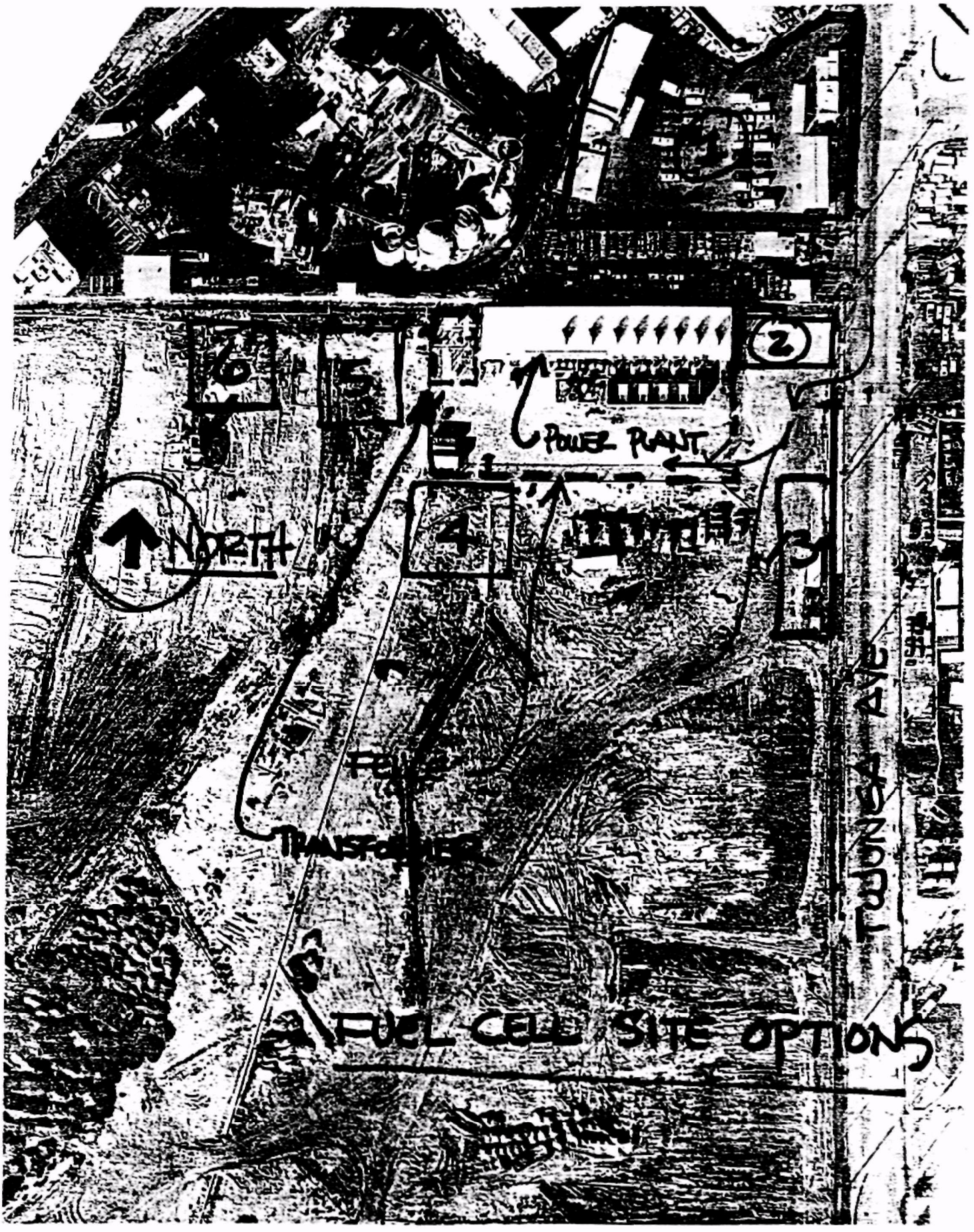

Figure 4-3. Fuel Cell Site Options
(Courtesy of Pacific Energy)

4.2 Landfill Gas Pretreatment Unit Process Design and Description

The process design of the landfill gas pretreatment unit cleaning process is dictated by the final gas purity requirements for the fuel cell, the composition of the incoming landfill gas and its complex mixture of trace contaminants, and the requirement that the gas cleanup process be capable of handling variations in inlet gas composition. The fuel cell gas quality must be essentially free from all sulfur and halogen contaminants so as to consist primarily of a mixture of methane, nitrogen, oxygen, and carbon dioxide. The landfill gas pretreatment unit design specification (See Appendix B, Attachment A, pB-19 to B-29) allows a maximum exit sulfur level of 3 ppmV and maximum halogen level of 3 ppmV. This level of sulfur can be successfully removed by the fuel cell power plant internal fuel cleanup subsystem while the halogen can be removed with the addition of an optional halide guard to the existing system. The EPA field test results described in Section 5.3 show landfill gas pretreatment unit contaminant cleanup levels far better than the specification requirements. Raw landfill gas trace contaminants and their concentration levels used as the original basis for the landfill gas pretreatment unit process design are shown in Table 4-4. The hydrocarbon and contaminant species in raw landfill gas consists of a mixture of saturated hydrocarbons, aromatics, halogenated hydrocarbons, hydrogen sulfide and organic sulfide gases.

Table 4-4. Raw Landfill Gas Contaminants and Concentrations at Penrose Test Site (Original Pre-EPA Program Data)

Landfill Gas Trace Contaminants	Raw Gas Concentration Level (ppm - by volume)
Hydrocarbons	
Isobutane	95
Isopentane	963
n-Pentane	198
Hexane	297
Octane	81
Aromatics	
Benzene	2
Ethylbenzene	13
Chlorobenzene	1
Toluene	35
Xylenes	22
Styrene	0.5
Halogenated Hydrocarbons	
Dichloroethene	3
Dichloroethane	3
Methylene Chloride	12
Cis-1, 2-Dichloroethene	5
Trichlorofluoroethane	0.6
Trichloroethylene	70
Tetrachlorethylene	6
Vinyl Chloride	1.4
Sulfides	
Hydrogen Sulfide	103
Methyl Mercaptan	5
Ethyl Mercaptan	5
Dimethyl Sulfide	8
Dimethyl Disulfide	0.02

4.2.1 Process Operation

A simplified schematic of the landfill gas pretreatment system is shown in Figure 4-4. The process consists of ambient temperature H_2S removal followed by cooling, condensation, drying, further cooling, hydrocarbon removal and final filtration. The process is designed to remove the hydrogen sulfide contamination and water vapor in the early process steps, so that final polishing can be accomplished over an activated carbon bed which is maintained at a constant low temperature, to insure consistent high trace contamination removal. This design makes the process relatively insensitive to changes in the gas inlet gas concentration with time, and thus makes it an excellent candidate for landfills. The landfill gas pretreatment system is comprised of the following 3 major subsystems:

- Clean Gas Production Process
- Regeneration Process
- Refrigeration Process

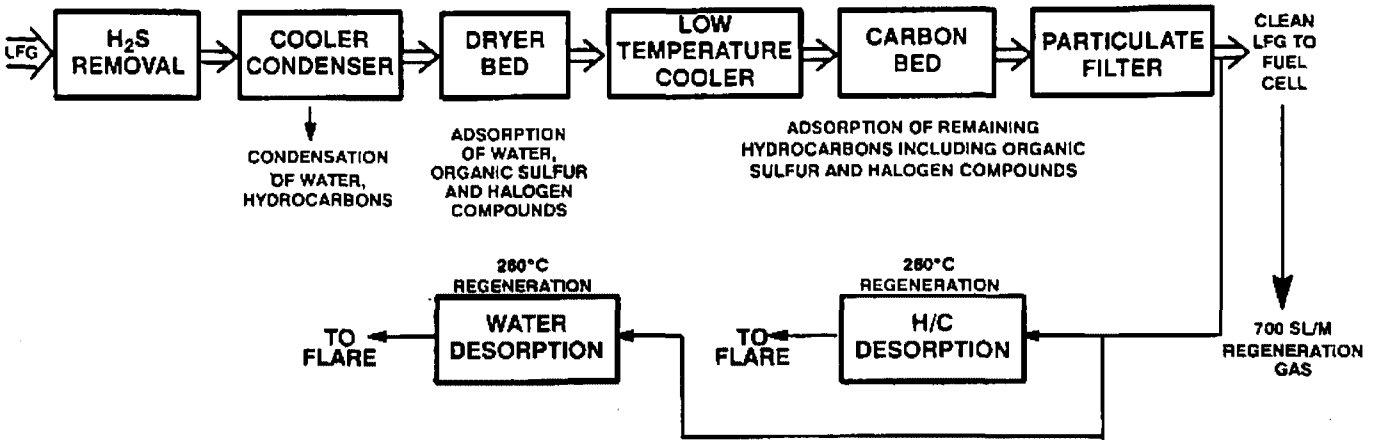

Figure 4-4. Landfill Gas Pretreatment Unit System

4.2.1.1 Clean Gas Production Process - The purification process is represented in a block flow diagram in Figure 4-5. The process operates on raw landfill gas which is regulated down to 1.52×10^5 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 contaminants from the landfill gas.

The H_2S removal bed reacts H_2S with O_2 found in the landfill gas to produce elemental sulfur. This bed contains 119 liters (43 cm diameter x 81 cm deep) of activated carbon impregnated with potassium hydroxide, from Westates Carbon. This bed is non-regenerable and is replaced periodically. The first stage cooler condenser operates at approximately +2°C and the second stage cooler operates at -28°C.

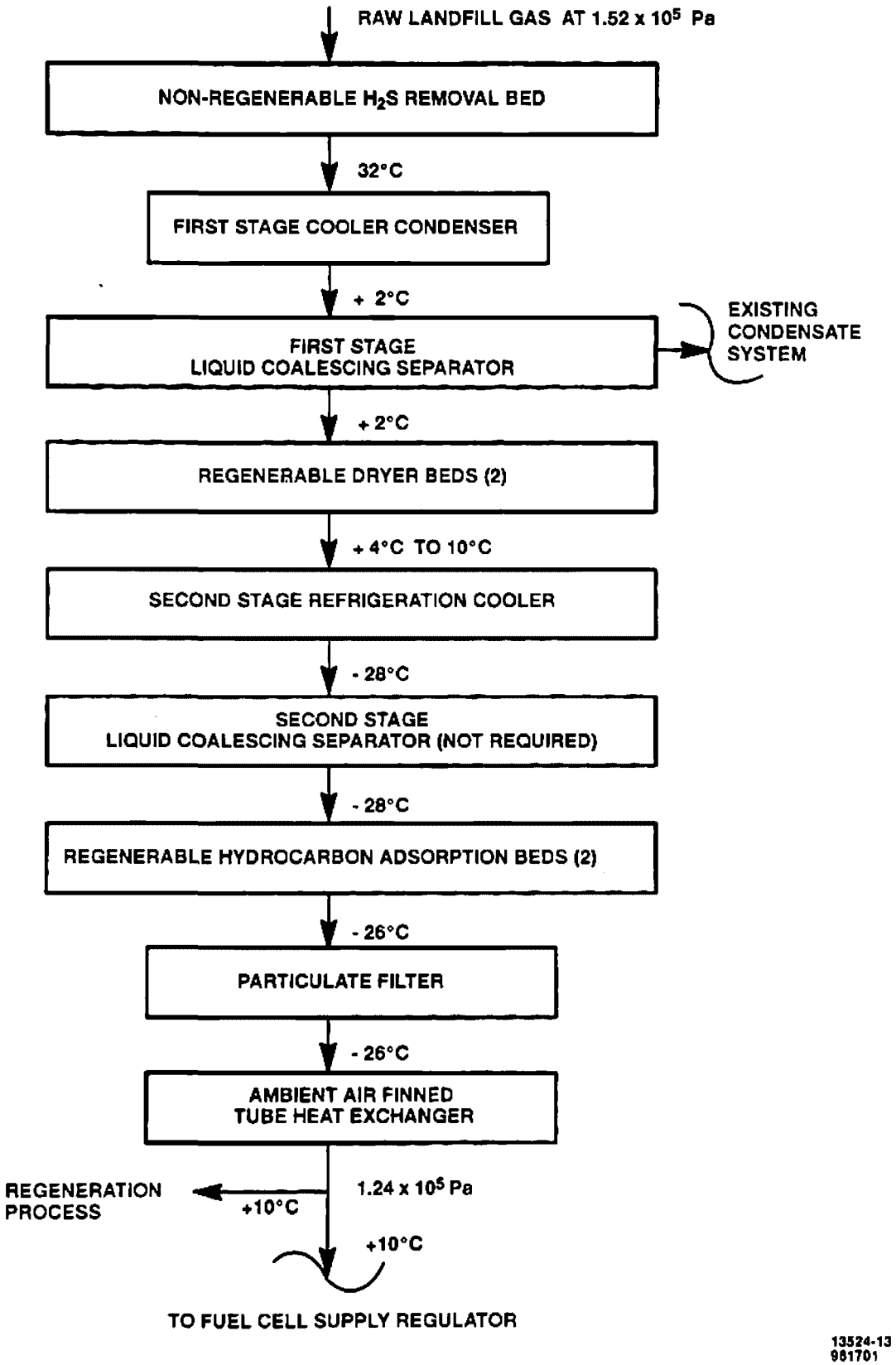

Figure 4-5. Gas Purification Process

The first 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 demonstration landfill gas pretreatment unit (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 landfill gas to be treated in the pretreatment unit. All remaining water in the landfill gas, as well as some sulfur and halogen compounds, are removed in a regenerable dryer bed which has a high capacity for adsorbing the remaining water vapor in the landfill gas. The bed is 119 liters total volume (43 cm diameter by 81 cm deep) filled with 71 liters of Alcoa F200 aluminia, 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 landfill gas is then fed to the second stage cooler. This cooler can be operated as low as -32°C and potentially can condense out heavy hydrocarbons if present at high enough concentrations. In addition the second stage cooler reduces the temperature of the carbon bed therefore enhancing its adsorption performance[7]. 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 the landfill gas. This unit consists of two beds, each containing 119 liters of activated carbon (Barneby and Sutcliffe, type 209C) so that one is always operational while the other is being regenerated. Both the regenerable dryer 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°C before being fed to the fuel cell unit. The GPU process operating pressure is nominally 1.38×10^5 Pa with minimal pressure loss across the equipment. A final regulator reduces the landfill gas pressure to the fuel cell, which operates at 1×10^3 to 3.5×10^3 Pa inlet pressure. The elevated operating pressure relative to the supply pressure provides a reserve to accommodate flow up transients to the fuel cell.

4.2.1.2 Regeneration Process - The refrigeration process is represented in a block diagram shown in Figure 4-6. This process heats clean product landfill gas from the production process and regenerates the dryer and hydrocarbon adsorption beds in the reverse flow direction during their regeneration cycle and destructs the spent regenerant gas in an enclosed flare. An electric heater is used to heat the recycled clean landfill gas to 288°C. This heated, regeneration gas is used first to regenerate the hydrocarbon adsorption bed. Second, the dryer bed is regenerated. Third, the regeneration gas heater is 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. During transition from adsorption to regeneration modes the regeneration gas is bypassed around the beds. 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.

4.2.1.3 Refrigeration Process - The refrigeration process shown in Figure 4-7 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 properties of d-limonene are given in Appendix F. The refrigeration process incorporates a double-stage hermetically-sealed 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 process operates with a claimed greater than 99 percent reliability based on past operating experience. Both refrigerant R-22 and d-limonene coolant are completely recycled and are not purged or vented from the process.

7. "Recovery of VOC's Using Activated Carbon"; Graham, James R. and Ramaratnam, Mukuno; Chemical Engineering, February 1993

