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DEMONSTRATION OF FUEL CELLS TO RECOVER ENERGY FROM LANDFILL GAS

PHASE I FINAL REPORT: CONCEPTUAL STUDY

by

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16. ABSTRACT

The report discusses results of a conceptual design, cost, and evaluation study of energy recovery from landfill gas using a commercial phosphoric acid fuel cell power plant. The conceptual design of the fuel cell energy recovery system is described, and its economic and environmental feasibility is projected. A conceptual design of the project demonstration was established from the commercial system conceptual design. It addresses the key demonstration issues facing commercialization of the concept. Candidate demonstration sites were evaluated, which led to selection and EPA approval of the demonstration site. A plan is discussed for construction and testing of a landfill gas pretreatment system which will render landfill gas suitable for use in the fuel cell. The final phase of the study will be a demonstration of the energy recovery concept.

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ABSTRACT

International Fuel Cells Corporation is conducting a U. S. EPA sponsored program to demonstrate energy recovery from landfill gas using a commercial phosphoric acid fuel cell power plant. The U.S. EPA is interested in the fuel cell for this application because it is potentially one of the cleanest energy conversion technologies available. This project report discusses the results of Phase I, a conceptual design, cost, and evaluation study. The conceptual design of the fuel cell energy recovery system is described and its economic and environmental feasibility is projected. A conceptual design of the project demonstration was established from the commercial system conceptual design. It addresses the key demonstration issues facing commercialization of the concept. Candidate demonstration sites were evaluated, which led to selection and EPA approval of the demonstration site for this project.

A plan for Phase II activities is discussed. Phase II will include construction and testing of a landfill gas pretreatment system which will render landfill gas suitable for use in the fuel cell. Phase III will be demonstration of the energy recovery concept.

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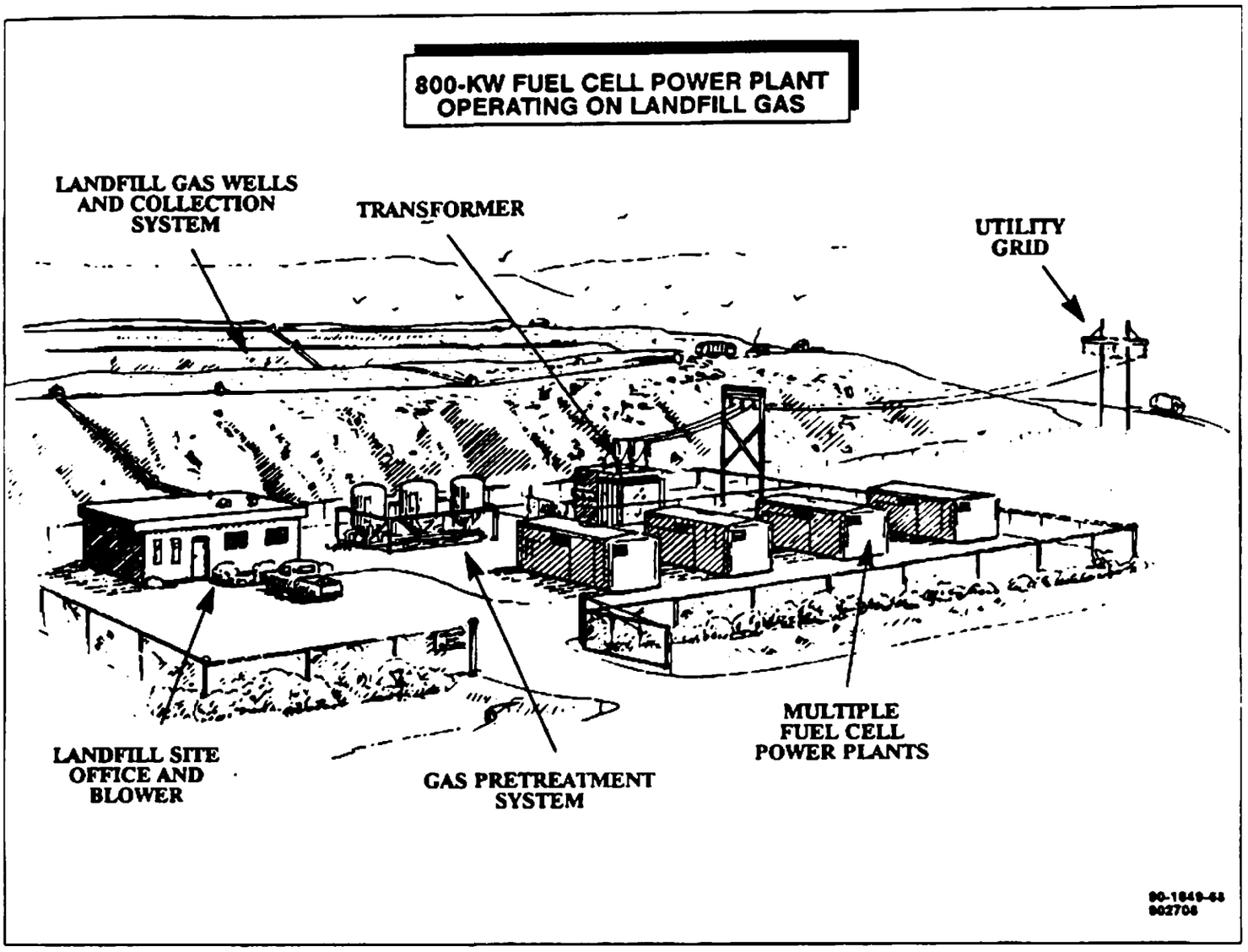