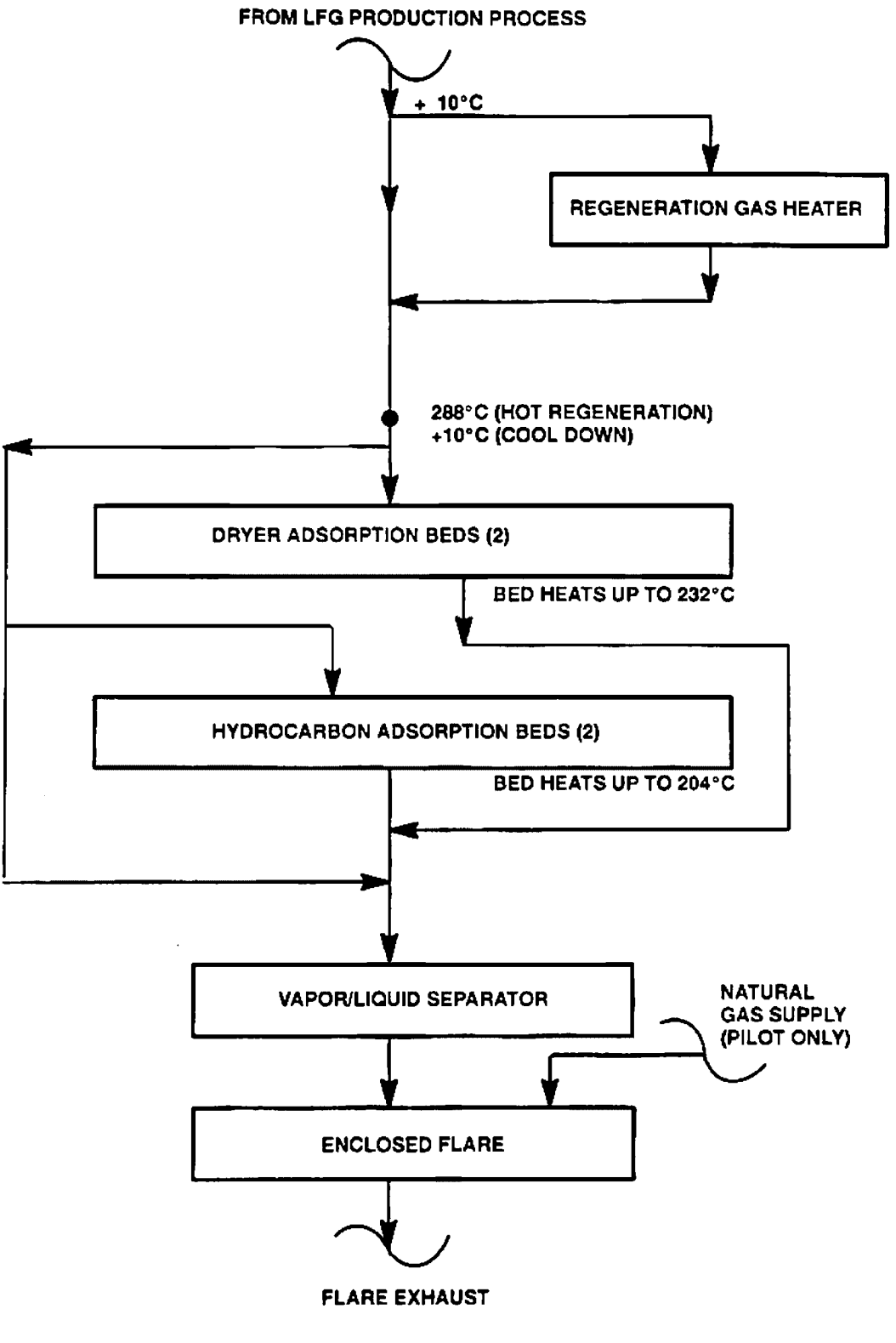

Figure 4-6. Regeneration Process

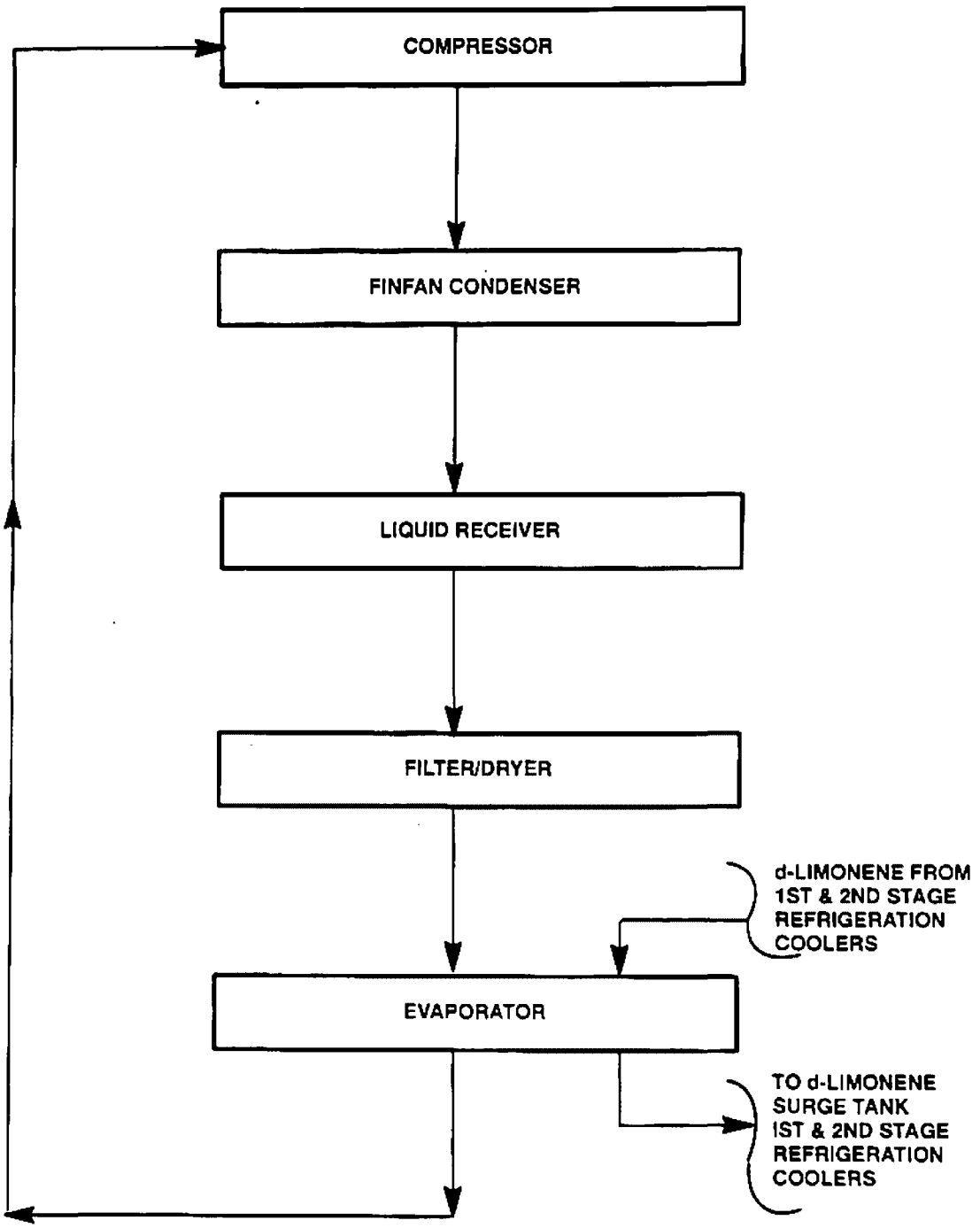

Figure 4-7. Refrigeration Process Unit

4.3 PC25 Power Plant Design Modifications

4.3.1 Introduction and Background

In the Phase I Conceptual Study a preliminary list of modifications to the fuel cell were identified to achieve 80 kW, 140 kW, 175 kW and full rated 200 kW power. These preliminary studies were based on a nominal gas composition of 50% methane and 50% carbon dioxide with a 4.45 kcal per standard liter heating value. At the time of the Phase I Conceptual Study, natural gas blending with the landfill gas was considered as a means to maintain the gas heating value to the fuel cell at 4.45 kcal per standard liter when the heating value of the landfill gas was less than 4.45 kcal per standard liter.

4.3.2 Phase II Summary

The results of the detailed Phase II engineering study to identify modifications required for the fuel cell power plant to operate on landfill gas are summarized in Table 4-5. The detailed Phase II study is based upon Penrose site landfill gas analyses (43.9% methane, plus 40.1% carbon dioxide, plus 15.6% nitrogen, plus 0.4% oxygen) with a heating value of 3.91 kcal per standard liter. Natural gas blending was dropped as an option, since the use of natural gas would lessen the value of the landfill-gas-to-energy demonstration to demonstrate ability to operate on a wide range of landfill gas, including low heating value. Of the four power levels considered, the 140 kW nominal output was selected as the appropriate level for the demonstration, since the identified power plant modifications could be readily installed in the field after the initial fuel cell startup and checkout on natural gas was completed.

Table 4-5. Modifications to PC25 A for Operation at 140 kW in Landfill Gas Demonstration

CHANGE TYPE I. OPERATE TO 140 KW ON LANDFILL GAS	DESCRIPTION OF CHANGE
1. Modify Control Software	• Modify reactant flow schedules for landfill gas, steam, burner air. • Modify landfill gas flow transducer calibration • Modify fuel properties for landfill gas • Review process parameter event & shutdown limits. • Review fuel control algorythms.
2. Cathode Exit Orifice	• Reduce cathode exit orifice (FO 120) diameter to balance stack cross pressure.
3. Recycle Orifice	• Enlarge recycle orifice (FO 310) to increase flow.
4. Inlet Fuel Controls	• Install larger fuel control valve (FCV 012). • Install low pressure drop fuel venturi (FE012).
II. IMPROVE HALIDE TOLERANCE	
5. Halide Guard Bed (Optional)	• Add separate halide guard bed (catalyst, heaters, thermal switch) within existing fuel processor.
III. STARTUP	
6. Start Burners	• Replumb start burners to natural gas supply. Add solenoid valve, CV040, to reformer start burner gas supply line.

The list of modifications in Table 4-5 is based on computer process simulations utilizing the measured landfill gas composition available at the Penrose site. These simulations were used to verify that no other issues existed, and to provide a basis for the software revisions which are required as part of the changes. The detail studies identified one potential issue. System simulations using the measured landfill gas composition indi-

cated that pumping requirements for the steam ejector would exceed the ejector capability at 140 kW on landfill gas. Additional component tests were conducted using steam and air, instead of nitrogen, as originally done. These more accurate tests indicate that the standard natural gas power plant ejector can provide 140 kW of process gas without modification. A total of seven modifications were identified for operation of the PC25 A natural gas power plant in the landfill demonstration in the Phase I study, and these were verified in Phase II. These modifications consist of four changes to achieve the 140 kW output power level, one change to provide enhanced halide tolerance, one to provide enhanced tolerance to ammonia, and one change to permit startup on natural gas after the power plant process inlet has been connected to landfill gas. These changes are described in more detail in the subsequent sections.

4.3.2.1 Modify Control Software - Control software changes permit the power plant to operate when the input process fuel properties change from natural gas with a nominal heating value of 8.89 kcal per standard liter to landfill gas with a heating value of only 3.91 kcal per standard liter. The input fuel properties and reactant schedules are changed to compensate for the difference in heating value and chemical content of the new landfill gas fuel. The changes in fuel properties and reactant schedules ensure that the power plant controller will provide the appropriate level of process fuel, steam, and burner air for the power plant. The fuel calibration curve for the landfill gas fuel flow transmitter is updated to ensure that the relationship between volumetric fuel flow and energy content is consistent with the properties of the landfill gas provided to the power plant. The fuel control software modifications assure accurate fuel flow control while operating on landfill gas.

4.3.2.2 Cathode Exit Orifice - The cathode exit flow orifice, FO120, is modified to maintain an acceptable cell cross pressure. This is accomplished by reducing the orifice diameter to increase the total pressure on the cathode side of the stack, and balance the increased anode side pressure caused by the increased volumetric fuel flow rate of dilute landfill gas.

4.3.2.3 Recycle Orifice - The recycle flow orifice, FO310, is enlarged to increase recycle gas flow to the fuel processor.

4.3.2.4 Inlet Fuel Controls - The inlet fuel controls will be modified to reduce pressure drop. This is accomplished by installing a larger fuel flow control valve, FCV012, and installing a new fuel venturi, FE012, with a lower pressure drop characteristic. These changes facilitate the higher inlet volumetric fuel flow of landfill gas required to provide adequate heating value to the fuel cell.

4.3.2.5 Halide Guard Bed (Optional) - The Phase I study determined that a pretreatment system would have to be designed to achieve total halide removal down to 0.15 ppm by volume to ensure a one year fuel processor life. This compares favorably to the maximum of 0.032 ppmV total halides which was measured during the Field Test (see Section 5.3.3). Therefore addition of a separate halide guard was not required. The total halide content exiting the GPU was monitored during the field test to insure that the halide concentration remained at safe levels. (See Section 6)

The halogen guard bed would be installed as a separate spool piece within the existing fuel processor section of the PC25 A fuel cell power plant. This guard bed would consist of 79 liters of a sodium oxide based adsorbent, heaters to maintain operating temperature of approximately 260°C, and a local thermal switch to control the heaters. The guard bed will remove halides including fluorides, chlorides and bromides which are hydrogenated in the existing PC25 A fuel processor.

4.3.2.6 Startup - The demonstrator PC25 A power plant will continue to use natural gas for the start burners which preheat the stack coolant and the reformer to their normal operating temperatures during initial startup. When the power plant process feed is changed to landfill gas, this will require replumbing the start burner gas supplies to natural gas. At this time a solenoid valve, CV040, will be added to the reformer start burner line as required by code.

4.4 Site Specific Process Design

4.4.1 Overall System and Site Description

A simplified description of the overall landfill-gas-to-energy demonstration is shown in Figure 4-8. The demonstration consists of the landfill gas wells and collection system provided by Pacific Energy at their Penrose Site, a modular gas pretreatment system, (described in greater detail in Section 3.1), a 200 kW PC25 A natural gas fuel cell power plant manufactured by ONSI Corporation modified for landfill gas operation, a cooling module, and an interconnection to the grid. Landfill gas from four separate landfills is collected at the site and compressed to 90 psig at the existing Pacific Energy facility before it is conveyed to the gas pretreatment unit where water vapor and contaminants are removed to very low levels for the fuel cell. The clean landfill gas is then converted to ac power for sale to the electric utility. Cogeneration heat generated by the fuel cell power plant will be rejected by an air cooling module for the demonstration.

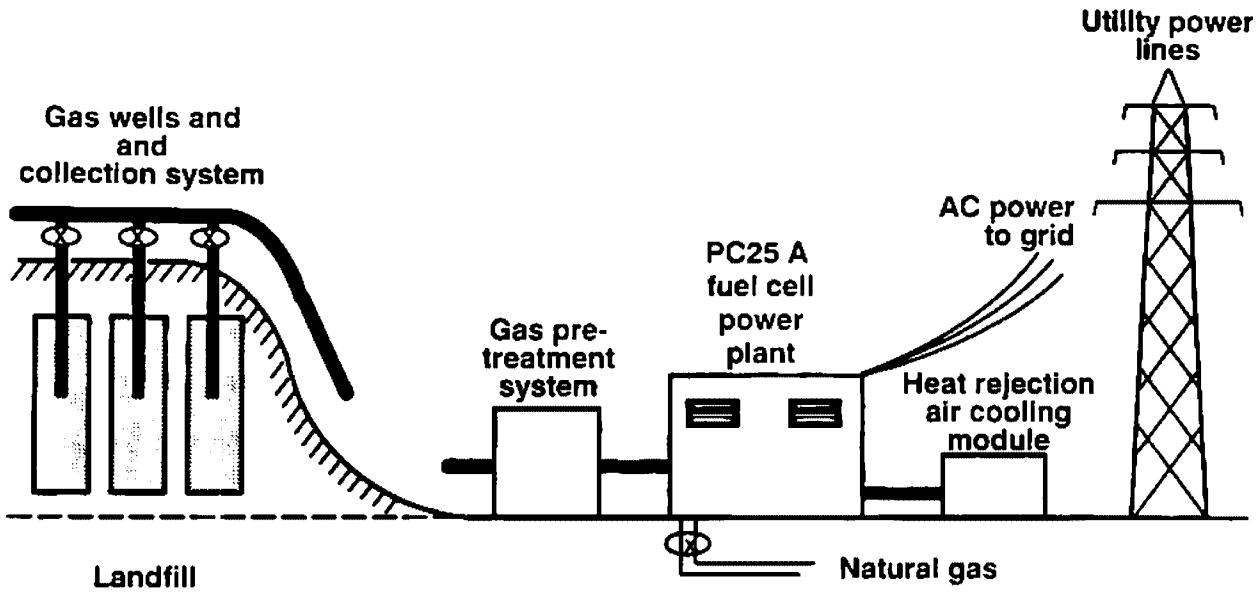

Figure 4-8. LFG Fuel Cell Demonstration Program

A simplified process description of the landfill gas pretreatment and fuel cell system is provided in Figure 4-9. The demonstration starts with the raw landfill gas at a flow rate of 2260 standard liters per minute. The landfill gas consists of 43.9% methane, 40.1% carbon dioxide, 15.6% nitrogen, with 0.4% oxygen on a dry gas basis. The gas also contains 130 to 475 ppm by volume non-methane hydrocarbons, which includes contaminants consisting of 45 to 65 ppmV total halides (measured as chlorides), about 100 ppmV hydrogen sulfide, and an additional 11 ppmV of organic sulfur compounds (measured as H_2S). The gas is saturated with water at 6.2×10^5 Pa at the inlet to the gas pretreatment unit.

The first stage in the gas pretreatment process is a carbon bed which removes virtually all of the hydrogen sulfide. This bed is not regenerated on site, but the carbon can be removed and regenerated off site if desired. The gas is next regulated down from 6.2×10^5 to 1.5×10^5 Pa, before being cooled to approximately 2°C in the first stage refrigeration condenser. The condenser stage reduces most of the water and some hydrocarbons, which are removed from the system as a condensate and returned to the existing Penrose site condensate treatment system. The next step is a regenerable adsorption bed which removes the water vapor to a dew point of minus 50°C and also removes additional sulfur and halides. The dry gas is then passed over a second stage cooler where the gas temperature is reduced to -28°C before going through a regenerable activated carbon bed for final removal of trace hydrocarbons, sulfur, and halides. The final step is fine pore filtration to remove any particulates or dusting which may come from the regenerable adsorbent beds. The clean dry gas is regulated down to about 3.5×10^3 Pa pressure. The resulting gas to the fuel cell is approximately 1560 standard liters per minute at 3.5×10^3 Pa pressure with major contaminants reduced to less than 0.05 ppm by volume total halides and total sulfur.

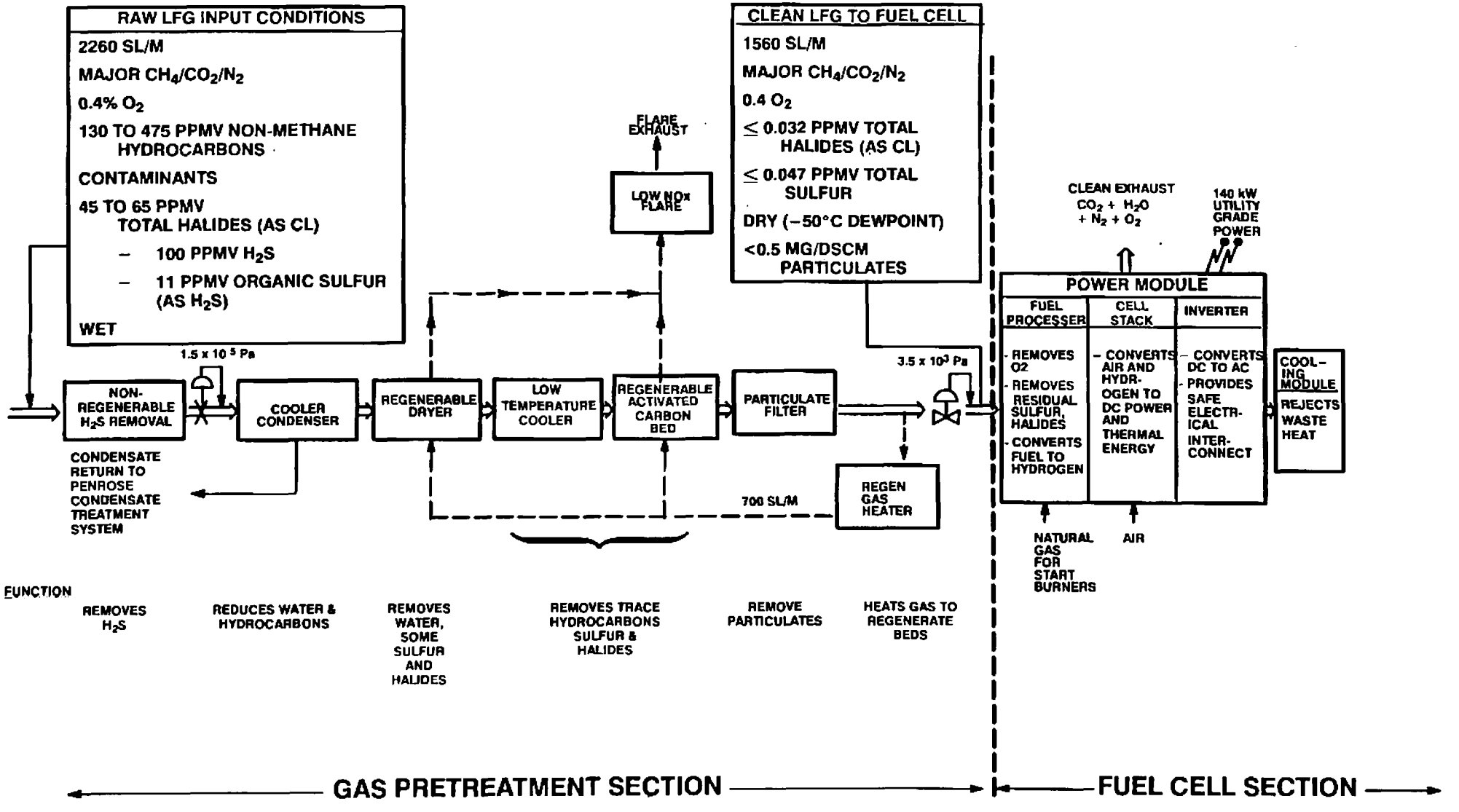

Figure 4-9. Demonstration Project Processes

13524-16
952404

The dryer and carbon beds are regenerated using clean dry landfill gas from the exit of the pretreatment system. The regeneration gas is heated to 288°C in an electric heater, and passed counter-current through the regenerable dryer and activated carbon beds to remove the water and contaminants. The contaminants are destroyed in a low NOx flare.

The fuel cell section of the demonstration consists of three major subsections: the fuel processor; the cell stack; and the inverter. The fuel processor removes oxygen and any residual sulfur in the landfill gas and converts the landfill gas to a hydrogen rich fuel. The next stage in the fuel cell power plant is the cell stack. The stack converts air and the hydrogen rich fuel from the fuel processor to make dc power and thermal energy. DC power is sent to the inverter which converts the dc power to 60 cycle ac at 480 volts and provides safe, electrical interconnect to the grid. All heat from the power plant during the demonstration will be rejected to the air by the cooling module.

The fuel cell power plant emits a clean exhaust stream consisting primarily of carbon dioxide, water vapor, nitrogen and oxygen. Typical secondary emissions for the natural gas powered PC25 A fuel cell is about 0.5 ppmV NOx, 1.1 ppmV carbon monoxide, and 0.03 ppmV non-methane hydrocarbons, all measured at 15% oxygen on a dry gas basis. During operation on landfill gas in Phase III the fuel cell exhaust emissions were measured as follows: NO_x = 0.12 ppmV; and carbon monoxide = 0.77 ppmV. These results are discussed in more detail in Section 6.3.3.

For a more detailed description of the gas pretreatment section process, refer to Section 4.2.

4.5 Site Specific Engineering Design

4.5.1 Site Location

The landfill gas to energy site is located at Pacific Energy's Penrose Power Station in Sun Valley, CA. Selection of this site was based upon site selection criteria which were developed and discussed in Section 4.1. The location of the selected site (labeled ②) at the Penrose Power Station facility is shown in Figure 4-10.

4.5.2 Site Arrangement

The site arrangement for the landfill gas to energy demonstration is shown in Figure 4-11. The demonstration site is completely enclosed by a chain-link fence. The gas pretreatment skid and refrigeration unit are installed in the middle of this demonstration site area in the lined zone. This area represents the limit of the zone which is classified Class I, Division 2 for electrical equipment by the National Electrical Code due to the presence of the gas pretreatment system. Lying outside this area to the north is the control panel for the Gas Pretreatment Unit control panel which is located inside an existing utility building. This building has also been outfitted with phone communications. To the right of the existing utility building is the flare for the gas pretreatment system. This flare functions to destroy the contaminants removed from the landfill gas while emitting low levels of secondary emissions.

The fuel cell power plant and cooling module are located directly due south of the gas pretreatment unit as shown in Figure 4-11. The fuel cell power plant installation is completely standard for an ONSI natural gas fuel cell power plant. The fuel cell pad is made of reinforced concrete approximately 335 cm wide by 762 cm long, while the cooling module pad is approximately 244 cm by 366 cm.

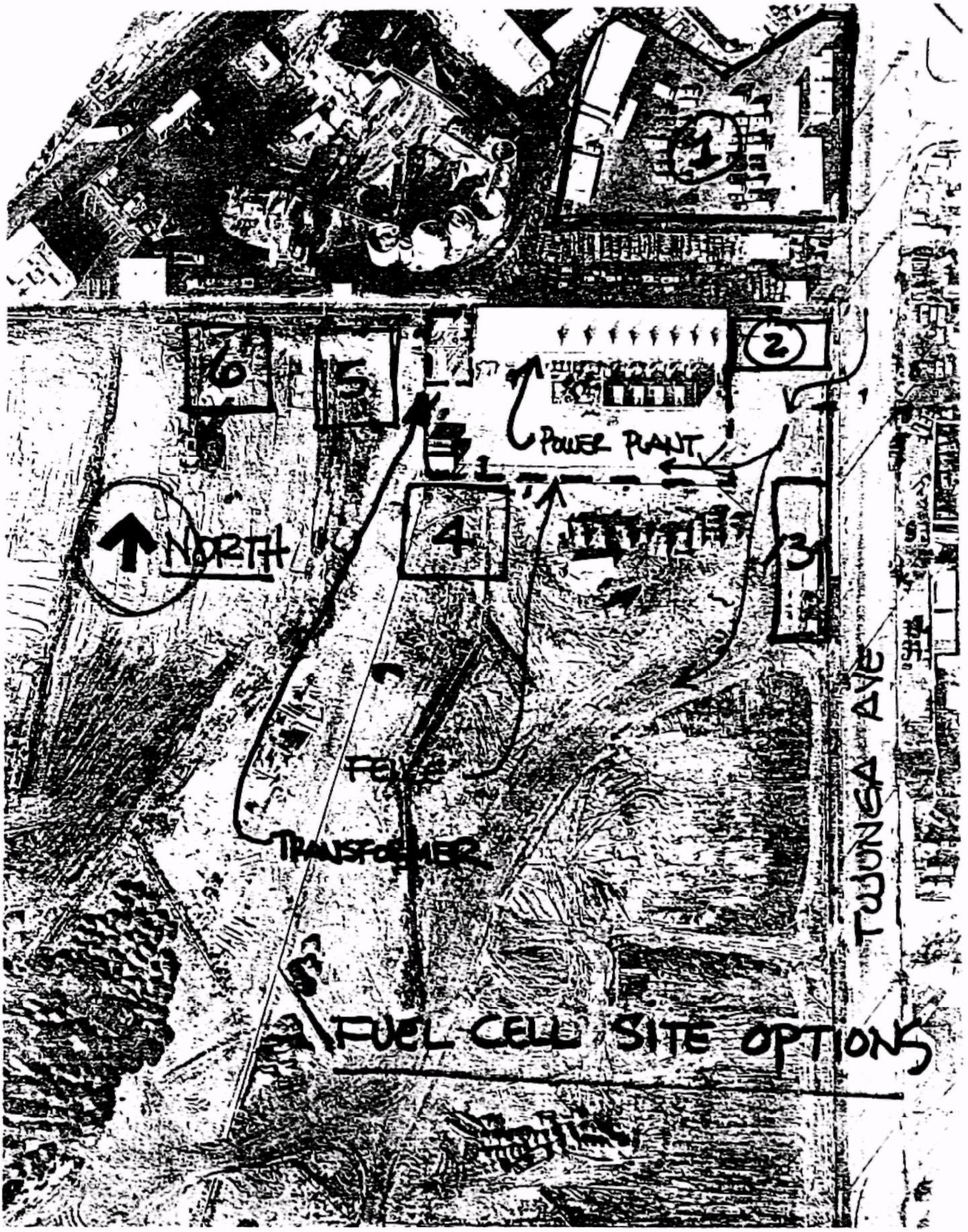

Figure 4-10. Fuel Cell Site Options: Site 2 Selected for Demonstration (Courtesy of Pacific Energy) (13047-09)

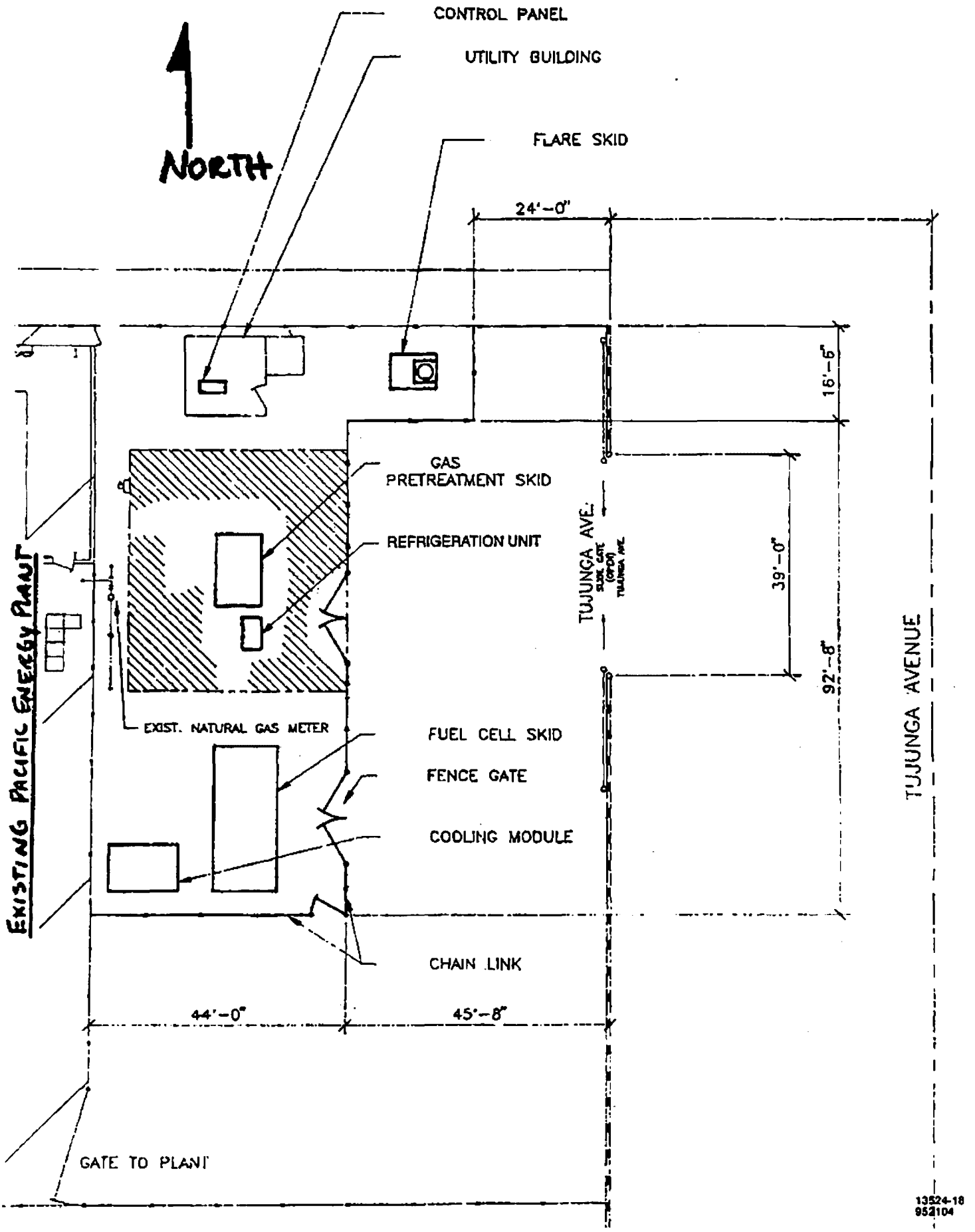

Figure 4-11. Site Layout (13047-09)

4.5.3 Site Design Details

The details of the EPA landfill gas site design are described in seven site blueprints shown in Table 4-6, which cover site plan and details, structural specifications, foundation plan and schedule, structural details, mechanical plan, mechanical piping plan, and P&ID drawing.

Table 4-6. Summary of Detail Site Design for EPA Landfill Gas Demonstration

PRINTS	DESCRIPTION
C-1	Site Plan & Details
S-1	Structural Specifications
S-2	Foundation Plan & Schedule
S-3	Structural Details
M-1	Mechanical Plan
M-2	Mechanical Piping Plan
PI-1	P&ID Drawing

5.0 GAS PRETREATMENT UNIT VERIFICATION TEST

This section describes the verification testing to confirm the performance of the gas pretreatment unit (GPU) prior to connection to the fuel cell power plant for the field demonstration of recovery of energy from landfill gas in Phase III. Major objectives of the verification test are: (1) process performance verification (demonstrate that the GPU meets contaminant removal requirements for the fuel cell of less than 3 ppm by volume total sulfur and less than 3 ppm by volume total halogens); (2) reliability demonstration of up to 500 hours total and at least 200 hours continuous operation; and (3) emissions testing of the GPU flare required by South Coast Air Quality Management District.

The specific test plan to achieve these objectives is discussed in Section 5.1 - Landfill Gas Pretreatment Module Test Plan. Section 5.2 discusses permitting requirements for the South Coast Air Quality Management District (SCAQMD) and L.A. City. All GPU test results including factory test, field checkouts, and the Phase II field test and SCAQMD tests, are discussed in Section 5.3 - Test Results.

5.1 Landfill Gas Pretreatment Module Test Plan

IFC developed a Test Plan (Appendix B) to ensure that all GPU objectives established in Phase I would be met.

The testing was divided into three parts: (1) Factory test at IFC in South Windsor, Connecticut, on nitrogen to verify the thermal, mechanical, and electrical operability of the GPU; (2) Site Checkout Test at the Penrose site in Sun Valley, California, on landfill gas to determine if adjustments were required prior to conducting the Phase II EPA field test; and (3) Phase II EPA Field Test to document contaminant removal performance and flare performance.

The Factory Test and Site Checkout Test are described in Appendix B, Section 2.0. These tests are designed to identify any mechanical or process issues early so they can be addressed and corrected prior to initiating the Phase II Field Test.

The Phase II EPA Field Test is described in Appendix B, Sections 3 and 4. Section 3 describes the Test Plan for the gas pretreatment unit process performance measurements to ensure that the contaminant removal of sulfur, halogens, and particulates from the landfill gas meet the requirements for the fuel cell power plant in the Phase III demonstration test. Section 4 describes the test for the South Coast Air Quality Management District permit requirements which include the emissions characteristics of the GPU flare. The complete test protocol for the Field Test is summarized in Table 5-1.

The results of all GPU testing are described in Section 5.3 Test Results.

Table 5-1. Test Protocol for Phase II EPA Field Test

				OUTLET GAS MEASUREMENTS – (PTU TO FUEL CELL)						INLET GAS MEASUREMENTS - (LANDFILL TO PTU)						CONDENSATES		FLARE TESTING			
				TOTAL SULFUR ONLY	H2S ONLY	INDIVIDUAL HALIDES	R-12* ONLY	TOTAL PARTICULATE	SPECIAL SCAQMD TESTING	R-12* ONLY	TOTAL & INDIVIDUAL SULFUR COMPOUNDS (TABLE A)	VOLATILE PRIORITY, HC + R-12* POLLUTANTS (TABLE C)	PHENOL	ELEMENTAL SILICON for SILANES & SILOXANES (TABLE D)	SPECIAL SCAQMD TESTING (TABLE B)	TOTAL ORGANICS (as carbon)		* SPECIAL SCAQMD TESTING *			
DAY	TIME PERIOD (HR)	OPERATING BED	INLET GAS CONDITIONS													VESSEL 1	VESSEL 2	FLARE INLET (TABLE B)	FLARE EXHAUST (TABLE E)	AMBIENT (TABLE E)	COMMENTS
				ON SITE fine SO2 detect (continuous strip chart recorder)	ON SITE fine	ON SITE fine GC/ECD	ON SITE fine	OFF SITE fine filter	OFF SITE bag	ON SITE fine (check 50ppm level)	ON SITE bag GC/FPD	OFF SITE bag GC/MS, GC/FID	OFF SITE tube HPCL	OFF SITE tube AAS	OFF SITE bag	OFF SITE liquid	liquid	OFF SITE bag	OFF SITE bag	OFF SITE bag	ANALYSIS COMPANY LOCATION SAMPLE METHOD ANALYSIS EQUIPMENT USED
				1 HR	1 HR	1 HR	1 HR	"BP"	24 HR	1 HR	1 HR	"BP"	"BP"	"BP"	24 HR	24 HR	24 HR	24 HR	24 HR	24 HR		TIMING FOR PRELIM RESULTS ("BP" - Best Practice)
*** PRE-TEST SAMPLE / ANALYSIS ***				--	--	--	--	--	--	--	YES	YES	YES	YES	--	--	--	--	--	YES	TRC CALIBRATION CHECKOUT
*** INITIAL PTU CHECKOUT ANALYSIS ***				YES	--	YES	--	--	--	--	--	--	--	--	--	--	--	--	--	--	OPTIONAL TRC TESTING TO CONFIRM & CALIBRATE PTU
*** PTU TESTING ***																					
1	0600-0630	A	LFG	YES		YES					YES	YES	YES	YES		YES					* PRE-CHALLENGE TESTING.
	0630-0900	A	+ R-12*				YES			YES											* CHALLENGE TEST OF BED A
	0900-1500	A	+ R-12*				YES														USING APPROX. 50 PPM OF
	1500-1600	A	+ R-12*	YES		YES	YES										YES				R-12* ADDED TO LFG.
	1600-2400	B	LFG																		
2	0000-0600	A	LFG																		
	0600-0900	B	LFG	use equip for flame test sample check				YES			YES	YES	YES	YES		YES		MULTI	MULTI	MULTI	NORMAL TEST OF SECOND BED
	0900-1500	B	LFG		YES			YES	YES						YES			YES	YES	YES	(MULTI - Multiple samples
	1500-1600	B	LFG	YES	YES	YES		YES									YES	YES	YES	YES	as practicable)
	1600-2400	A	LFG																		
3	0000-0600	B	LFG																		
	0600-0900	A	LFG	YES	YES	YES		YES			YES	YES	YES	YES		YES					NORMAL TEST OF FIRST BED
	0900-1500	A	LFG		YES			YES													AFTER AT LEAST 24 HOUR
	1500-1600	A	LFG	YES	YES	YES		YES									YES				USE SINCE CHALLENGE TEST
SAMPLE VALVE		LOCATION		SV300	SV132	SV300	SV300	SV132	SV300	SV206	SV206	SV206	SV206	SV206	SV206	SV171	SV170	SV148	STANDARD	--	
		FITTING TYPE		BOTH SAMPLE LINES HAVE 1/4 INCH SWAGELOK MALE FITTINGS						1/4 INCH SWAGELOK MALE FITTING						1/4" MALE		1/4" MALE	SAMPLE PORTS		
SAMPLE ANALYSIS EQUIPMENT				1.) SO2 detect: pulsed fluorescent SO2 detector 2.) GC/ECD: gas chromatograph / electron capture detector 3.) filter, gravimetric measurement on filter 4.) GC/FPD: gas chromatograph / flame photometric detector						5.) GC/MS: gas chromatography / mass spectroscopy 6.) GC/FID: gas chromatography / flame ionization detection 7.) HPLC: high pressure liquid chromatography 8.) AAS: atomic absorption spectroscopy											

(*) R-12 = Dichlorodifluoromethane

5.2 Permitting

Obtaining local permits is an essential part of the demonstration project. For the landfill gas demonstration, two major permits were required: South Coast Air Quality Management District for emissions; and the City of Los Angeles Building and Safety Department for local building and safety codes.