Figure S-1. Fuel Cell Energy Recovery Commercial Concept

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) has proposed standards and guidelines[1] for the control of air emissions from municipal solid waste landfills. Although not directly controlled under the proposal, the emission guidelines would result in the collection and disposal of waste methane, a significant contributor to the greenhouse effect. This EPA action will provide 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 U.S. EPA to demonstrate energy recovery from landfill gas using a commercial phosphoric acid fuel cell. IFC is conducting a three-phase program to show that fuel cell energy recovery is economically and environmentally feasible in commercial operation. This report covers the results of Phase I, a conceptual design, cost, and evaluation study, which addressed the problems associated with landfill gas as the feedback for fuel cell operation.

Phase II of the program includes construction and testing of the landfill gas pretreatment module to be used in the demonstration. Its objective will be to determine the effectiveness of the pretreatment system design to remove critical fuel cell catalyst poisons such as sulfur and halides. A challenge test is planned to show the feasibility of using the pretreatment process at any landfill in conjunction with the fuel cell energy recovery concept. A preliminary description of the gas pretreater is presented here.

Phase III of this program will be demonstration of the fuel cell energy recovery concept. The demonstrator will operate at Penrose Station, an existing landfill gas-to-energy facility owned by Pacific Energy in Sun Valley, California. Penrose Station is an 8.9 MW internal combustion engine facility supplied with landfill gas from four landfills. The electricity produced by the demonstration will be sold to the electric utility grid.

Phase II activities began in September 1991, and Phase III activities are scheduled to begin in January 1993.

Fuel Cell Energy Recovery Concept

During Phase I, a commercial fuel cell energy recovery system concept was designed. The system, shown in Figure S-1 is based on commercially available equipment adapted for operation on landfill gas. The system was sized to be broadly applicable to a large number of landfills.

Landfill gas is collected by a series of wells in the municipal solid waste landfill and piped to a gas pretreatment module. The pretreatment module removes contaminants such as sulfur and halides which affect the operation of the fuel cells. The contaminants are concentrated on absorption beds to a predetermined level. Then during a regeneration cycle they are stripped from the absorption media and destroyed by incineration. Hydrocarbon condensates which form in the pretreater are also incinerated. The resulting output is a medium Btu methane fuel suitable for use in the fuel cell.

The concept utilizes four modular 200-kW phosphoric acid fuel cells generating electricity to be sold to the electric utility grid. The fuel cell power plants are adaptations from the natural gas fueled PC25 fuel cell sold by ONSI Corporation, an IFC subsidiary. Only simple modifications are required to ensure that rated power is achieved from the dilute landfill gas.

Issues to be Resolved

To demonstrate that fuel cell energy recovery is economically and environmentally feasible, two key issues must be addressed. They are 1) to define a gas pretreatment system to render the landfill gas suitable for fuel cell use, and 2) to design the modifications necessary to ensure rated power is achieved from the dilute methane fuel.

The conceptual design of the future commercial system was used as the basis of our evaluation of the above issues. Requirements for the landfill site, the gas pretreatment system and the fuel cell power plant were established. These requirements were used by IFC to define demonstration site selection criteria, and pretreatment module and fuel cell power plant designs. With this level of definition, IFC was able to extract the demonstration project site-specific conceptual design shown in Figure S-2.

The site selected for the demonstration project during Phase I is the Penrose Station in Sun Valley, California. This site owned and operated by Pacific Energy, accepts landfill gas from four municipal solid waste landfills. Penrose Station presently produces 8.9 MW of electricity from landfill gas, using internal combustion engines. The demonstration will operate on a slip stream from Penrose's gas feed.

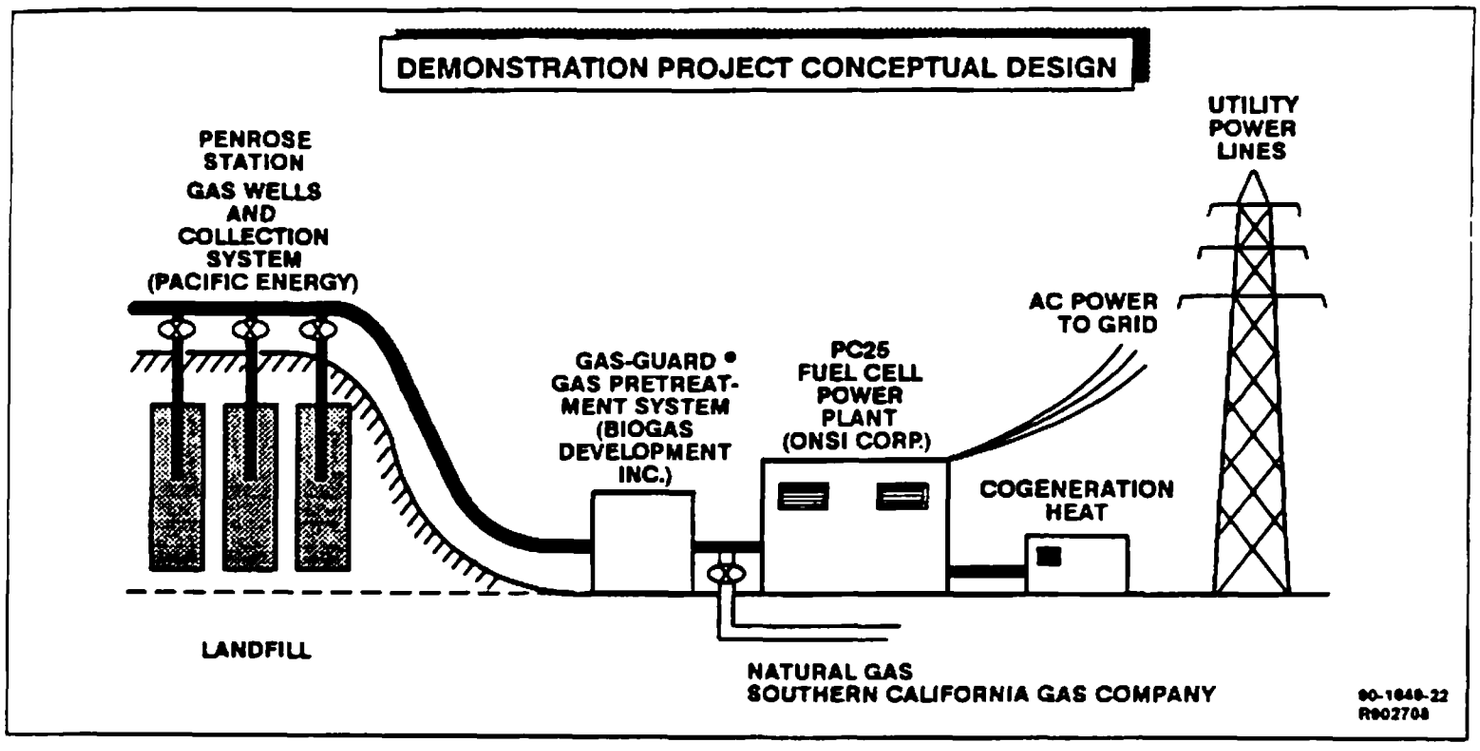


Figure S-2. IFC's Proposed Demonstrator Concept

Because Penrose accepts gas from four fills, some of which contain industrial waste, the composition and contaminant levels vary considerably. Average methane content is 44 percent and the gas typically contains 150 ppm_v sulfur and 78 to 95 ppm_v halides. The sulfur contaminant levels are higher than typically found in municipal solid waste landfill gas. A successful demonstration at Penrose will show broad applicability of the concept to the market.

Gas analyses from Penrose were used to guide the design of the gas pretreatment system by Bio-Gas Development Inc. The Bio-Gas system utilizes a combination of condensate removal by refrigeration and regenerable absorption beds to clean the gas to meet the fuel cell requirement. Our plan for Phase II is to construct and test the demonstration pretreater at Penrose prior to siting the fuel cell. This design verification test is intended to ensure a successful demonstration in Phase III.

IFC's evaluation study defined a set of modifications to the natural gas fueled PC25 which could be easily accomplished in the field. Southern California Gas Co., long active in on-site fuel cell development, will operate the fuel cell during the demonstration and do the in-field modifications.

IFC plans to closely monitor the demonstrator performance test, generating emissions data, landfill gas quality data, fuel cell performance (electrical and thermal) and system costs. These data will be evaluated to show the effectiveness of our concept in commercial application. To ensure high quality data, we plan to conduct a coordinated quality assurance program which will oversee the generation of measurement data.

Conclusions

The approach used to establish the conceptual design of the demonstration project enabled IFC to focus on the key issues to be resolved by the demonstration. Our commercial concept generated a set of requirements which translate directly to demonstrator requirements and are easily verifiable.

We have selected a site which we feel is representative, and which will demonstrate the applicability of the concept throughout the market. Gas analyses from Penrose enabled Bio-Gas to anticipate the

incoming gas quality and design equipment to meet the challenge. The Bio-Gas design also has built-in flexibility to accommodate upsets in the contaminant level that may result from weather or natural phenomenon, thus providing added confidence in the concept. We feel confident the gas pretreatment system design will produce a quality fuel cell fuel.

The fuel cell modifications required to achieve 200 kW on landfill gas have been identified. Two options will be provided to EPA for the demonstration fuel cell. These changes are simple and require only re-engineering. A list of necessary changes at minimum cost will provide a 140 kW rating. Additional changes which can be accomplished in the field at additional cost to the program will yield 175 kW. The complete list of changes, which would require some engineering and needs to be incorporated at the time of manufacture, will provide the full 200 kW power rating required in the commercial concept.