5.2.1 South Coast Air Quality Management District Permit

The gas pretreatment unit flare requires a SCAQMD permit to construct and operate. A copy of the permit to construct and operate is given in Appendix B, Attachment D.

The permit to construct and operate is based on 18 permit conditions. The key technical condition is given in Condition No. 11 which requires that "a temperature of not less than 760°C as measured by the temperature indicator shall be maintained in the flare stack." The second critical condition is No. 16 which requires that performance tests be conducted and the results forwarded to the South Coast Air Quality Management District. The required SCAQMD tests were included as part of the test plan protocol discussed in Section 4.1. These tests were conducted as part of the GPU qualification test conducted on October 19, 20 and 21, 1993.

5.2.2 L.A. City Permits

The L.A. City Department of Building and Safety administers local codes to ensure that minimum safety standards are met for mechanical and electrical equipment. This process includes submittal of site construction drawings for plan checks plus inspection of electrical and mechanical aspects of the gas pretreatment unit system by field inspectors and/or the L.A. City Test Labs. For the gas pretreatment unit separate permits were required for the pretreatment skid, the water chiller (refrigeration unit), and the flare. The pretreatment skid and the flare have been approved. The water chiller has passed field inspection and all issues have been settled with the L.A. City Test Labs. A brief chronological summary of the activities associated with obtaining the L.A. City permits over a period of 17 months is summarized in Table 5-2.

Table 5-2. Permit Activities for EPA Gas Pretreatment

September 14, 1992	Submitted applications for L.A. City Building and Safety Plan Checks.
October 22, 1992	Received plan correction sheet from L.A. requesting additional information.
January 5, 1993	L.A. City Building and Safety Permits are approved.
February 19, 1993	Installation Contract awarded to Unit Construction.
March 19, 1993	Additional Electrical permit required
April 20, 1993	Pretreatment Skid, Water Chiller and Flare required an additional Special Equipment Permit. Pretreatment Skid and Flare was approved. The Water Chiller required approval from the L.A. City Test Labs, because it was a listed piece of equipment.
June 8, 1993	Application for the Water Chiller was submitted to the L.A. City Test Labs.
June 11, 1993	Application for a variance to operate Water Chiller was submitted. Variance was approved on June 24, 1993.
August 2, 1993	Field inspection was made by L.A. City Test Labs on the Water Chiller, a L.A. City Test Lab report was issued on August 5, 1993.
February 24, 1994	All of the issues have been settled with L.A. City Test Labs.

5.3 Test Results

This section describes the results of the tests described in Section 5.1, Landfill Gas Pretreatment Module Test and Quality Assurance Plan. These test results are reported in three sections: (1) Factory test on nitrogen to verify the thermal, mechanical and electrical operability of the gas pretreatment unit; (2) Site Checkout Tests on landfill gas to determine if adjustments are required prior to conducting Phase II EPA Field Test; and (3) the Phase II EPA Field Test to document contaminant removal performance and document flare performance.

5.3.1 Factory Test Results

The Factory Test on nitrogen was conducted at International Fuel Cells' facility in South Windsor, CT. The test demonstrated that the Gas Pretreatment Unit (GPU) can be operated and controlled at its designed temperature, and verified the pressure drop in the GPU at design flow is approximately 4.1×10^4 Pa with nitrogen gas. This compares favorably with design value of 3.4×10^4 Pa psi pressure drop with landfill gas. Based upon this successful factory test, the GPU was shipped to the Penrose site in Sun Valley, California. The test results are described in more detail in Appendix B, Attachment C.

5.3.2 Site Checkout Test Results

The initial Site Checkout Test was performed at the Penrose site between April 25 and May 2, 1993, after repairs were made to correct minor damage which occurred during shipping. The GPU was operated briefly on landfill gas to assess operability and gas pretreatment performance. An analysis of gas samples taken during operation indicated that the hydrogen sulfide (H_2S) present in the landfill gas was being converted to carbonyl sulfide (COS) during processing in the GPU.

Laboratory testing confirmed that the source of carbonyl sulfide is reaction of hydrogen sulfide with carbon dioxide in the landfill gas over dry (regenerated) alumina desiccant:[$H_2S + CO_2 \leftrightarrows COS + H_2O$]. The laboratory testing confirmed that mass extraction of water vapor by the dry regenerated alumina drives the reaction to almost 100 percent conversion to COS. (See Appendix F).

The high concentration of carbonyl sulfide would cause the gas to the fuel cell to exceed the 3 ppmV specification, since carbonyl sulfide removal from the landfill gas by the downstream activated carbon bed is limited. IFC therefore elected to eliminate the carbonyl sulfide formation by removing the hydrogen sulfide from the raw landfill gas upstream of the first stage condenser. An activated carbon impregnated with potassium hydroxide was selected to remove the H_2S. Testing of the impregnated carbon material on landfill gas has shown that it removes all H_2S, plus some organics, and halogens from landfill gas. The H_2S removal was also confirmed in laboratory tests at IFC and the manufacturer. The IFC and manufacturer test data are summarized in Appendix C. Based upon these tests, the GPU was modified by the addition of a single H_2S removal bed, upstream of the first stage condenser.

The second Site Checkout Test was conducted between September 6 and September 8, 1993. This checkout confirmed complete H_2S removal in the new bed, validated that the gas pretreatment processes were functioning as expected, and confirmed that the GPU was ready for verification testing. Gas sampling was taken during 3 days of operation. Operation during that time was not continuous, due to a problem with the refrigeration unit, which caused several shutdown/restarts. The problem was determined to be loss of Freon due to a leak, probably caused during shipping of the unit. The leak was repaired and the unit recharged, which restored normal operation. The unit accumulated approximately 36 hours of operation, during which 21 bag samples were taken at strategic sampling points in the process.

The results of the H_2S analysis, as well as those of other sulfur compounds, are shown in Table 5-3 at a point in time approximately 18 hours into the checkout test and at eight different sample locations in the GPU. As predicted by lab tests, the results show that all the H_2S was removed to below detectable levels in the new H_2S removal bed. No COS was formed in the alumina dryer bed (C), and overall, there was no detectable sulfur at the exit of the system (E). One species, dimethyl sulfide, which appears to be absorbed on the dryer

bed (C) is removed during regeneration (G) indicating that sulfur is not building up in the dryer bed. Based on these results, it was decided to proceed into the GPU Field Testing portion of the program.

Table 5-3. Gas Pretreatment Unit Sulfur Removal Performance ~18 Hours into September 1993 Site Checkout Test

	Exit Gas Concentration (PPM) at Sample Port Locations							
SPECIES	LFG INTO UNIT	A	B	C	D	E	F	G
		H_2S REMOVAL	COOLER CONDENSER	REGENERABLE DRYER	LOW TEMPERATURE COOLER	ACTIVATED CARBON BED	REGENERATION GAS FROM ACTIVATED CARBON BED	REGENERATION GAS FROM DRYER BED
Hydrogen Sulfide	80.3	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)
Carbonyl Sulfide	0.16	ND(2)	0.07	0.08	ND(2)	ND(2)	0.59	ND(2)
Methyl Mercaptan	3.26	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)	0.31
Ethyl Mercaptan	0.51	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)	ND(2)
Dimethyl Sulfide	6.25	9.07	8.25	ND(2)	ND(2)	ND(2)	ND(2)	34.9
Carbon Disulfide	0.06	0.09	0.09	0.03	0.04	ND(1)	0.60	ND(1)
Dimethyl Disulfide	ND(1)	0.09	0.1	ND(1)	ND(1)	ND(1)	ND(1)	0.67

ND = None Detected
(1) – 0.02 ppm Detection Limit
(2) – 0.04 ppm Detection Limit

5.3.3 Phase II, EPA Field Test

The Phase II Field Test of the gas pretreatment unit (GPU) was successfully completed during October 20, 21, and 22, 1993 according to the Test Plan (Appendix B) discussed in Section 5.1. The results from this testing are provided in a report by TRC Environmental, Inc., in Appendix D. These results show that the GPU operated well within process specifications for sulfur and halide removal. Total particulates at the exit were less than detectable. Emissions from the flare are consistent with SCAQMD requirements. Subsequent to the Field Tests in October, the operational reliability of the GPU was successfully demonstrated and the unit was voluntarily shut down on March 3, 1994 after completing 216 hours of continuous operation and a total of 616 hours since first startup. Based upon these results, the GPU was declared ready for operation with the fuel cell power plant in the Phase III Field Test Demonstration.

The Phase II Field Test was performed under the direction of IFC personnel with assistance from Pacific Energy site personnel. TRC Environmental, Inc. was responsible for all gas analyses. Testing was conducted over a 3 day period. "Day 1" was devoted primarily to challenge testing of the unit's "A" or even numbered regenerable dryer and activated carbon beds by adding a light halogenated species to the landfill gas entering the GPU. Dichlorodifluoromethane was selected as the challenge gas for this test. Raw inlet gas composition and outlet gas composition were analyzed according to the requirements given in the test protocol in Table 5-1. "Day 2" was devoted to testing of the "B" or odd number regenerable beds with raw landfill gas without the dichlorodifluoromethane addition and to testing the flare for the South Coast Air Quality Management District. Additional gas analysis was performed on the raw inlet gas, outlet gas, and regeneration gas flare inlet and exhaust as well as ambient air reference samples. The flare inlet and exit were monitored three times during regeneration per the test protocol in Table 5-1. "Day 3" was devoted to retesting of the "A" beds on raw landfill gas without dichlorodifluoromethane addition following at least a 24 hour period since the addition of dichlorodifluoromethane challenge gas on "Day 1." Raw inlet gas and outlet gas compositions were analyzed. The "Day 3" testing was initiated immediately following the "Day 2" activities to expedite the verification procedures.

The results of the Phase II Field Test of the GPU are in Figure 5-1 and Table 5-4. Figure 5-1 shows the sampling locations, dichlorodifluoromethane injection location, plus inlet and outlet gas conditions on a simplified block diagram of the GPU including the new H_2S removal bed at the inlet. The tests were all conducted with an inlet landfill gas flow of 2260 standard liters per minute, and an outlet flow of 1560 standard liters per minute of clean landfill gas, which is sufficient to generate 140 kW of continuous electric power using the PC25 A fuel cell power plant. The output conditions in Table 5-4 show that the major contaminant removal requirements have been met by a wide margin. Total halogens (measured as chloride) were less than or equal to .032 ppmV which is over 90 times less than the 3 ppmV requirement. Total sulfur (measured as H_2S) was less than or equal to .047 ppmV which is over 60 times less than the requirement of less than 3 ppmV.

The overall results of the Phase II field testing of the gas pretreatment unit are summarized in Table 5-4. Total halogens (as chloride) were reduced from an average inlet concentration of 60 ppmV (average of 6 tests) to an outlet concentration ranging from non-detectable to 0.032 ppmV. The only species detected at the exit was methylene chloride. Taking the highest total outlet halogen level (0.032 ppmV as chloride) divided by the average inlet total halogens of 60 ppmV as chloride yields a removal efficiency of at least 99.95 percent for halogens. During the dichlorodifluoromethane challenge test an inlet level of 7.4 ppmV dichlorodifluoromethane was reduced to non-detectable (less than 0.002 ppmV) for a removal efficiency of greater than 99.97 percent. Total sulfur (measured as H_2S) averaged 113 ppmV at the H_2S adsorber inlet(average of 3 tests), with outlet levels of non-detectable to 0.047 ppmV, for an overall removal efficiency of at least 99.96 percent. The only sulfur species detected at the GPU exit was carbonyl sulfide. Particulates were measured at the GPU exit on three occasions with all three test results being less than detectable. The third test was run at the lowest detection limit of 0.5 Mg per dry standard cubic meter, indicating that the gas going to the fuel cell is virtually particulate free. Silanes and siloxanes were also measured several times with increasing sensitivity but were at all times less than the detection limit at the inlet. The third test found no measurable silanes or siloxanes at a detection limit of 0.076 milligrams per dry standard cubic meter. Consequently, no measurements were taken at the GPU outlet. Likewise, phenol was measured and found to be less than the detection limit of 0.03 ppmV at the inlet.. In summary, the gas pretreatment unit is operating with an overall contaminant removal efficiency of greater than 99.9 percent, and the gas available to the fuel cell power plant for the demonstration easily meets all fuel cell requirements.

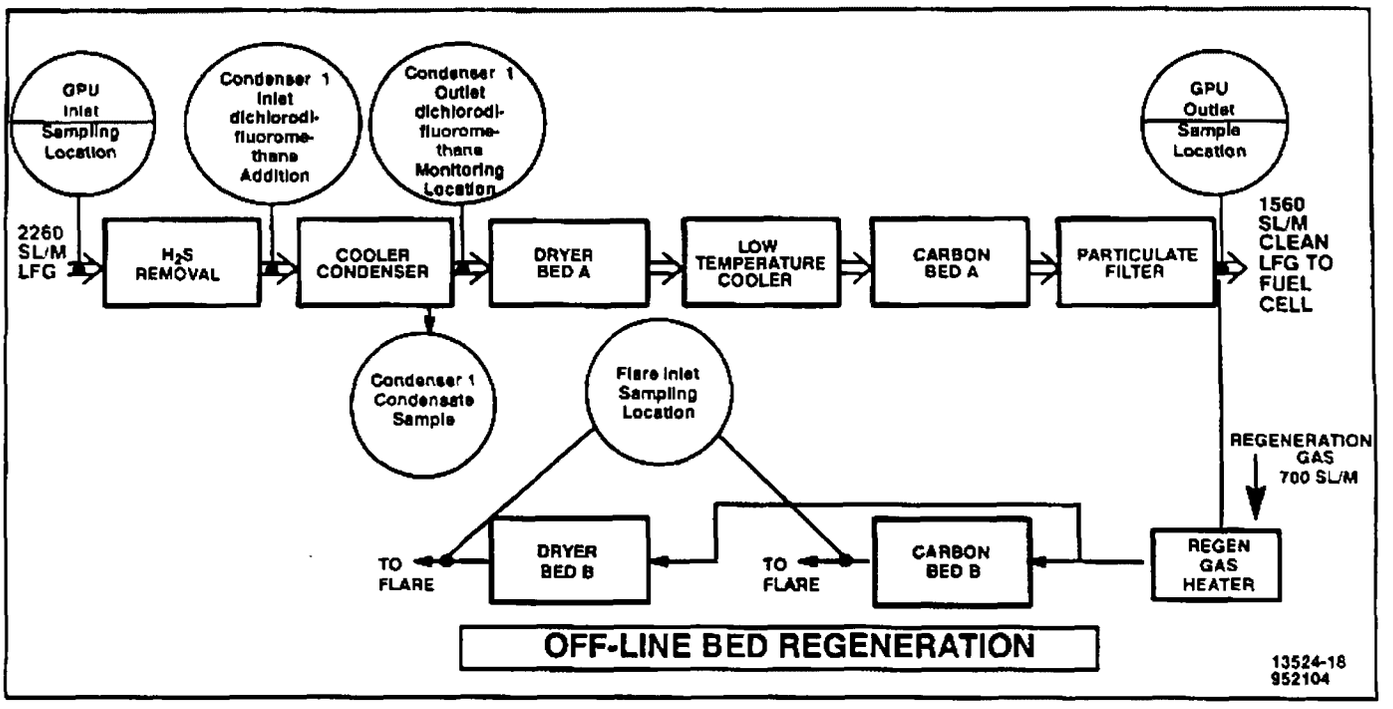

Figure 5-1. Phase II Gas Pretreatment Unit Sample Locations. Shown with "A" Beds On Line, and "B" Beds being Regenerated.

Table 5-4. Summary of Phase II Field Testing of Gas Pretreatment Unit

TEST CATEGORY	INLET TO GPU	OUTLET OF GPU	REMOVAL EFFICIENCY (5)	REMARKS
Total Halogens (as chloride) (1)	60 ppmV	ND to .032 ppmV	99.95%	• ONLY species detected is methylene chloride
dichlorodifluoromethane	7.4 ppmV	ND (2)	99.97%	• Challenge test with Freon-12 added to GPU inlet
Total Sulfur (as H_2S) (3)	113 ppmV	ND to 0.047 ppmV (4)	99.96%	• Major species detected is carbonyl sulfide
Particulates	—	< .05 $\frac{MG}{DSCM}$	—	• Below detection limit of 1 mg
Silanes, Siloxanes	< .076 $\frac{MG}{DSCM}$	—	—	• Below detection limit at inlet
Phenol	< .03 ppmV	—	—	• Below detection limit at inlet
Non methane organics (as CH_4)	5700 ppmV	13.8 ppmV	99.8%	

NOTES: *(1) Total halogens as chloride = sum of each individual halogen compound detected times number of halogen atoms (chlorine, fluorine) in that compound (e.g., 1 ppmV of Freon-12 (dichlorodifluoromethane) = 4 ppmV as chloride)*

(2) Non-detectable to .002 ppmV as the species

(3) Total sulfur as H_2S = sum of each individual sulfur compound times the number of sulfur atoms in that compound

(4) Non-detectable to 0.004 ppmV to 0.010 ppmV.

(5) Removal Efficiency = $\left[1 - \frac{exit}{inlet}\right] \times 100$

A good overall indicator of GPU cleanup performance is total nonmethane organics. Total nonmethane organics (as CH_4) showed a reduction from 5700 ppmV at the inlet to 13.8 ppmV at the GPU outlet, for an overall removal efficiency of 99.8 percent. In addition to hydrocarbons containing sulfur and halogen, the nonmethane organics include nonhaloginated and nonsulfur species such as propane, butane, pentane, hexane, benzene, toluene, xylene, acetone, ethyl acetate and heavier compounds such as d-limonene which were all detected at low levels in the raw landfill gas. These compounds do not need to be removed from the landfill gas for the fuel cell power plant, but the high removal efficiency of these compounds is a further indication of the overall capability of the gas pretreatment unit.

The overall result of the Phase II Field Test of the GPU flare are summarized in Figure 5-2 and Table 5-5. The data show that the flare achieves high destruction efficiencies even while operating on the regeneration gas from the dryer bed "A" hot regeneration, which showed the highest contaminant levels to the flare. Sample destruction efficiencies during the dryer bed hot regeneration are consistently above 99 percent: dichloromethane at greater than 99.97 percent; tetrachloroethylene at greater than 99.85 percent, dimethyl sulfide at greater than 99.2 percent; and total nonmethane organics at 99.2 percent. The flare efficiency test results are discussed in greater detail in Appendix D.