We believe we have a demonstration project conceptual design which addresses all the key issues facing commercial application of the concept. In the next phase, we plan to verify the ability of the gas pretreatment equipment to yield a quality fuel. We will also prepare a site-specific detailed design for the demonstration. This design will address not only hardware detail, but also test plans and an updated demonstration cost estimate.

1.0 INTRODUCTION

This report summarizes the work performed under Phase I of U.S. Environmental Protection Agency Contract 68-D1-0008, "Demonstration of Fuel Cells to Recover Energy from Landfill Gas." This work was initiated in January 1991 and establishes the conceptual design of a fuel cell energy recovery concept and the site specific demonstration hardware. The Phase I study addressed the problems associated with landfill gas as the feed stock for fuel cell operation.

The commercial concept of the fuel cell energy recovery system is based on commercially available equipment adapted for operation on landfill gas. The first major effort of Phase I was a power system study which reviewed the competitive requirements for the commercial concept, produced the conceptual design, and defined the technology development requirements. This effort is discussed in Sections 2.1 and 2.2 of the report.

A conceptual design of the fuel cell energy recovery demonstrator was extracted from the commercial concept. The demonstrator addresses the two major technical issues impeding commercialization of the concept: decontamination of the landfill gas; and power plant power rating on the dilute-methane fuel. This design is discussed in Section 2.3 together with our conclusion from the evaluation study.

In Phase II of the program we plan to construct and test the gas pretreatment module to be used in the demonstration. Our objective will be to determine the effectiveness of the pretreatment system design to remove critical fuel cell catalyst poisons such as sulfur and halides. We plan to conduct a challenge test to show the feasibility of using the pretreatment process at any landfill in conjunction with the fuel cell energy recovery concept. A detailed description of the gas pretreater as well as the site-specific detailed design for the Phase III demonstration will be documented at the end of Phase II. The details of our plan are presented in Section 2.3.3.

The third major effort of this program will be the demonstration of the fuel cell energy recovery concept in Phase III. The demonstrator will operate at an existing landfill gas energy recovery facility owned by Pacific Energy in Sun Valley California. The Penrose Station is an 8.9 MW internal combustion engine facility supplied with landfill gas from four separate landfills. The electricity produced will be sold to the electric utility grid. Site specific data and site requirements are discussed in Section 2.3 of this report.

IFC plans to begin Phase II activities in September 1991 with the approval of the EPA. Phase III activities are scheduled to begin in January 1993.

2.0 CONCEPTUAL DESIGN, COST AND EVALUATION STUDY RESULTS

2.1 REQUIREMENT FOR LANDFILL GAS APPLICATION

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

2.1.1 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 100,000 SCFD* of landfill gas to generate 200 kW, assuming a heating value of 500 Btu per cubic foot.**

The potential power generation market available for fuel cell energy recovery was evaluated using an EPA estimate of methane emissions in the year 1997[2] and an estimate of landfill gas production rate of 0.1 SCF/yr per ton*** of refuse in place.[3] An estimated 4370 MW of power could be generated from the 7480 existing and closed sites identified as shown in Table 2.1-1. 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. Sites in this range are also less well served by competing options, especially Rankine and Brayton Cycles which exhibit poorer emission characteristics at these power ratings.

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 2.1-1. 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

(*) 1SCFD = 0.028 SCMD
(**) 1Btu/ft^3 = 37.3 kJ/$_m^3$
(***) 1 ton = 2000 lb = 908 kg

2.1.2 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.

A summary of landfill gas characteristics is shown in Table 2.1-2. The heating value of the landfill gas varies from 350 to 600 Btu per cubic foot, with a typical value of 500 Btu per cubic foot. 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 120°F.*

Table 2.1-2. Landfill Gas Characteristics

Characteristic	Range	Typical
Heating Value (HHV)	350-600 (Btu/ft^3)	500 (Btu/ft^3)
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	2700 ppmv

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[4]. 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[5]. 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.

(*) °C = 5/9 (°F-32)

2.1.3 Emission Requirements

Existing U.S. regulations do not address methane emissions from landfills directly. Proposed new EPA regulations[1] 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 emissions 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.

2.1.4 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).

2.1.5 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.

2.2 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.

2.2.1 Overall System Description

The commercial landfill gas to energy conversion system is illustrated in Figure 2.2-1. 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 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.