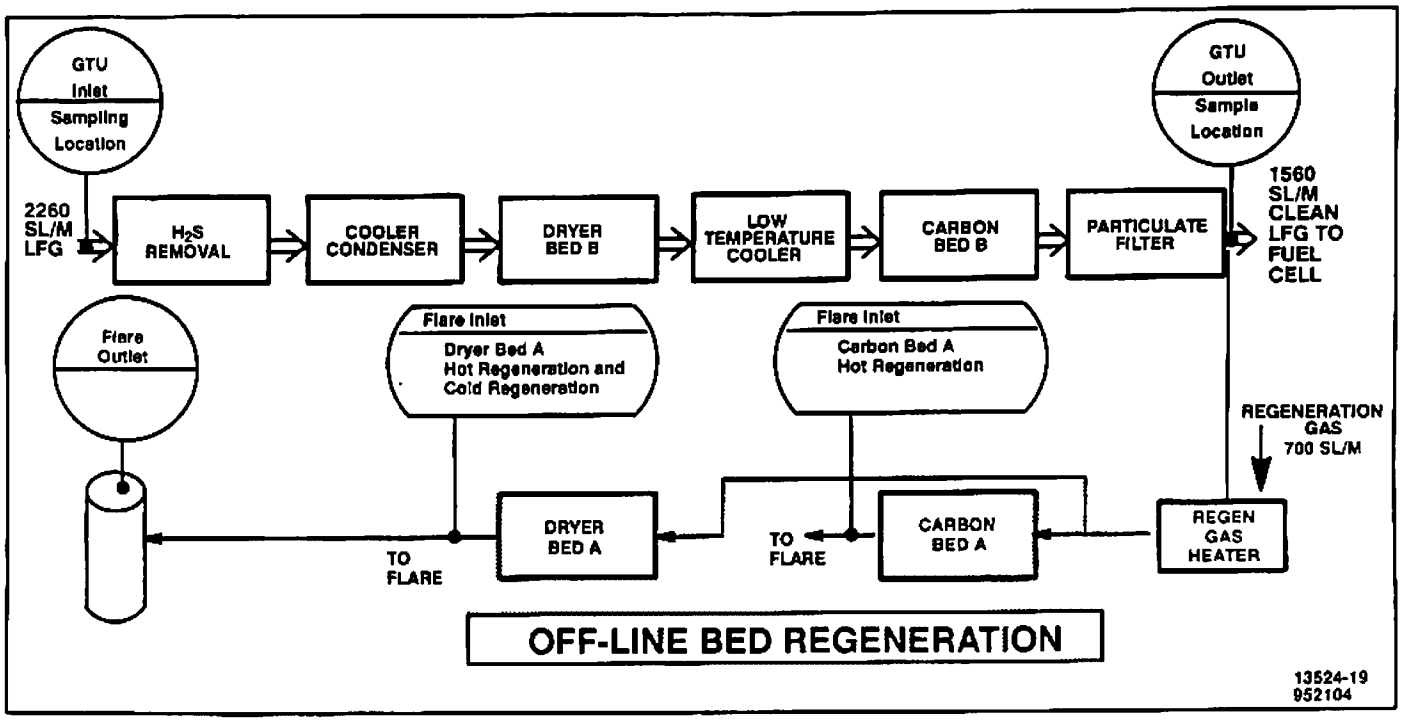

Figure 5-2. Landfill Gas Pretreatment Unit Sample Locations for GPU Flare Tests. Shown with "B" Beds On Line, and "A" Beds being Regenerated.

Table 5-5. Landfill Gas Pretreatment Unit Field Test Results for GPU Flare

- Data taken October 21, 1993 by TRC Environmental
- Gas Pretreatment Unit Inlet Flowrate 2260 SL/M, Output 1560 SL/M, Regeneration 700 SL/M

Requirement	Equipment Tested	Landfill gas pretreatment unit		Flare		Flare		Flare	
Requirement	Time	1000 – 1700		1030 – 1130		1230 – 1330		1730 – 1830	
	Process Activity	"B" Beds on-line, "A" Beds on-regen,		Carbon Bed "A" Hot Regeneration		Dryer Bed "A" Hot Regeneration		Dryer Bed "A" Cold Regeneration	
	Sample Location	GPU Inlet	GPU Outlet	Flare Inlet	Flare Outlet	Flare Inlet	Flare Outlet	Flare Inlet	Flare Outlet
A.Methane (ppmV)		472,000	483,000	440,000	<1	448,000	<1	463,000	<1
B.Total Non-Methane Organics (ppmV)		5,700	13.8	1,860	11.7	21,100	11.5	250	6.8
C.Oxides of Nitrogen (ppmV) [4]		NR[1]	NR	NR	7.5	NR	8.9	NR	14.9
D.Carbon Monoxide (ppmV) [4]		NR	NR	NR	5.8	NR	1.7	NR	1.6
E.Total Particulates (Micrograms/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
F.Hydrogen Sulfide (ppmV)		106	<0.004	<.004	NR	<.016	NR	<.004	NR
G.C_1 through C_3 Sulfur CPDS [Total AS H_2S]		117	0.017	0.254	NR	80.4	NR	0.05	NR
Carbonyl Sulfide (ppmV)		0.16	0.017	0.061	NR	<0.016	NR	0.014	NR
Methyl Mercaptan (ppmV)		2.79	<0.004	<0.004	NR	0.087	NR	<0.004	NR
Ethyl Mercaptan (ppmV)		0.44	<0.004	<0.004	NR	0.016	NR	<0.004	NR
Dimethyl Sulfide (ppmV)		6.57	<0.004	0.042	NR	73.9	NR	0.031	NR
Carbon Disulfide (ppmV)		<0.04	<0.002	0.146	NR	<0.008	NR	<0.002	NR
Dimethyl Disulfide (ppmV)		<0.04	<0.002	<0.002	NR	0.908	NR	0.005	NR
H.Carbon Dioxide (%)		[2]	[2]	[2]	6.3[6]	[2]	6.2[6]	[2]	7.7[6]

(Continued)

Table 5-5. Landfill Gas Pretreatment Unit Field Test Results for GPU Flare (Continued)

Requirement	Equipment Tested	Landfill gas pretreatment unit		Flare		Flare		Flare	
Requirement	Time	1000 – 1700		1030 – 1130		1230 – 1330		1730 – 1830	
	Process Activity	"B" Beds on-line, "A" Beds on-regen,		Carbon Bed "A" Hot Regeneration		Dryer Bed "A" Hot Regeneration		Dryer Bed "A" Cold Regeneration	
	Sample Location	GPU Inlet	GPU Outlet	Flare Inlet	Flare Outlet	Flare Inlet	Flare Outlet	Flare Inlet	Flare Outlet
I.Toxic Air Contaminants									
Benzene (ppmV)		1.7	<0.002	0.03	<0.002	16	<0.002	<0.04	<0.002
Chlorobenzene (ppmV)		1.4	<0.002	<0.02	<0.002	3.8	<0.002	0.07	<0.002
1,2 Dichloroethane (ppmV)		<0.35	<0.002	<0.02	<0.002	<2.5	<0.002	<0.04	<0.002
Dichloromethane (ppmV) (Methylene chloride)		4.1	<0.002	0.28	<0.002	110	<0.002	0.07	<0.002
Tetrachloroethylene (ppmV) (tetrachloroethene)		4.8	<0.002	0.17	<0.002	19	<0.002	0.1	<0.002
Tetrachloromethane (ppmV)		<0.23	<0.001	<0.02	<0.001	<1.6	<0.001	<0.03	<0.001
Toluene (ppmV)		47	<0.002	1.2	0.007	230	0.004	0.83	0.0025
1,1,1 Trichloroethane (ppmV)		<0.26	<0.001	<0.02	<0.001	<1.9	<0.001	<0.03	<0.001
Trichloroethylene (ppmV)		2.4	<0.002	0.02	<0.002	17	<0.002	<0.03	<0.002
Trichloromethane (ppmV)		<0.29	<0.001	<0.02	<0.001	<2.1	<0.001	<0.03	<0.001
Vinyl Chloride (ppmV)		1.4	<0.002	1.5	<0.002	<3.9	<0.002	<0.05	<0.002
Xylene (ppmV)		28.2	<0.002	0.04	<0.002	43.8	<0.002	1.8	<0.002
ADDITIONAL CONTAMINANTS									
Dichlorodifluoromethane (ppmV)		0.26	<0.002	3.6	<0.002	<2.0	<0.002	<0.03	<0.002
Cis - 1,2 - Dichloroethene (ppmV)		5.8	<0.002	<0.02	<0.002	62	<0.002	<0.04	<0.002
1,1 - Dichloroethane (ppmV)		2.8	<0.002	<0.02	<0.002	32	<0.002	<0.04	<0.002
Ethyl Benzene (ppmV)		12	<0.002	0.04	<0.002	25	<0.002	0.76	<0.002
Styrene (ppmV)		1.1	<0.002	<0.02	<0.002	<2.4	<0.002	<0.03	<0.002
Acetone (ppmV)		15	<0.005	<0.07	<0.005	150	0.065	<0.12	0.02
2 - Butanone (ppmV)		3.7	<0.004	<0.06	<0.004	28	<0.004	<0.99	<0.004
Ethyl Acetate (ppmV)		10.8	<0.002	<0.04	<0.002	5.4	<0.002	<0.04	<0.002
Ethyl Butyrate (ppmV)		8.4	<0.002	<0.04	<0.002	2.1	<0.002	<0.04	<0.002
Alpha-Pinene (ppmV)		18	<0.002	0.05	<0.002	3.6	<0.002	1.8	<0.002
d-Limonene (ppmV)		18	<0.002	0.07	<0.002	1.4	<0.002	3.6	<0.002
Tetrahydrofuran (ppmV)		2	<0.002	<0.04	<0.002	0.99	<0.002	<0.04	<0.002
J.Oxygen (%)		[2]	[2]	[2]	14.9	[2]	15.03	[2]	13.5
K.Nitrogen (%)		[2]	[2]	[2]	78.8[6]	[2]	78.8[6]	[2]	78.8[6]
L.Moisture (%)			<0.01	<0.1	9.2	<0.1	9.1	<0.1	8.6
M.Temperature (°F)				80	1186	80	929	79	990
N.Flow Rate (SLM)		2260	1560	700	11,240[1]	700	11,440[3]	700	9170[1]

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 micrograms per cubic meter (equivalent to 0.000116 Grains/Dry Standard Cubic Foot).

[6] Calculated based on 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.

5.3.4 Conclusions from Phase II GPU Field Test

The Gas Pretreatment Unit (GPU) was successfully installed and tested at the landfill gas site in Los Angeles (Sun Valley), California, and is ready for operation with the fuel cell power plant. The GPU functioned autonomously, purifying landfill gas to a level which is more than suitable for fuel cell use. In addition the GPU flare has received permits from the South Coast Air Quality Management District, a district with very strict air quality regulations. A summary of the performance of the GPU is as follows:

- The GPU removed total sulfur in the landfill gas (measured as H_2S) from 113 ppmV to $\leq$ 0.047 ppmV. This is a removal efficiency of at least 99.96%, and is over 60 times better than the specified limit of 3 ppmV total sulfur at the exit.
- The GPU removed total halogens (measured as chlorides) from 60 ppmV to $\leq$ 0.032 ppmV. This is a removal efficiency of at least 99.95%, and is over 90 times better than the specified limit of 3 ppmV total halogens at the exit.
- During a challenge test, the GPU removed 7.4 ppmV of dichlorodifluoromethane (added at the inlet) to less than 0.002 ppmV at the exit. This represents a removal efficiency of greater than 99.97%.
- The GPU flare safely disposed of the landfill gas contaminants removed by the GPU by achieving high destruction efficiencies above 99%. The flare was permitted by the South Coast Air Quality Management District for operation in the Los Angeles area.
- A total of 616 operating hours was logged on the GPU, including a 216 hour endurance run which was voluntarily terminated.

6.0 FUEL CELL DEMONSTRATION TEST

This section describes the results of the Phase III demonstration test activities beginning in January 1994 and ending in June, 1995. During this third phase of the program, IFC developed a Test and Quality Assurance Project Plan, completed all permitting activities for the fuel cell with the City of Los Angeles, installed and checked out the fuel cell power plant at the site on natural gas, modified the fuel cell for operation on landfill gas, and then connected the fuel cell to the gas pretreatment unit and operated the demonstration test, including obtaining critical emissions and operating data. The demonstration operated at the existing Penrose Station landfill gas energy recovery facility owned by Pacific Energy in Sun Valley, California. Internal combustion engines presently generate up to 8.9 MW of electricity at this site with landfill gas from four separate landfills. Electricity produced by the fuel cell was sold to the Los Angeles Department of Water and Power electric utility grid.

6.1 Test and Quality Assurance Project Plan (QAPP)

The Test and Quality Assurance Project Plan (QAPP) for the Phase III Demonstration Test is given in Appendix G. The QAPP describes the program objectives plus the test quality requirements, measurements, calculations and quality audits required to assure that the proposed testing meets the EPA requirements. The plan was written to meet the requirement of an EPA Category II quality assurance plan and a site-specific test plan. The QAPP is designed to measure fuel cell and GPU performance while operating for an extended period on landfill gas. Fuel cell performance includes efficiency, availability, operating and maintenance costs, and emissions. GPU performance includes contaminant removal effectiveness of sulfur and halide species which are deleterious to long term fuel cell performance. Results of these tests are described in Section 6.3.

6.2 Test Preparation

6.2.1 Permitting

All site construction and equipment installation activities require approval by local government authorities, in this case the Los Angeles Building and Safety Department and the South Coast Air Quality Management District for emissions. The Building and Safety and SCAQMD permitting for the GPU is described in Section 5.2. The fuel cell has a blanket exemption from emissions from the SCAQMD, so no fuel cell emission permitting was required.

Permitting activities with the L.A. Building and Safety Department were initiated in August 1993, to allow adequate time, since this demonstration is the first-ever fuel cell power plant to be permitted for operation within the jurisdiction of the City of Los Angeles. After working closely with the L.A. City Building and Safety Department, a variance was granted in April 1994 to permit operation of the landfill gas fuel cell power plant. The conditions of approval for the variance are shown in Appendix A, page A-3. Subsequent to the variance, the normal plan checks of the site mechanical drawings were completed in May and June and the on-site inspections of the mechanical installation were completed during July and August. Electrical site inspections of the demonstration site equipment were completed during August with final approval in September. Final approval of the electrical drawings was delayed due to the added requirement to install load shedding equipment to protect an existing grid interface transformer in Pacific Energy's Penrose plant. This equipment was installed during September, with final approval coming in October 1995.

6.2.2 Site Preparation

The bulk of the site preparation for the fuel cell power plant and cooling module was completed in 1993, when the GPU was installed on the site. Final site preparations, including repair of the fuel cell foundation drain, and extension of the concrete mounting pad for the cooling module, were completed during May 1994.

6.2.3 Fuel Cell Installation and Checkout on Natural Gas

The fuel cell and cooling module were delivered and set on their concrete pads at the Penrose site on June 7th, 1994. A photograph showing the fuel cell being lowered onto the pad is shown in Figure 6-1.

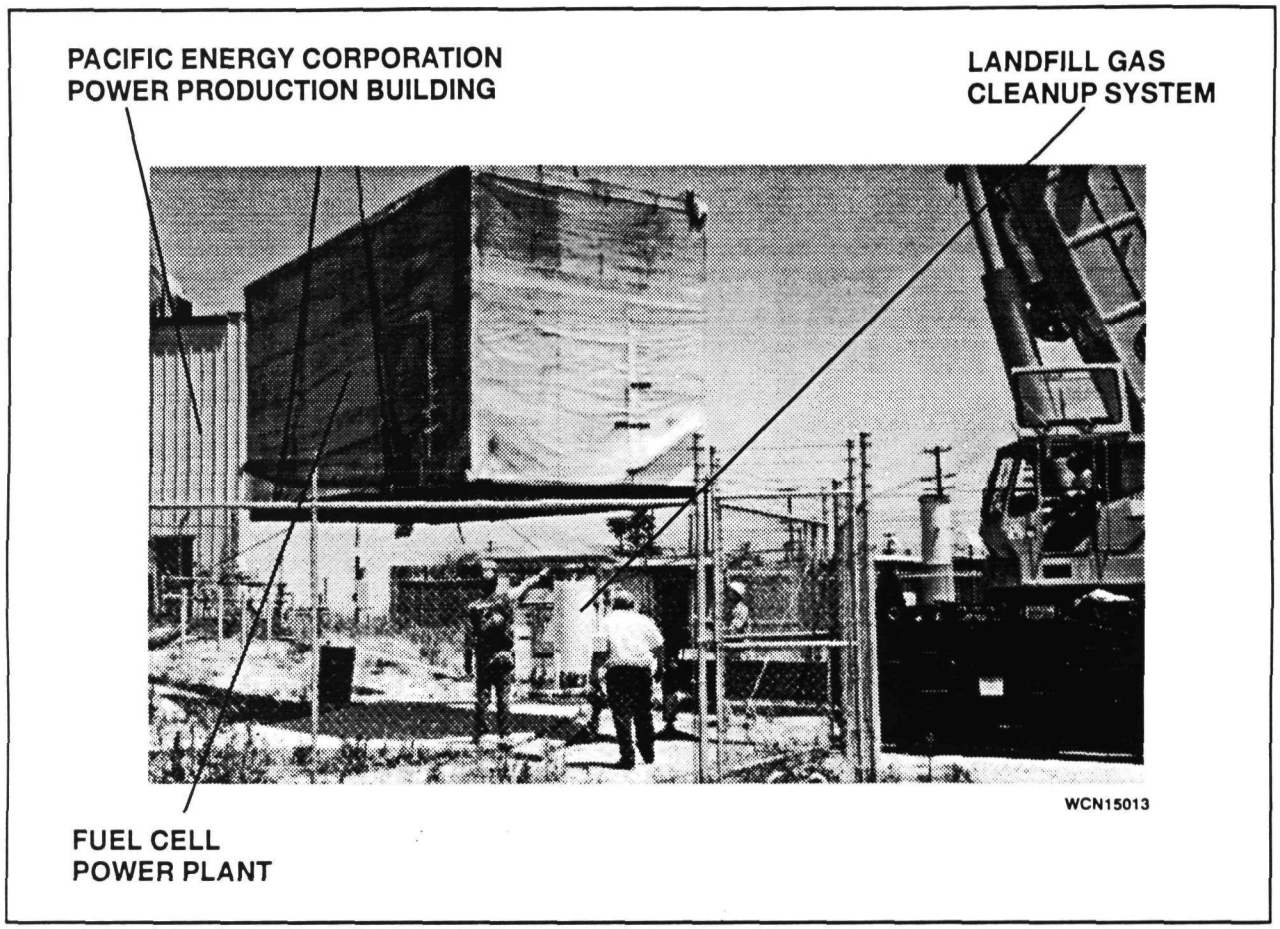

Figure 6-1. Installation of PC25 at Los Angeles Landfill

Mechanical and electrical installation of the fuel cell and cooling module were completed during July. The mechanical work included installation of piping to bring clean landfill gas from the GPU to the fuel cell, installation of natural gas lines to the fuel cell, and installation of coolant piping from the fuel cell to the cooling module. The electrical installation work included connection of the power plant to the grid, installation and hookup of the electrical metering cabinet and meters, (provided by the L.A. Department of Water and Power), installation of the telephone wire to the fuel cell controller modem (to enable remote monitoring of the power plant by ONSI and IFC) and installation of power lines from the fuel cell to the cooling module. A layer of gravel was added to the site to control dust. A photograph showing the completed installation is in Figure 6-2.

After completion of the installation, and inspection by the L.A. City Building and Safety Department, ONSI Corporation initiated startup and checkout of the fuel cell on natural gas. This step was taken to verify proper operation of the fuel cell prior to modification for landfill gas.

The fuel cell power plant was successfully started on natural gas and operated for a total of 113 hours in two runs. During this time safety shutdown tests were demonstrated for the City of Los Angeles Building and Safety Department to demonstrate safe operation in the event of loss of electricity to the power plant and safe shutdown in the event of a loss of fuel to the power plant, loss of water, or over temperature in the steam accumulator. Also, during this operating time, stack performance plus system temperatures and pressures were checked against factory test data and found acceptable, except for a slightly low temperature in the fuel processor. A thermal control valve was replaced, and the correct temperature was obtained during the second run.

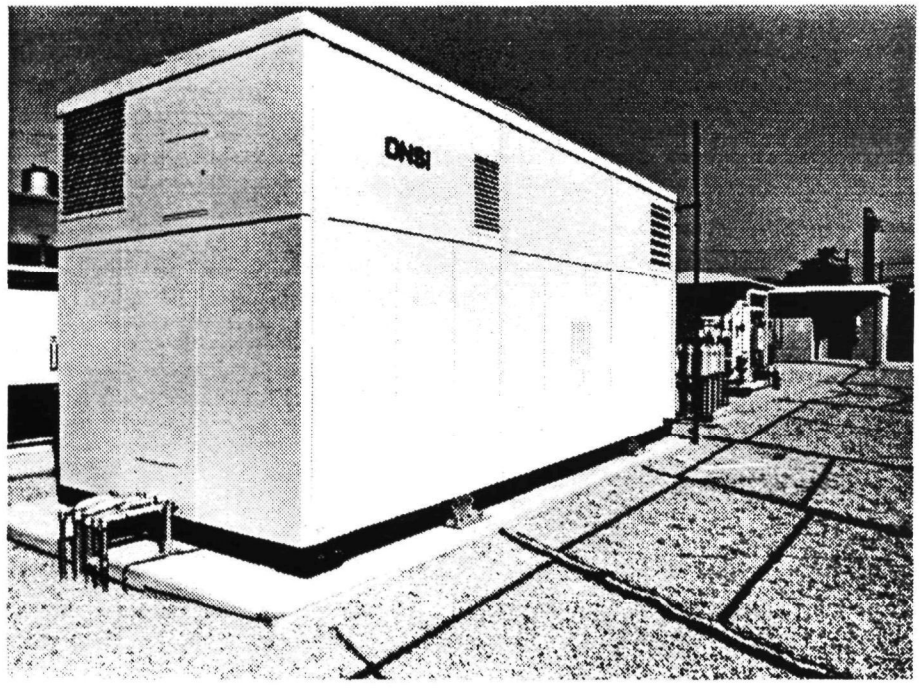

Figure 6-2. Photograph of the GPU and Power Plant Installed at the Penrose Site

6.2.4 Modifications for Landfill Gas

The fuel cell modifications for operation on landfill gas are described in Section 4.3. The modifications were installed on site under the direction of an IFC field engineer, from modification kits designed and fabricated by IFC. The modifications included a larger fuel control valve and fuel flow venturi, a new process fuel recycle orifice, a new cathode exit orifice, and new redundant start fuel shut off valve for the reformer burner. The modification kit installations were completed in early November.

6.2.5 Checkouts for Landfill Gas Operation

Fuel cell checkouts on landfill gas were initiated in November. Prior to the first startup of the fuel cell on landfill gas, the GPU was checked out and tested for contaminants. Results of the GPU exit gas samples taken in October verified that after over 800 total hours of operation, the GPU was still producing gas far cleaner than originally specified for the fuel cell. Samples were taken during the last hour of the "make" cycle, just prior to regeneration, (after at least seven hours on line). A sample was taken from the even number beds (DAB104 and CAB106) on October 16th and from the odd number beds (DAB105 and CAB107) on October 27th. The results, summarized in Table 6-1 show total sulfur averaging under 0.050 ppmV and total halides at just 0.003 ppmV. The only contaminant species detected were carbonyl sulfide, methylene chloride, and trace quantities of xylene, detected at approximately 0.001 ppmV.

The fuel cell was started and operated on clean landfill gas from the GPU for the first time on November 17, 1994. Gross power of up to 80 kW was obtained while checkouts were performed at idle (0 net kW to the grid) for slightly over two hours. During this initial run, two operating issues were identified with the fuel control valve: control system instability; and lower than anticipated capacity. Corrections were identified for both issues, and were installed in the fuel cell in early December.

Table 6-1. GPU Validation Test Results Prior to Start of Fuel Cell Demonstration Field Test

Sample Location	Sample ID	Date	Time	Total S as H_2S	Total Halide as HCL	Other
GPU Exit ("A" Beds, DAB104/CAB106) on line	9405858	10-26-94	12:05	0.041 ppmV (1)	0.003 ppmV (2)	0.001 ppmV Toluene
	9405849	10-26-94	12:14	0.052 ppmV (1)	0.003 ppmV (2)	0.001 ppmV Toluene
	9405849 Dup (4)	10-26-94	12:14	0.051 ppmV (1)	0.002 ppmV (2)	0.001 ppmV Toluene
GPU Exit ("B" Beds, DAB105/CAB106) on line	9405874	10-27-94	N.A	0.049 ppmV (1)	0.003 ppmV (2)	0.001 ppmV Toluene
	9405875	10-27-94	N/A	0.048 ppmV (1)	0.003 ppmV (2)	0.001 ppmV Toluene
	9405875 Dup (4)	10-27-94	N/A	0.046 ppmV (1)	0.002 ppmV (2)	0.001 ppmV Toluene

NOTES:

(1) All as carbonyl sulfide (COS)
(2) All as methylene chloride (dichloromethane)
(3) Limit <3 ppmV total sulfur, <3 ppmV total halide
(4) Laboratory duplicate
(5) All samples taken during last hour of "make" cycle, with approximately 800 total run hours on GPU

6.3 Demonstration Test Results

6.3.1 GPU Performance

6.3.1.1 Operation and Reliability – GPU operating experience during Phase III is summarized in Table 6-2. During Phase III, the GPU ran 1681 hours in 26 runs, with the longest run being 342 hours. Total GPU operation including Phase II is 2297 hours. The causes of GPU system shut downs have been identified and corrected, and no outstanding operational issues exist in the GPU at the present time.

Reliability of the GPU has improved as the causes of the shut downs were identified and corrected, so that extended operation of the GPU should now be possible. Five of the initial six shutdowns were caused by known or suspected loss of the flare UV flame sensor signal. This was corrected by adjusting the flare time-out relay. Shut down of runs 7, 14, 15 and 24 were caused by loss of coolant temperature control in the d-limonene loop. This loss of temperature control is caused by ice build-up in the d-limonene system, due to water vapor entering the d-limonene system through the air vent in the d-limonene surge tank. Short term, this issue was corrected by installing a dryer cartridge on the air vent to prevent further water vapor ingestion, and by instituting an "on the fly" de-icing procedure. The long term solution would include the vent dryer, plus draining and drying the d-limonene system and recharging with dry d-limonene. Run 8 shutdown was due to a condenser tank overfill which was attributed to a high (40 gallons in several hours) condensate influx at the site. No corrections were made and this failure did not reoccur. Run 13 experienced a lockup to the PLC controller due to a control valve position switch being out-of-limits. The valve limit switch was repositioned and tightened, and the PLC controller program was modified to prevent the program lock up from reoccurring. Run 25 shut down due to loss of flare flame signal. This was traced to a loose ultraviolet sensor. This was corrected by reseating the sensor in the socket. The remaining 13 shut downs included six voluntary shut downs plus seven site related shut downs due to loss of power, or loss of landfill gas pressure to the GPU. In summary, the GPU System shutdown causes have been identified and corrected, and no known outstanding issues exist in the GPU at the time of last shutdown.

The GPU adjusted reliability during the demonstration test period, (December 7, 1994 through February 19, 1995) was 87.3% (see discussion in Section 6.3.2.1).

Table 6-2. GPU Run Summary

Start Date	Run No.	Run Hours	Total Hours	Reason for Shut Down	Corrective Action Taken to GPU
Thru March 1994	—	—	616	—	—
Oct. 11, 1994	1	9.5	626	Flare U.V. sensor	• Cleaned dust off sensor
Oct. 12	2	7.7	634	N/A	• Restarted
Oct. 13	3	7.5	641	Step 2 timeout	• Checked Step 2 valve position switches - all ok
Oct. 14	4	5	646	Flare U.V. sensor	• Restart with U.V. jumpered
Oct. 17	5	22.3	668	Flare U.V. sensor	• Increase flare timer from 15 to 32 seconds
Oct. 20	6	18	686	Flare U.V. sensor	• Increase LFG inlet regulator pressure from 47 psig to 55 psig
Oct. 21	7	167	853	Flare U.V. sensor	• No action taken due to high LFG condensate (40 gal. in one day)
Nov. 3	8	11	864	First stage condensate tank overfill	• No action taken. S/D due to high LFG condensate (40 gal. in one day)
Nov. 8	9	3.5	878	Loss of LFG pressure	• None
Nov. 9	10	19	887	Voluntary	• None
Nov. 10	11	16	903	Penrose power failure	• See below
Nov. 14	12	130	1033	Program stopped at 1033 hours but flare and refrigerator stayed on at 25 CFM flow	• Tightened loose collar on valve 138 positioner switch, checked and tightened all other valve positioner switches • Installed new PLC program
	13	82	1115	Voluntary	• None
Nov. 28	14	342	1457	Hi d-limonene surge tank temperature	• None
Dec. 13	15	5	1462	High d-limonene surge tank temperature	• None
Dec 14	16	24	1486	Voluntary	• None
Jan 9, 1995	1	20	1506	Voluntary	• Installed new PLC program (PTU7)
Jan 10	18	29	1535	Penrose breaker trip	• None
Jan 12	19	91	1626	Penrose breaker trip	• None (reset current trip for Penrose breaker from 5 sec to 10 sec
Jan 16	20	21	1647	Voluntary	• None
Jan 17	21	45	1692	LFG pressure loss @ Penrose	• None
Jan 19	22	6	1698	Penrose breaker trip	• None (checked out current trip and ground fault trip for Penrose breaker)
Jan 19	23	20	1718	Voluntary	• Serviced refrigerator (added R-22)
Jan 23	24	177	1895	Hi d-limonene tank temp.	• Thaw out refrigerator overnight and restart
Feb 2	25	319	2214	Loss of flare flame signal	• Reseated loose U.V. detector
Feb 16	26	83	2297	Loss of flare flame signal due to loss of gas pressure after Bradley S/D	• None

6.3.1.2 GPU Contaminant Removal Performance – The GPU consistently removed contaminants in the landfill gas to levels significantly below the initial goals of < 3 ppmV total sulfur and < 3 ppmV total halides for over 2200 hours, as shown in Figure 6-3. All Phase III sample were taken by TRC Environmental, during the last hour before regeneration, per the Test and Quality Assurance Project Plan in Appendix G. The GPU data is summarized in Appendix D (for Phase II Field Testing), Table 6-1 (Phase III Pre-Start Check), Table 6-3 (Phase III testing), and Appendix H (Phase III testing).

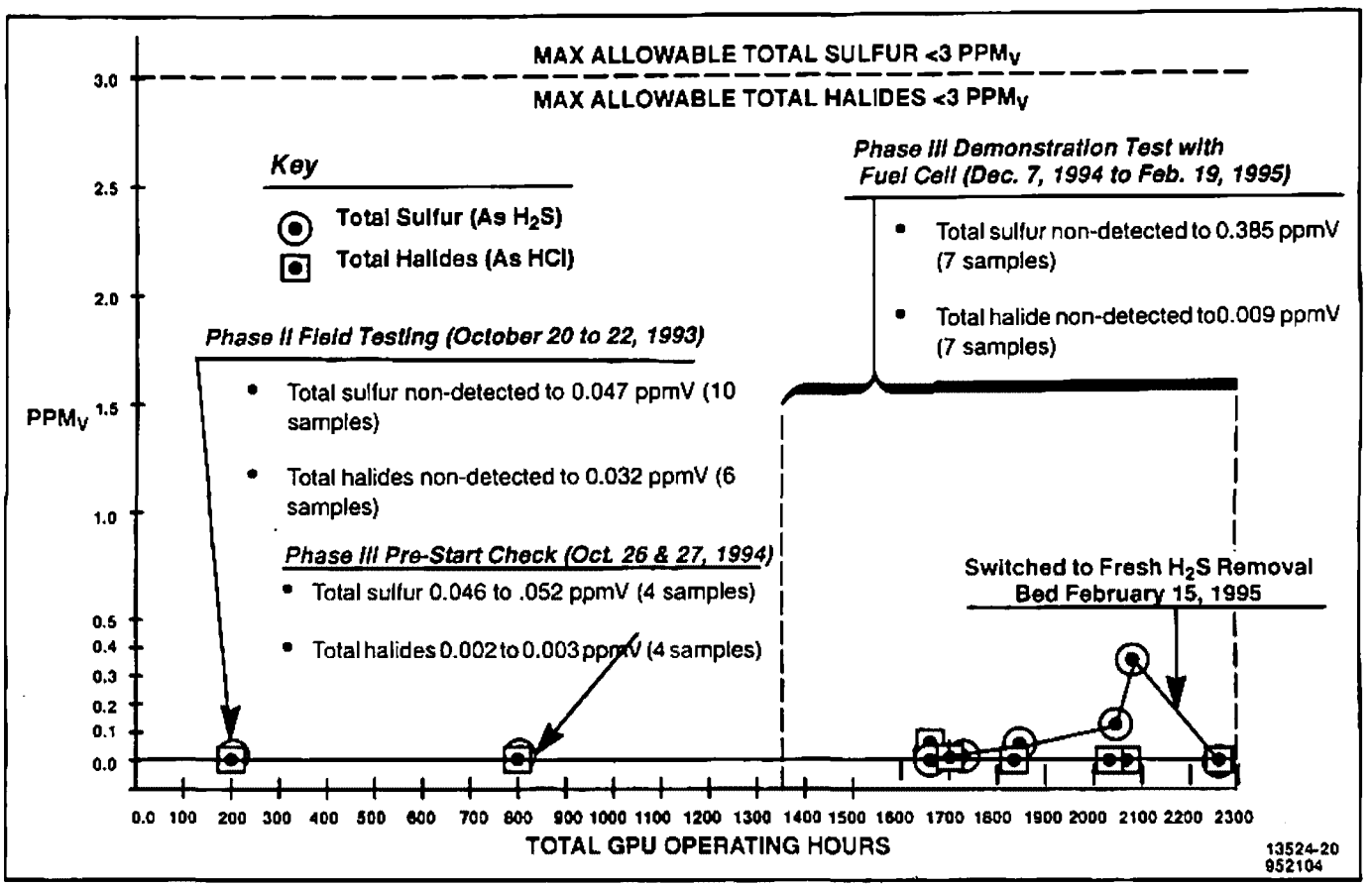

Figure 6-3. GPU Exit Contaminant Concentration vs. Time

The GPU has consistently removed total halides (as HCl) from inlet levels of 45 to 60 ppmV in the raw landfill gas to very low or undetectable levels at the outlet. During the Phase II Field Testing on October 20 to 22, 1993, with 200 hours on the GPU, four samples showed no detectable halides (0.002 ppmV detection limit), while one sample tested at 0.008 ppmV and one sample tested at 0.032 ppmV. During the Phase III Pre-Start Testing, four samples showed detectable total halides averaging 0.048 ppmV. During the Phase III testing the sample at 1685 hours tested at 0.009 ppmV total halides. All six (6) remaining samples out to 2235 hours showed no detectable halides (individual species detection limits 0.001 to 0.020 ppmV). The excellent halide removal performance of the GPU allowed IFC to eliminate the addition of a halide guard bed in the PC25 power plant, as was originally planned.

Total sulfur (as H_2S) was reduced from about 110 ppmV (about 10 ppmV from organic sulfur, plus 100 ppmV H_2S) to between non-detectable to 0.385 ppmV. The only sulfur species detected was carbonyl sulfide. The elevated levels of 0.173 to 0.385 ppmV of carbonyl sulfide measured on February 9th and 10th, 1995 are believed due to a slight increase in H_2S exiting the non-regenerable H_2S removal bed, since hydrogen sulfide at the H_2S bed exit was measured at 1.0 to 2.7 ppmV on February 14th. Earlier laboratory work at IFC showed that H_2S is converted to carbonyl sulfide over the activated alumina in the downstream drier bed by the reaction: $H_2S + CO_2 = COS + H_2O$, due to the removal of the product water by the alumina. The resulting carbonyl sulfide is not readily removed by the low temperature carbon bed. The non-regenerable H_2S removal bed

was switched over to a fresh bed on February 15, 1995, and the exit H_2S level returned to non-detectable. The carbonyl sulfide level measured shortly after, on February 17th, also fell to just 0.061 ppmV.

Based on the Penrose operating experience, the useable life of the hydrogen sulfide removal beds is 21 days, which yields an apparent capacity of 12 grams of sulfur per gram of carbon in the bed. The small, 119 liter bed volume of the two beds used in the demonstration test was selected for proof of principle only. The commercial installation would use large, commercial tanks designed for low cost, ease of servicing, and long changeout times.

Table 6-3. GPU Contaminant Removal Performance During Phase III

SAMPLING DATE (1995)	Jan 19	Jan 20	Jan 25	Jan 26	Feb 9	Feb 10	Feb 17
Total GPU Operating Time (Hours)	1685	1701	1710	1826	2046	2069	2235
Sampling Time	17:00	09:22	16:14	08:26	10:41	09:29	12:55
GPU Process Counter	24969	24900	53080	52362	no data	23146	23217
SULFUR COMPOUNDS (ppmV)							
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	nd	nd	0.071	0.077	0.173	0.385	0.061
VOLATILE ORGANIC COMPOUNDS (ppmV)							
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

NOTES:
1. nd = non-detected
2. All GPU exit samples were collected during the last hour before regeneration

6.3.1.3 GPU Exit Gas Heat Content – The heat content of the GPU exit gas was measured to provide an accurate basis for fuel cell efficiency calculations. The average GPU exit gas heat content was determined by averaging the hourly on-line gas chromatograph data provided by Pacific Energy for the raw landfill gas at the GPU inlet, and adjusting this using a correction factor. The correction factor was based on a comparison of six GPU exit gas ASTM heat content measurements which were compared to the Pacific Energy hourly average reading for the inlet gas taken at the same time. The GPU exit gas heat contents averaged one percent higher than the inlet samples taken at the same time, so a correction factor of 1.01 was applied to the on-line inlet gas data. The summary of the correction factor data and calculation is given in Table 6-4. Additional heat content data is given in Appendix H (see Section 3.5 and Appendix B).