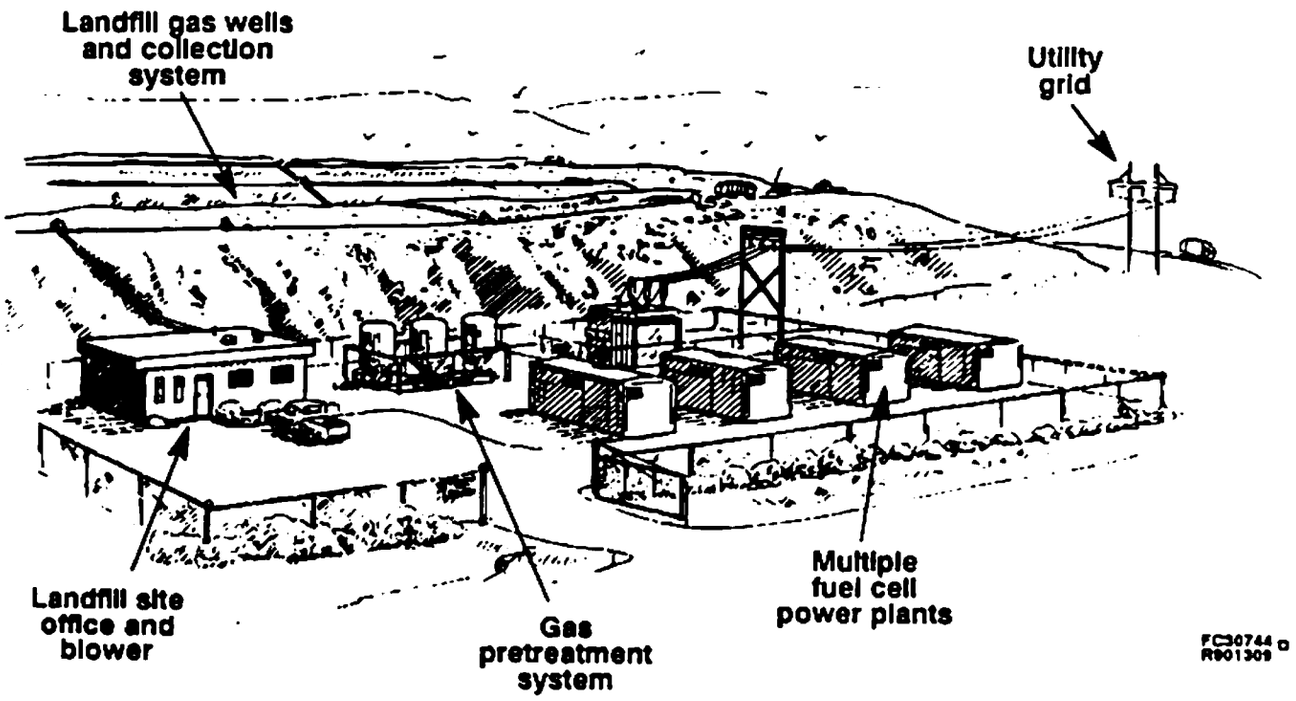


Figure 2.2-1. Commercial Fuel Cell Landfill-Gas-to-Energy Conversion Concept

The commercial energy conversion system shown in Figure 2.2-1 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 500 Btu per standard cubic foot and for accommodating higher contaminant concentra-

tions. 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 2.2-1, the commercial system can process approximately 18,000 standard cubic feet per hour of landfill gas (mitigate 9050 SCFH 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.

Fuel Pretreatment System

A block diagram of the landfill gas pretreatment system is shown in Figure 2.2-2. The fuel pretreatment system incorporates two stages of refrigeration combined with three regenerable adsorbent steps. The use of staged refrigeration provides tolerance to varying landfill gas constituents. The first stage reduces the water content to a uniform dew point of approximately 33°F, and removes some heavier hydrocarbons from the landfill gas. This concept is based on Bio Gas Development landfill gas condensate removal composition data and experience at similar operating conditions. The first stage 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 molecular sieve bed next reduces the dew point from 33°F to less than -50°F, to prevent freezing in the second refrigeration step. The second refrigeration step removes additional hydrocarbons and enhances the effectiveness of the activated carbon and molecular sieve beds, which remove the remaining volatile organic compounds and hydrogen sulfide 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.