Table 6-4. GPU Exit Gas Heat Content
Comparison of ASTM Method Heat Content Measurements on Treated GPU Exit Gas to On-Line Raw Landfill Gas Heat Content Measurements

Penrose Landfill - Phase III Fuel Cell Energy Recovery Demonstration
January 19 - February 17, 1995

SAMPLING DATE	Jan 19	Jan 20	Jan 25	Jan 26	Feb 9	Feb 10	Feb 17
SAMPLING TIME	16:44	09:27	16:09	08:31	10:37	09:26	13:33
Treated Landfill Gas Composition Measured By ASTM Method at GPU Exit (%)							
nitrogen	16.266	17.251	16.244	16.34	23.888	17.656	20.096
carbon dioxide	35.542	38.896	39.555	39.531	36.042	38.863	34.908
methane	44.165	43.807	44.142	44.092	40.07	43.481	44.996
ethane	0.024	0.029	0.049	0.037	nd	nd	nd
propane	nd	nd	nd	nd	nd	nd	nd
iso-butane	nd	nd	nd	nd	nd	nd	nd
iso-pentane	nd	nd	nd	nd	nd	nd	nd
n-pentane	nd	nd	nd	nd	nd	nd	nd
hexanes	nd	nd	nd	nd	nd	nd	nd
heptanes	nd	nd	nd	nd	nd	nd	nd
GPU Exit HHV by ASTM Method							
Btu/standard cubic foot	446	443	447	446	405	439	454
Kcal/standard liter	3.97	3.94	3.98	3.97	3.60	3.91	4.04
GPU Exit LHV by ASTM Method							
Btu/standard cubic foot	402	399	402	401	364	395	409
Kcal standard liter	3.58	3.55	3.58	3.57	3.24	3.52	3.64
GPU Inlet HHV by Pacific Energy On-Line Analyzer							
HHV (Btu/standard cubic foot)	437	435	445	445	436	429	no data
HHV (Kcal/standard liter)	3.89	3.87	3.96	3.96	3.88	3.82	no data
Heat Content Correction Factor							
[GPU Exit HHV/GPU Inlet HHV]	1.02	1.02	1.00	1.00	0.93	1.02	no data

NOTES:
1. nd = non-detected
2. Standard Conditions at 20 °C
3. Average correction factor is 1.01 (Exclude Feb. 9 data from average-suspected sampling error.)

6.3.2 Fuel Cell Performance

6.3.2.1 Fuel Cell Operation and Availability – The fuel cell operation on landfill gas is summarized in Table 6-5. Checkouts on landfill gas were conducted in November 1994. During this time the fuel cell was started twice for a total of two hours, and issues with the fuel control valve capacity and stability were identified and corrected.

The field test began with Run No. 3 on December 7, 1994 until the end of Run No. 10 on February 19, 1995. During this period the fuel cell operated for 707 additional hours on landfill gas with no forced outages. Only one of the eight shutdowns was due to the fuel cell. Of the eight shutdowns, four were due to site related causes (one power loss due to Penrose breaker trip, one loss of landfill gas pressure when the Penrose power station was shut down for maintenance, and two by bad gas when the Bradley landfill went off-line). Three shutdowns were due to the GPU (two due to refrigeration over temperature and one due to a loose flame sensor on the flare), and one shutdown (Run No. 9) was due to a bad sense module in the fuel cell control system.

Table 6-5. Summary of Fuel Cell Operations on Landfill Gas

Type Operation	Run #	Start Time	Date	Shut-down Time	Date	Run Hours	Total LFG Hours	Reason For Shutdown	Corrective Action Taken to Fuel Cell
LFG check-outs	1	11:19	11/16/94	11:19	11/16/94	0	0	• Frozen fuel control valve caused valve motor fuse to blow	• Freed stuck fuel control valve • Replaced fuse
	2	14:56	11/17/94	17:05	11/17/94	2	2	• Unstable fuel flow control, and insufficient fuel flow	• Replaced 1/2" fuel control valve with 1" valve & adjusted controller
Field Test	3	12:16	12/7/94	16:02	12/12/94	124	126	• GPU shut down	• None required • Replaced leaking feedwater shut off valve during shut-down
	4	10:28	1/14/95	08:23	1/16/95	46	172	• Penrose breaker trip	• None required
	5	15:12	1/17/95	07:19	1/19/95	40	212	• Penrose shutdown for maintenance	• None required
	6	10:32	1/23/95	17:01	1/30/95	175	387	• GPU shutdown	• None required
	7	11:55	2/3/95	15:35	2/4/95	27	414	• Bad gas from Bradley Landfill	• None required
	8	12:45	2/6/95	19:12	2/15/95	223	637	• GPU shutdown	• None required
	9	08:00	2/16/95	08:15	2/16/95	0	637	• Intermittent failure of inverter cooling fan sense module	• Replaced bad fan sense module
	10	18:50	2/16/95	08:38	2/19/95	72	709	• Bradley landfill shut down	• None required

The fuel cell was operated at up to 137 kW, which is 3 kW below the goal for operation on landfill gas. Measurements taken on the landfill gas fuel cell indicate that the standard natural gas fuel pump used in the power plant (a steam ejector) is not providing the anticipated suction. This deficiency can be overcome by modifying the ejector specifically to provide the required suction using landfill gas. The recurring cost for a modified ejector would be essentially the same as the standard natural gas ejector.

An endurance operating condition of 120 kW was selected for the bulk of the field test operation to provide a margin for steady fuel cell operation during periods of sub-standard gas quality, which occur periodically due to upsets in gas quality from the active landfill (Bradley) which supplies gas to the Penrose site.

The fuel cell adjusted availability was completed per the Quality Assurance Project Plan (Appendix G pg 16).

- Fuel cell availability is adjusted to compensate for factors which are not caused by the power plant, as follows:

  Raw availability (OPERATING TIME divided by elapsed clock time since first start) is adjusted to account for

  - unforced outages not due to power plant
  - shutdowns due to operator error
  - waiting time for replacement parts where parts were recommended the customer have on hand
  - periods of time when power plant could be worked but manpower not available (weekends, vacations)

$$\text{Adjusted availability} = \frac{\text{OPERATING HOURS}}{\text{[(elapsed clock time) - adjustment]}}$$

During the test period, the only unavailable time due to the fuel cell is the 10.6 hours between the shutdown of run No. 9 due to the failed sense module at 08:15 on February 16th, to the startup of Run No. 10 at 18:50. This yields an adjusted availability $\frac{707}{1782.3\text{-}1064.7} = 98.5\%$

The GPU adjusted availability was also computed for the same test period. The availability of the fuel cell and GPU was segregated to provide direct comparison of the landfill gas powered fuel cell to the measured reliability of the commercial natural gas fueled fleet of fuel cell power plants. The separate availabilities also recognize the fact that the fuel cell is a commercial piece of equipment, while the GPU is a first-of-a-kind experimental demonstration unit whose main objective is to demonstrate the critical technical and operational issues for the commercial landfill gas cleanup system.

During the test period the GPU experienced three shutdowns that resulted in lost time. The first shutdown on December 13 at 1602 was caused by high temperature in the d-limonene tank, and resulted in 46 lost hours until the GPU was checked out and ready to provide gas to the fuel cell. The second shutdown at 1700 on January 23 was also due to high d-limonene tank temperature, and caused 43.7 hours of lost time. The third shutdown on February 15 at 1915 was caused by a loose UV detector and resulted in 13 hours of lost time. The total lost time during the test period was 102.7 hours.

The adjusted availability for the GPU during the test period is therefore:

$$707\ (1782.3 - 972.6) = 87.3\%$$

6.3.2.2 Fuel Cell Power Plant Efficiency – The fuel cell efficiency was calculated over two periods during the field test. The first period covered six days from January 24, 1995 through January 30, 1995. Efficiency during this six day period of continuous operation was 37.1 percent. The second period covered eight days

from February 9th, 1995 through February 17, 1995. Average efficiency for this eight day period, which included a brief shutdown, was 36.5 percent. The details of the calculation are given in Table 6-6.

Table 6-6. Fuel Cell Electrical Efficiency on Landfill Gas
Penrose Landfill - Phase III Fuel Cell Energy Recovery Demonstration
January 24 - February 17, 1995

Period	Energy Output (LADWP Meter)	Gas Consumption (Yokagawa Meter)	Lower Heating Value	Energy Input (Kcal)	Efficiency
	(kWh)	(SL)	(Kcal/SL)	(Kcal)	
1/24/95 (0707) to 1/30/95 (1023)	16800	1.11E + 07	3.50	3.894E + 07	37.1%
2/9/95 (1102) to 2/17/95 (0733)	18400	1.26E + 07	3.45	4.33E + 07	36.5%

NOTES:
1. Heating value data is from Pacific Energy's on-line raw gas analyzer HHV hourly averages corrected to GPU exit LHV. A correction factor (1.01) was developed from a comparison of six GPU Exit ASTM measurements to six GPU Inlet HHV on-line averages. The HHV was then converted to the LHV using the correction factor 0.900. The following equation was used for the complete conversion:

   Exit LHV = GPU Inlet HHV x 1.01 x 0.900

2. Efficiency = $\frac{\text{Energy Output (kWh) x 860.5 Kcal/kWh x 100}}{\text{Gas Consumed (SL) x LHV (Kcal/L)}}$

   SL = standard liters at 15.5°C

The fuel cell power plant electrical efficiency was measured by recording output kW hours at Location (C) on Figure 6-4 and dividing by the input landfill gas lower heating value at Location (B) on Figure 6-4. The electric power was measured using a utility grade meter calibrated by LADWP. The landfill gas to the fuel cell was measured using a Yokogawa YFCT Flow Computing Totalizer (Style B). The determination of the heating value of the landfill gas is discussed in Section 6.3.1.3. Additional details of the data and calibrations is given in Section 3.1 of Appendix H.

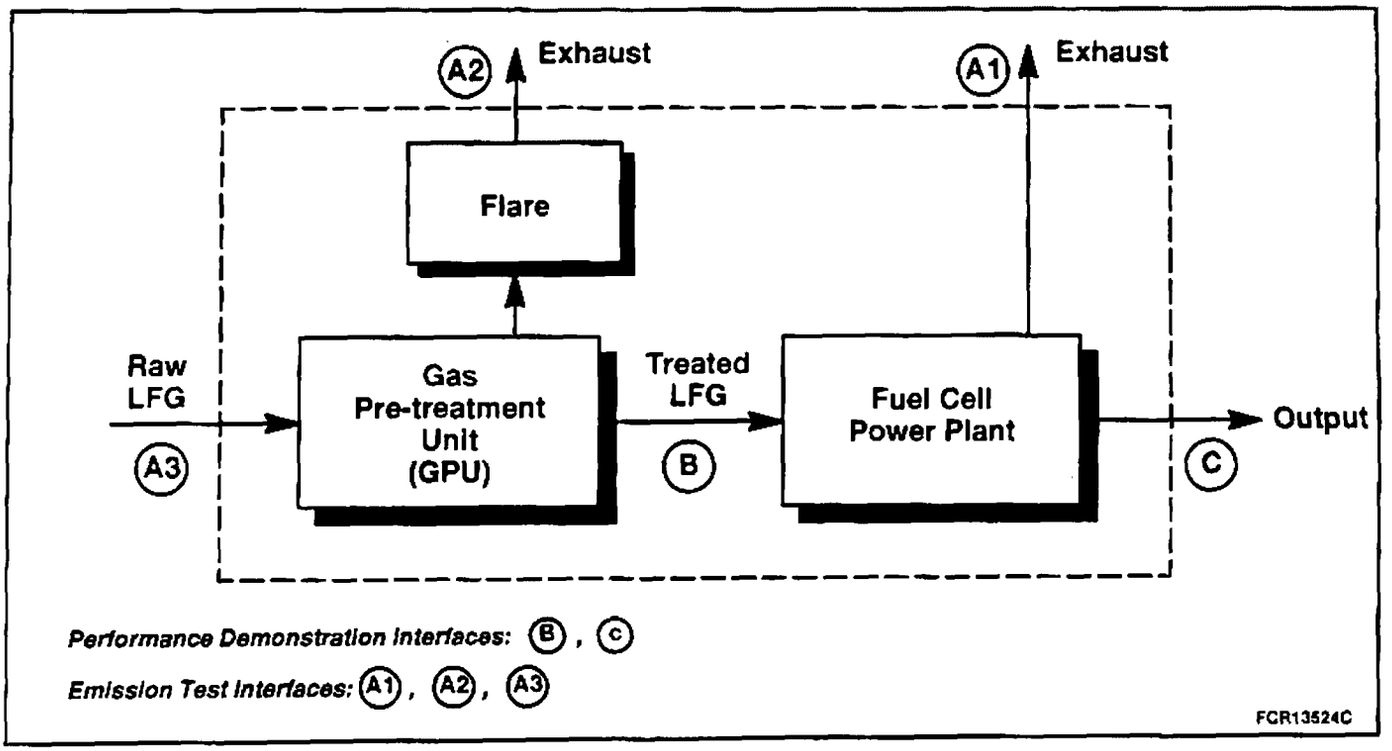

Figure 6-4. Demonstrator System Schematic

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952104

6.3.2.3 Fuel Cell Maintenance and Operator Requirements – The operation and maintenance cost factors for the landfill gas fuel cell demonstration are compared with the PC25A commercial fuel cell experience in Table 6-7. Based upon a comparison of the operation and maintenance cost factors after 707 hours, the O&M costs for the landfill gas fuel cell power plant project to be comparable to slightly higher than for natural gas, depending upon Nitrogen content of the fuel. A longer period of steady endurance operation on landfill gas is desirable to develop a firmer basis for long term O&M costs for the LFG fuel cell.

Operation factors for the landfill gas fuel cell demonstration including startup, operation and availability are comparable with commercial natural gas experience. The efficiency based on fuel lower heating value is 37 percent for the landfill gas at 120 kW. This efficiency is in line with the Phase I projection of 36.4 percent at 200 kW shown in Table 3.5. The lower efficiency requires about 8 percent higher fuel flow, for the landfill gas fuel cell, but this is offset by the lower fuel costs for landfill gas. The demonstrated maximum output of the PC25 A power plant is 137 kW, with a steady state output of 120 kW. This output must be increased to 200 kW steady output using landfill gas to achieve comparable operating costs. The means to achieve a 200 kW rating are discussed in more detail in Section 7.

The maintenance cost factors for unscheduled maintenance project to comparable cost using landfill gas fuel, based upon the limited mean time between forced outages and availability data generated in the 707 hours of operation on landfill gas. No scheduled maintenance has been performed to date, but the landfill gas power plant scheduled maintenance is anticipated to be the same as the natural gas power plant.

Table 6-7. Operation and Maintenance Cost Factors for Commercial Applications

Factor	PC25 A Natural Gas Fuel Cell Commercial Experience	PC25 A Landfill Gas Fuel Cell Demonstration	Comments
Operation			
Startup from energized off	5 hours or less	5 hours or less	• LFG utilizes electric start option
Normal operation	Unattended, automatic	Unattended, automatic	
Availability	95%	98.5%	
Rated output	200 kW	120 kW (137 kW max)	• PC25 C can be modified to make 200 kW on LFG
Efficiency (LHV)	40%	37%	• Lower efficiency requires 8% higher fuel flow, but this is offset by lower fuel costs for Landfill Gas
Heat recovery	192,000 kcal/hr @ 200 kW	Not demonstrated	• Projected heat recovery 208,000 kcal/hr on LFG
Fuel Heating Value HHV LHV	Natural Gas 8.72-10.68 Kcal/SL 7.86-9.62	LFG 3.92 kcal/SL 3.53 kcal/SL	• Penrose LFG heating value at low end of the range
Maintenance			
Scheduled	@ 2,000 hours (during operation) @ 8,000 hours (while shutdown)	Not demonstrated Not demonstrated	• Projected same as natural gas
Unscheduled MTBFO [1] availability	2,600 hours 95%	None in 707 hours 98.5%	• Operation to date indicates LFG fuel cell comparable to natural gas experience

Notes: [1] Mean time between forced outages

6.3.3 Emissions

The fuel cell power plant emissions at 120 kW on landfill gas are summarized in Table 6-8. The average emissions are as follows: NO_x = 0.12 ppmV; Sulfur Dioxide = non detectable (0.23 ppmV detection limit); and Carbon Monoxide = 0.77 ppmV. All readings are reported as parts per million, dry gas, corrected to 15 percent O_2. The results are also presented as a mass emissions rate in grams per hour, and grams per kilowatt hour.

Table 6-8. Fuel Cell Emissions Summary on Landfill Gas
Penrose Landfill Phase III Fuel Cell Energy Recovery Demonstration
February 17, 1995

SAMPLING TIME	Measurement Method	0800-0900	0950-1050	1155-1255	1332-1442	1457-1557	1622-1722	Average
EMISSION CONCENTRATION (actual dry measurements)								
nitrogen oxides (ppmV)	A	0.3	0.17	0.31	0.17	0.41	0.18	0.26
sulfur dioxide (ppmV)	B	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.50
carbon monoxide (ppmV)	C	1.5	1.8	2.1	2.3	0.6	1.9	1.70
oxygen (%)	D	7.96	8.01	7.88	7.8	8.03	7.91	7.93
carbon dioxide (%)	E	12.5	12.6	12.7	12.3	12.4	12.5	12.50
EMISSION 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)		10.1	10.1	9.4	9.4	9.7	9.7	9.7
STACK TEMPERATURE (°C)		56.7	56.7	43.3	43.3	42.8	42.8	48
MASS EMISSION RATE (grams/hour)								
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 (grams/kilowatt-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

NOTES:
1. dscm/m = dry standard cubic meters per minute at 20°C
2. grams/hour = actual ppm x Mol. Wt. x flowrate (dscm/m) x 0.0025
3. grams/kilowatt-hr = grams/hour/120 kilowatts

A = Thermo-electron Corporation Model 10A Chemiluminescent NO/NO_x Analyzer
B = Western Research model 721 SO_2 Analyzer
C = California Instruments, Inc. Nodispersive Infrared Gas Analyzer
D = Horiba Model PMA – 200 O_2 Analyzer
E = Infra-red Industries, Inc. Infrared CO_2 Analyzer

The fuel cell emissions data are based upon six, one-hour continuous monitor measurements conducted on February 17, 1995. The continuous emission monitors were calibrated before and after each test for zero and span drift. The details of the test procedures and data analysis are discussed in more detail in Appendix H.

The results of the emissions testing conducted over the six, one-hour periods are believed to be representative of longer term continuous emissions, since the fuel cell power plant controller continuously adjusts the fuel and air to maintain constant temperature inside the reformer burner where the carbon monoxide and NO_x are generated. In addition, the results for the landfill gas power plant are in good agreement with other emissions data measured on PC25 A power plants. The average results for 16 fuel cell power plants tested at the factory using natural gas fuel are: 0.46 ppmV NO_x, and 1.1 ppmV CO. Emissions tests were also conducted on a PC25 A sited at the SCAQMD Headquarters building in Diamond Bar, CA. The results showed 0.45 ppmV NO_x and 1.1 ppmV carbon monoxide. The Diamond Bar site results were confirmed by two independent laboratories, and were used by the agency as the basis for a blanket exemption from air permit requirements for fuel cells in the Los Angeles basin. The slightly lower NO_x emissions for the landfill gas power plant are likely a result of the lower reformer burner flame temperatures associated with the low heating value of the landfill gas fuel.

6.3.4 Quality Assurance

A summary of the quality assurance goals and test results is given in Table 6.9. The goals for accuracy and precision are based on the QAPP in Appendix G, and the quality assurance test results are based on the test data summarized in Appendix H. Typical concentrations, detection limits, and blank results for targeted compounds in the raw landfill gas at the Penrose Landfill are summarized in Table 6.10.

The quality assurance measurements for accuracy of hydrogen sulfide and for 3 of the 4 tested halogenated volatile organic compounds did not meet the 15% goal. The GPU removed all of these selected compounds to below the detection limit in the GPU exit gas, so these errors are not significant to the conclusions regarding the overall effectiveness of the GPU for sulfur and halide removal. The 30.7% high reading for hydrogen sulfide could lead to an overstatement of the apparent sulfur capacity of the hydrogen sulfide removal bed except that a nominal 100 ppmV value (based on historical Penrose data, in Table 4-4) was used for these calculations. The 100 ppmV H_2S value was corroborated by Drager tube measurements taken at the site during the demonstration test.

The accuracy of the ASTM D3588-91 method did not meet the 2% goal for all constituents, most notably methane at -3.5%. All other hydrocarbon species were negligible in these tests. The impact of the 3.5% error could be an overstatement of the apparent fuel cell efficiency by 3.5% (e.g., the reported 37.1% efficiency could be 35.8%). The close agreement between heating value measured by the Pacific Energy on-line analyzer and the ASTM method indicates the real error is probably less than 3.5% (see Table 6-4 on page 65).

The quality assurance tests of the emissions monitors showed that the SO_2, CO, CO_2 and O_2 measurements generally met or bettered the QA goals. The NO_x emissions tests exceeded the stated QA goals for accuracy and precision. Accuracy measured -22.4% and -20.7% vs. the 15% goal. Precision, measured as zero drift (-28 to 35.2%), and span drift (-32 to +21.5%) failed to meet the 10% goal. The NO_x QA results indicate a higher degree of uncertainty in the NO_x data, which is not surprising due to the low average value of just 0.12 ppm. An attempt was made to minimize the impact of zero and span drift by recalibrating the thermoelectron Model 10A chemiluminescent NO/NO_x analyzer before each 1 hour continuous analysis period, and using the average for the six periods. Even a 100% error in the final result would not change the conclusion that the exhaust NO_x level of the fuel cell operating on landfill gas is exceptionally low.

Table 6.9 Summary of Quality Assurance Goals and Test Results

				PRECISION			ACCURACY			
	Measurement	Method	Operating Range	Goal	Results		Goal	Results		Effect on Data Conclusions
1	Sulfur Compounds Hydrogen Sulfide	EPA 16 & 18	(A) 0 – 102 ppmV	5%	0.6%	(B)	15%	30.7%	(B)	H_2S not detected at GPU exit, so accuracy not significant to conclusion regarding GPU effectiveness.
2	Volatile Organic Compounds Vinyl Chloride	EPA – TO14	(A) 0.1 – 1.4 ppmV	15%	19.0%	(B)	15%	54.5%	(B)	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) is not significant to conclusion regarding GPU effectiveness.
	cis-1, 2-dichloroethene 1,1-dichloroethane tetrachloroethene		3.9 – 5.9 ppmV 1.2 – 2.9 ppmV 2.4 – 4.8 ppmV	15% 15% 15%	5.8% 6.9% 6.4%	(B) (B) (B)	15% 15% 15%	17.6% 13.2% 31.3%	(B) (B) (B)	
3	GPU Input Gas Heat Content	On-line Analyzer	N/A	2%	N/A		2%	1.1%	(C)	Meets QA goal for accuracy
4	GPU Output Gas Heat Content	ASTM D3588-91	3.56 – 4.09 kcal/sl	2%	0.11%	(D)	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 Exhaust Emissions				**Zero Drift**	**Span Drift**				
5	SO_2 Emissions	EPA–6C	0 – 100ppmV	5%	-2.1 to +.9%	-1.2 to +1.3%	5%	-4.0%	(E)	Meets QA goals
6	NO_x Emissions	EPA–7E	0 – 2.5ppmV	10%	-28 to +35.2%	-32 to +21.5%	15%	-22.4%, -20.7%	(E)	Low absolute NO_x values make higher uncertainty less significant
7	CO Emissions	EPA–10	0 – 100ppmV	10%	2.8 to +1.9%	-30 to + 2.1%	10%	-5.4%	(E)	All but 1 span drift meets QA goals
8	CO_2 Emissions	EPA–3A	0 – 25%	5%			5%	1.3%	(E)	Meets QA goal
9	O_2 Emissions	EPA–3A	0 – 25%	5%			5%	0.8%	(E)	Meets QA goal

(A) Typical value in landfill gas at Penrose – See Table 6.10

(B) Appendix H, Table 11-2, page H-51

(C) Relative standard deviation compared with 4 ASTM samples taken within 1 hour, Appendix H, Table 11-1, page H-50

(D) Appendix H, Table 11-1, page H-50

(E) Appendix H, Table 11-3, page H-53

Table 6.10 Typical Concentrations, Detection Limits, and Blank Results for Targeted Compounds in the Raw Landfill Gas at the Penrose Landfill			
Sulfur Compounds (ppmV)	**Typical Value in Untreated Landfill Gas**	**Detection Limit Objective**	**Blank Samples**
1. H_2S	102.0	0.04	<0.002
2. Methyl mercaptan	3.0	0.04	<0.002
3. Ethyl mercaptan	0.5	0.04	<0.002
4. Dimethyl sulfide	6.5	0.04	<0.002
5. Dimethyl disulfide	<0.07	0.02	<0.002
6. Carbonyl sulfide	0.2	0.04	<0.002
7. Carbon disulfide	<0.07	0.02	<0.002
8. Total sulfur as H_2S (ppmV)	109.0	0.28	<0.002
Volatile Organic Compounds (ppmV)			
1. Dichlorodifluoromethane	0.3 – 0.9	0.009	<0.001
2. 1,1-dichloroethane	1.2 – 2.9	0.002	<0.001
3. Benzene	1.1 – 1.7	0.002	<0.001
4. Chlorobenzene	0.6 – 1.4	0.002	<0.001
5. Ethylbenzene	4.5 – 12.0	0.002	<0.001
6. Methylene chloride	4.0 – 11.0	0.003	<0.001
7. Styrene	0.5 – 1.1	0.003	<0.001
8. Trichloroethene	1.3 – 2.4	0.001	<0.001
9. Trichlorofluoromethane	0 – 0.6	0.004	<0.001
10. Toluene	28.0 – 47.0	0.002	<0.001
11. Tetrachloroethene	2.4 – 4.8	0.002	<0.001
12. Vinyl chloride	0.1 – 1.4	0.005	<0.001
13. Xylene isomers	5.0 – 28.0	0.005	<0.001
14. cis-1,2-dichloroethene	3.9 – 5.9	0.003	<0.001
15. Total halides as Cl	47.0 – 67.0	0.086	

7.0 PHASE IV GUIDELINES AND RECOMMENDATIONS

The purpose of this phase is to prepare guidelines and recommendations as to how the PC25 C power plant can be modified to achieve full rated power when operated on landfill gas, based upon the experience gained testing the PC25 A model in this program.

The PC25 C power plant is designed to produce 200 kW of net power when operated on natural gas having a higher heating value range of 8.72 kcal/SL to 10.68 kcal/SL. Landfill Gas (LFG) contains significant amounts of N_2 and CO_2 which lower the higher heating value. A Landfill Gas with 50 percent methane and a higher heating value of 4.45 kcal/SL was used for this study. A PC25 C power plant operated on LFG having 4.45 kcal/SL higher heating value would produce a projected 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. This phase investigated approaches to achieve increased fuel flows.

Fuel flow in the PC25 C power plant is achieved by using a steam driven ejector. This approach has the benefit of reducing parasitic power and provides an inherent fail safe feature in that a loss of steam flow will automatically terminate fuel flow and prevent damage to the fuel processor. The injector also has a finite pumping capacity which requires all components in the fuel delivery system to have small pressure drops.

Increasing fuel flows result in a corresponding increase in pressure drops, so the impact of replacing or modifying components in the fuel delivery system to minimize pressure drop increases was determined. The PC25 C fuel delivery train (Figure 7-1) to the hydro-desulfurizer contains two fuel isolation valves and a check valve having inside diameters (I.D.) of 2.54 cm and a fuel control valve having an I.D. of 1.27 cm connected with 2.54 cm diameter piping. Increasing the I.D. of the isolation valves and the check valve to 3.81 cm, the I.D. of the fuel control valve to 2.54 cm, and the connecting plumbing to 3.81 cm (Figure 7-2) would accommodate the increased flow without producing unacceptable pressure drops. These changes would not require major modifications to the power plant.

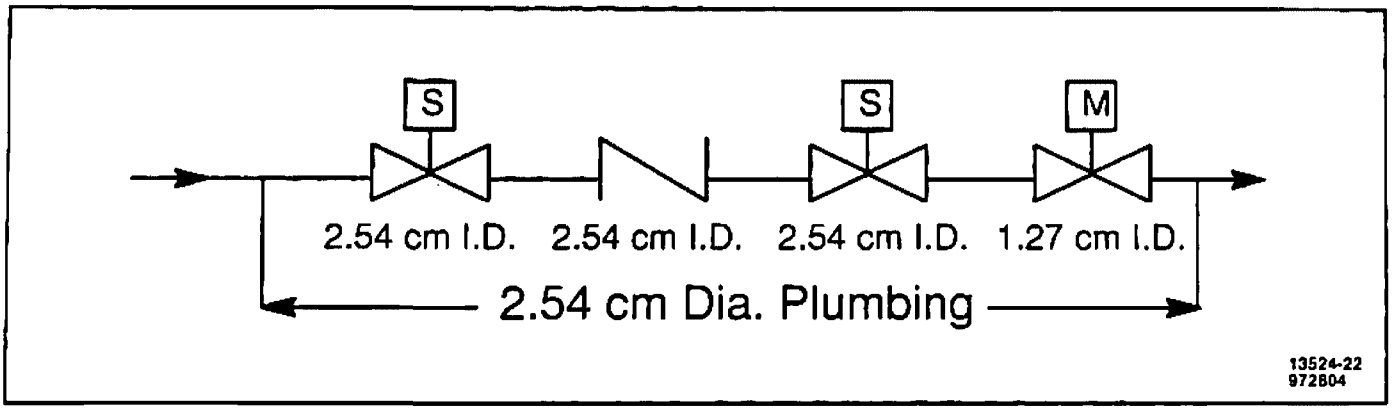

Figure 7-1. PC25 C Fuel Delivery Train

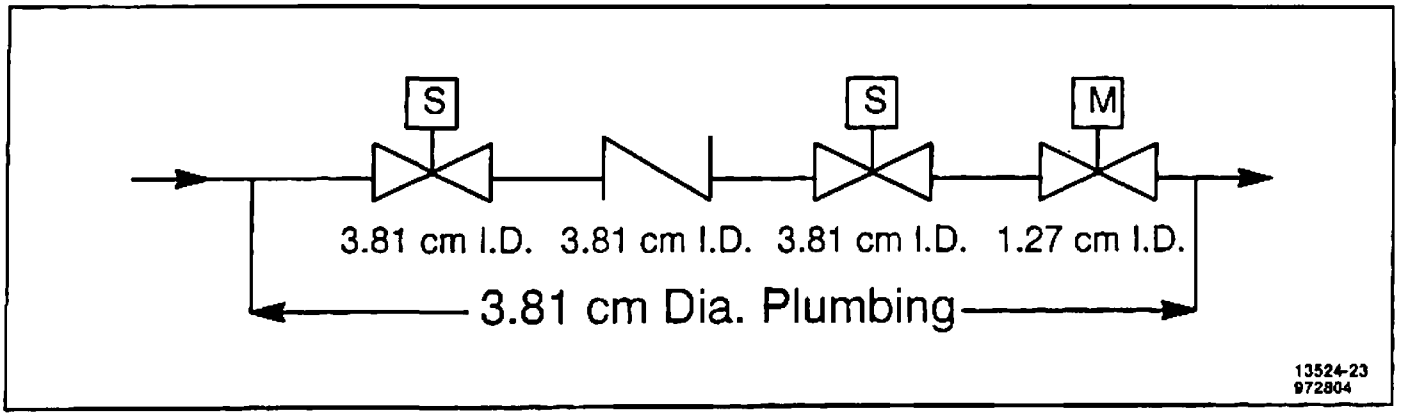

Figure 7-2. PC25 C Fuel Delivery Train Modified for Operation on Landfill Gas

The high flow rates of landfill gas 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. Two approaches were considered for lowering the fuel inlet pressure: increasing the cross-sectional area of the flow fields and adjusting the flow directors in the CSA fuel manifolds with a corresponding change in the size of the cathode exit flow orifice.

The fuel flow-field depths would have to increase by forty percent to obtain an inlet pressure which results in an acceptable reactant cross pressure. While theoretically possible, this approach could create a manufacturing disruption and results in a taller CSA. Both consequences could have a negative cost impact on the power plant. Slight adjustments to the flow directors in the fuel manifold and a corresponding reduction in the size of the cathode exit flow orifice would result in a reactant cross pressure which would be acceptable at flows sufficient to produce 175 kW of power. For flows to produce 200 kW of power the magnitude of the cathode exit flow orifice size reduction results in the need for a larger cathode air blower. This approach has a minimum impact on CSA production costs and CSA height, and is recommended as the preferred choice.

The operating characteristics of the PC25 C ejector at LFG flows required to produce 200 kW was not available and bench tests were conducted to generate the data. A modified ejector having ten percent larger secondary mixing tube was also characterized. The data indicate that the PC25 C ejector is capable of providing LFG flows sufficient to produce 175 kW of net power but does not have the capacity to provide flows required to produce 200 kW of net power. The data obtained for the modified ejector indicate that it would be capable of providing LFG flows required to produce 200 kW of power. The use of a modified ejector would have a minimal cost impact.

8.0 CONCLUSIONS

1. Based on the environmental and economic evaluation of the commercial fuel cell energy system, there is a large potential market for fuel cells:
   - The fuel cell landfill gas to energy conversion system provides net reduction in total emissions while simultaneously mitigating the methane from the landfill gas.
   - With the initial product prices, fuel cells will be competitive in landfill sites located in high electric cost areas in sites with average commercial rates; where heat can be utilized or where there is a credit for the environmental reductions from the fuel cell energy conversion system.
   - When the projected mature product price is achieved, fuel cells will be competitive for most application scenarios. In many situations, fuel cells will provide net revenues to the owners of the operating landfills. This could, in the long term, result in methane mitigation without additional cost of any sort to the ultimate consumer.
2. The gas pretreatment unit (GPU) for cleaning landfill gas to fuel cell was successfully designed, installed, permitted, tested, and validated:
   - A permit was granted by South Coast Air Quality Management District for operation in Los Angeles basin.
   - Total 2297 hours of operation, including 709 hours operation with the fuel cell.
   - Adjusted availability of the GPU during the fuel cell demonstration test period was 87.3%.
   - Documented total sulfur removal betters fuel cell requirements (< 3 ppmV total sulfur).
   - Documented total halide removal betters requirements for fuel cell (< 3 ppmV total halides).
   - GPU flare safely disposed of landfill gas contaminants by achieving destruction efficiencies above 99 percent.
   - The observed hydrogen sulfide removal bed capacity was 12 grams of sulfur per gram of impregnated carbon.
3. Fuel cell modifications for operation on landfill gas were successfully demonstrated with a commercially available PC25 A fuel cell power plant:
   - Operation up to 137 kW.
   - Efficiency of 37.1 percent at 120 kW.
   - Exceptionally low secondary emissions (dry gas, corrected to 15 percent O_2)

carbon monoxide	=	0.77 ppmV
nitrogen oxides	=	0.12 ppmV
sulfur dioxide	=	not detected

   - No forced outages, and adjusted availability of 98.5 percent.
   - Total 709 hours operation on landfill gas.

4. The fuel cell can be modified to operate at rated 200 kW power on landfill gas.
   - The model PC25 C power plant should be able to generate 200 kW with modifications to the fuel control plumbing, stack manifolds, ejector, and process air blower, assuming the land fill gas contains 50% methane (a higher heating value of 4.45 kcal/sl), and an average sustainable net flow of 2830 scmd (100,000 scfd) of clean landfill gas to the fuel cell.
   - The recurring cost changes for these modifications is minimal.
5. Additional testing is recommended to demonstrate endurance operation on landfill gas and provide data for reducing the cost of the gas cleanup system.

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16. ABSTRACT The report summarizes the results of a four-phase program to demonstrate that fuel cell energy recovery using a commercial phosphoric acid fuel cell is both environmentally sound and commercially feasible. Phase I, a conceptual design and evaluation study, addressed the technical and economic issues associated with operating the fuel cell energy recovery system of landfill gas. Phase II included the design, construction, and testing of a landfill gas pretreatment unit (GPU) to remove critical fuel poisons such as sulfur and halides from the landfill gas, and the design of fuel cell modifications to permit operating on low heating value (LHV) landfill gas. Phase III was the demonstration test of the complete fuel cell energy recovery system. Phase IV described how the commercial fuel cell power plant could be further modified to achieve full rated power on LHV landfill gas. The demonstration test successfully demonstrated operation of the energy recovery system, including the GPU and the commercial phosphoric acid fuel cell modified for operation on landfill gas. Demonstration output included operation up to 137 kW; 37.1% efficiency at 120 kW; exceptionally low secondary emissions (dry gas, 15% O2) of 0.77 ppmV carbon monoxide, 0.12 ppmV nitrogen oxides, and undetectable sulfur dioxide; no forced outages with adjusted availability of 98.5%; and 709 hours operation on landfill gas.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Methane	Pollution Prevention	13B 07C
Energy	Carbon Dioxide	Stationary Sources	14G
Fuel Cells	Sulfur	Global Warming	10B
Phosphoric Acids	Halides		07B
Earth Fills			13C
Gases			07D

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