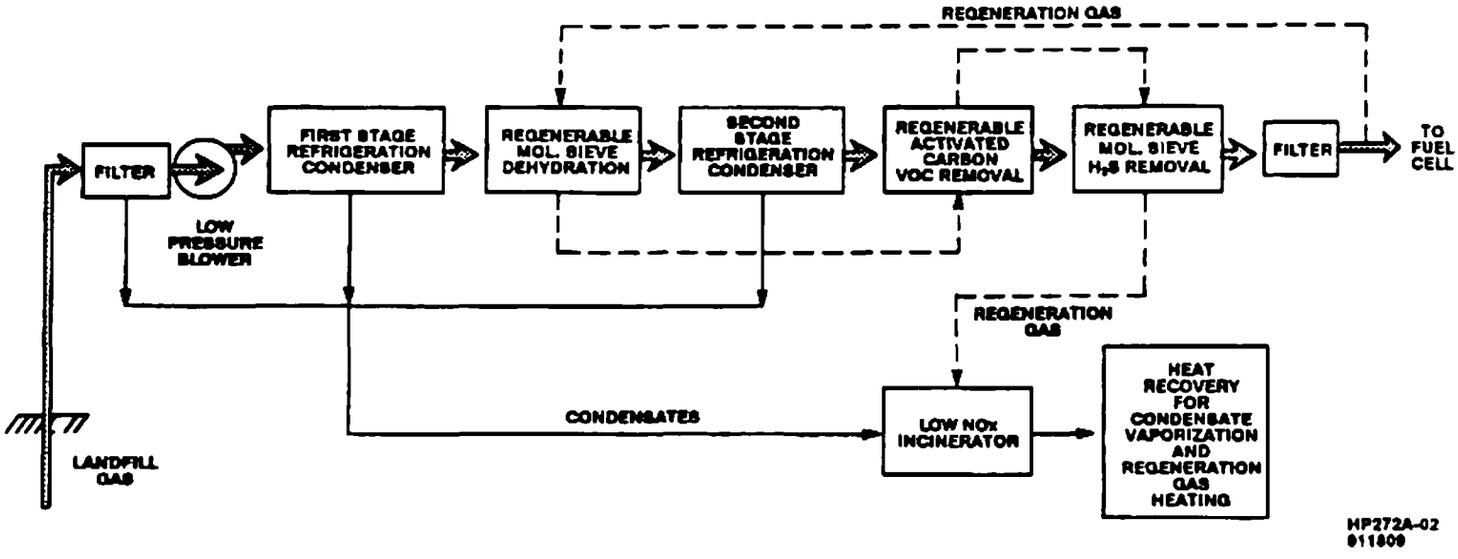
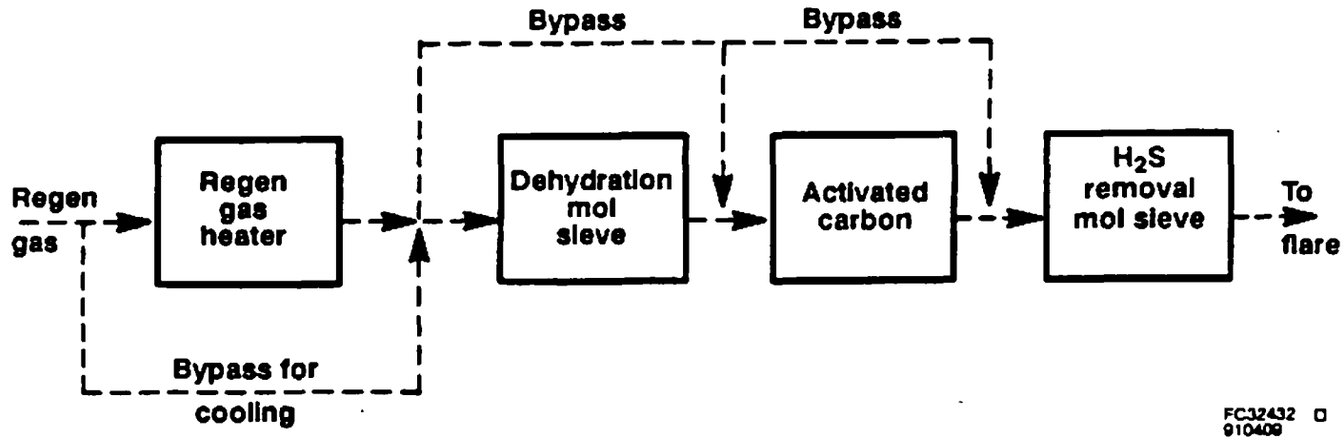


Figure 2.2-2. Simplified Block Diagram of Commercial LFG Pretreatment System

The three adsorbent beds are regenerated by using cleaned, heated gas from the process stream. 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 2.2-2. 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 2.2-3 with its accompanying sample regeneration sequence shows the regeneration process in more detail. This sys-

tem 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.



Staged Regeneration of Adsorbent Beds

8 Hour Sequencing						
Step	Duration (hrs)	Mode	Regen gas heater	Dehydration bed	Activated carbon bed	H_2S removal bed
1	0.5	Heating	On	Bypass	Regen	Regen
2	1.5	Heating	On	Regen	Regen	Regen
3	0.5	Heating	On	Bypass	Regen	Regen
4	1.5	Heating	On	Bypass	Bypass	Regen
5	2.0	Cooling	Bypass	Regen	Regen	Regen
6	1.0	Cooling	Bypass	Bypass	Regen	Regen
7	1.0	Cooling	Bypass	Bypass	Bypass	Regen

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Figure 2.2-3. Staged Regeneration of Adsorbent Beds and Sample Regeneration Sequence

Key features of the design and the related product benefits are summarized in Table 2.2-1. The system design provides flexibility for operation on a wide range of landfill gas compositions, and has minimal

solid wastes, 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.

Table 2.2-1. Key Features of Commercial Pretreatment System Conceptual Design

Design Feature	Product Benefit
• 7 psig 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
• All dry beds regenerable	• Minimal solid waste 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

The pretreatment system was analyzed to estimate the overall thermal efficiency, the internal electric power requirements, and its maintenance characteristics. These characteristics are summarized in Table 2.2-2. 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, and replacement of fully regenerated spent bed materials on an annual basis. The maintenance cost for the system is estimated to be 0.2¢/kWhr.

Table 2.2-2. 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%
• Maintenance Cost	• ~0.2 ¢/kWh

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 0.06 pounds per million Btu* 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 bed materials at the

(*) 1 lb/10^6 or million Btu = 0.43 kg/10^6 or million kJ

factory and treatment by an EPA approved processor for reclamation. The bed materials are routinely handled and processed by qualified waste processors.

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 2.2-4. 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.

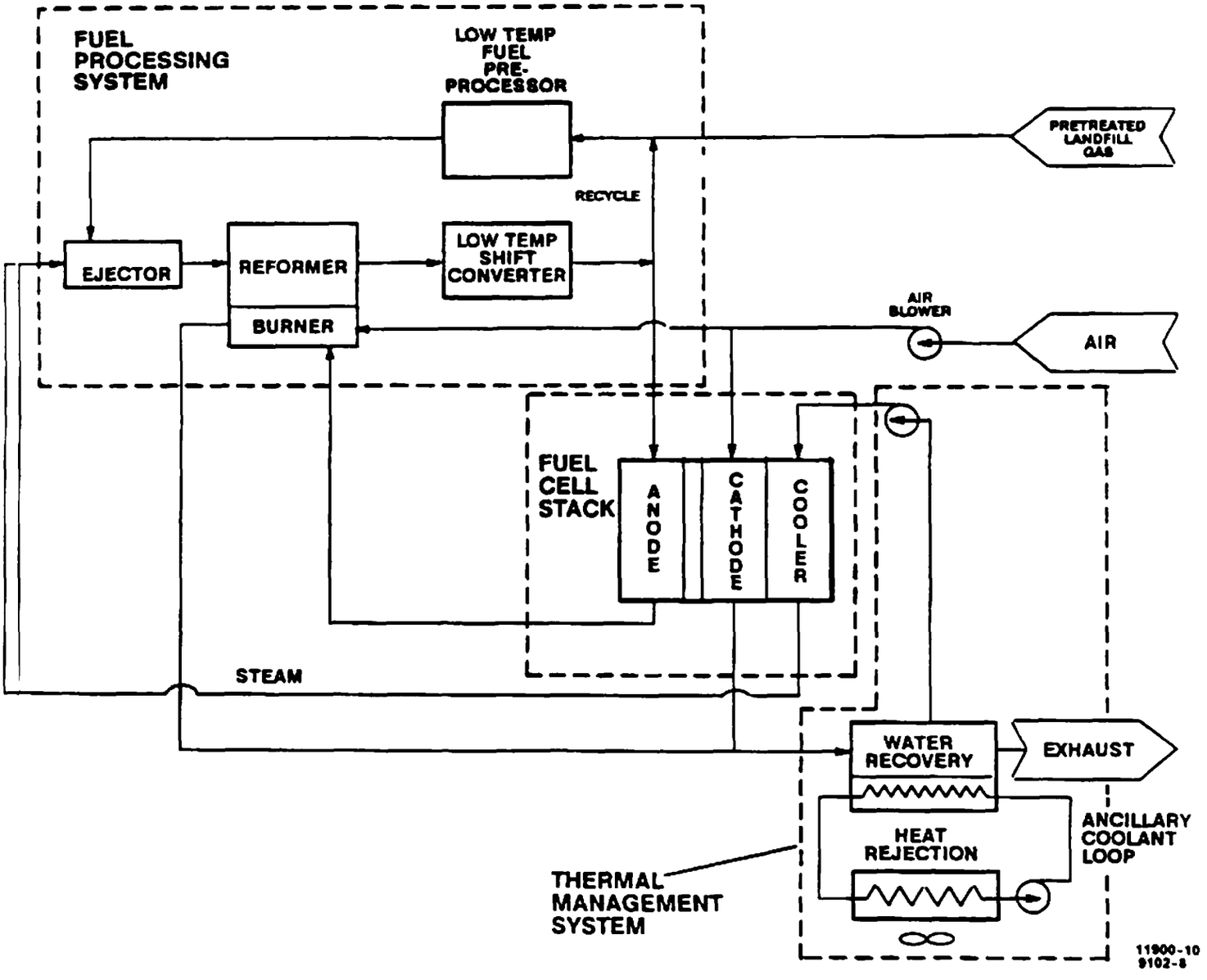

Figure 2.2-4. Functional Schematic Fuel Cell Landfill Gas Power Unit

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 2.2-3.

Table 2.2-3. Performance Comparison for Nominal 200 kW Output

	NATURAL GAS POWER PLANT	LFG POWER PLANT
Fuel	Natural Gas	Landfill Gas
Electrical Efficiency (LHV) - %	40	36.4
Heat Rate (HHV) - Btu/kWhr	9,500	10,410
Available Heat - Btu/hr	760,000	825,000
Ambient Temperature for Fuel Water Recovery - °F	95	95
Startup Fuel	Natural Gas	Landfill Gas

The estimated air emissions of the fuel cell power plant is provided in Table 2.2-4. 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 2.2-4. Estimated Fuel Cell Air Emissions

	LFG FUEL CELL
Emissions - Lbs/10^6 Btu	
NO_x	0.02–0.04
SO_x	0.00003
Particulates	0.000003
Smoke	None
CO	0.04–0.08
Total Hydrocarbons	0.02–0.03

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 434,000 standard cubic feet of landfill gas per day. The gas contains approximately 50 percent methane by volume with a heating value of 500 Btu per standard cubic foot. The system is capable of supplying 784 kW of net electric power to the grid and has an available thermal energy of 3.36 million Btu per hour. Overall system performance is outlined in Figure 2.2-5.

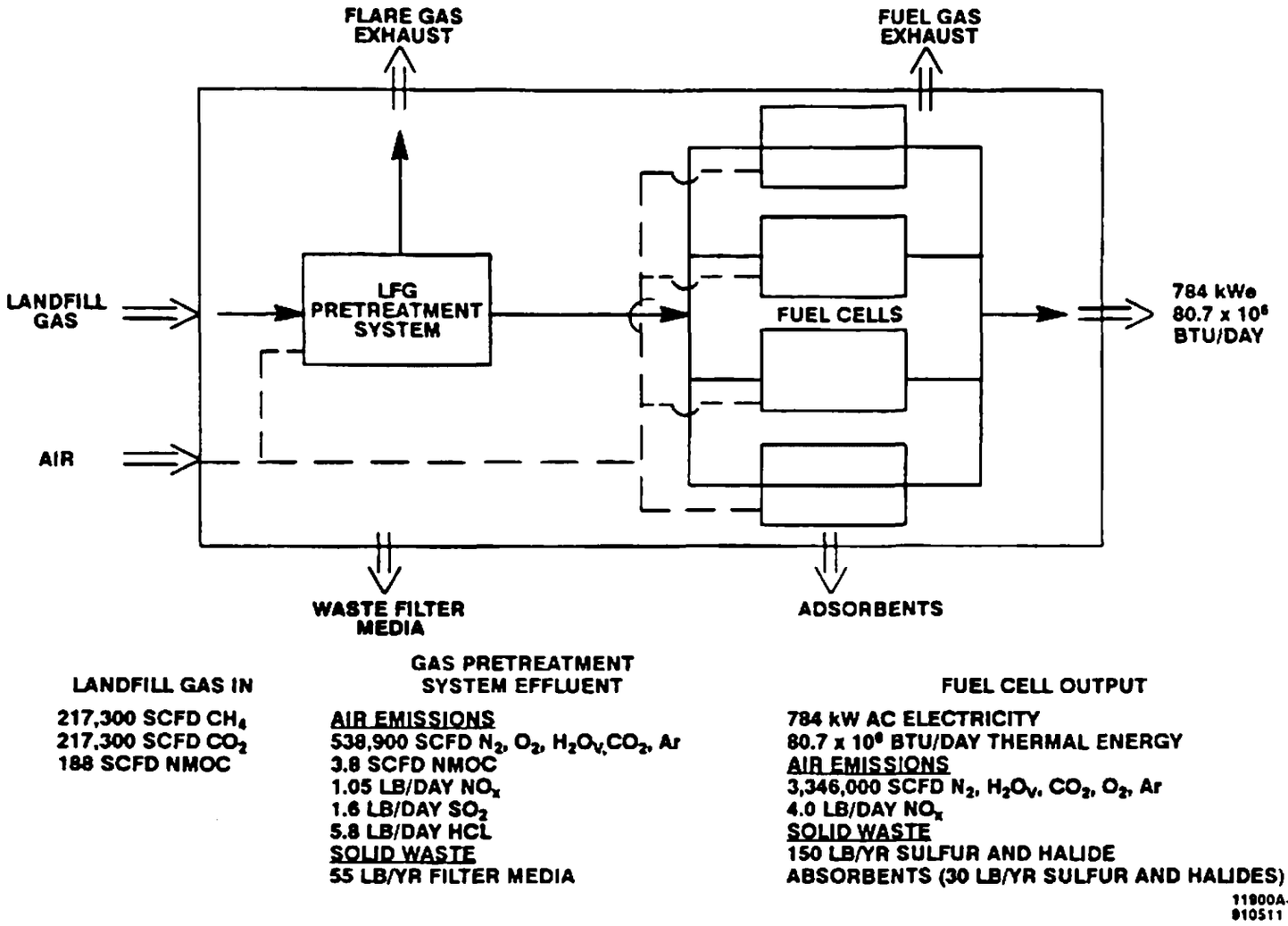

Figure 2.2-5. Overall System Schematic and Performance Estimate for Fuel Cell LFG-to-Energy Conversion System

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 2.2-6 shows the impact of changing the landfill gas heating value from 400 to 600 Btu/SCF 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 2.2-6. A reduction in methane content or heating value below 500 Btu/SCF result in a loss in energy input and power output. Above 500 Btu/SCF the power plant automatic flow controls will self-adjust maintaining 200 kW output. In order to maintain 200 kW capability below 500 Btu/SCF some amount of natural gas blending may be required to maintain the gas heating value.

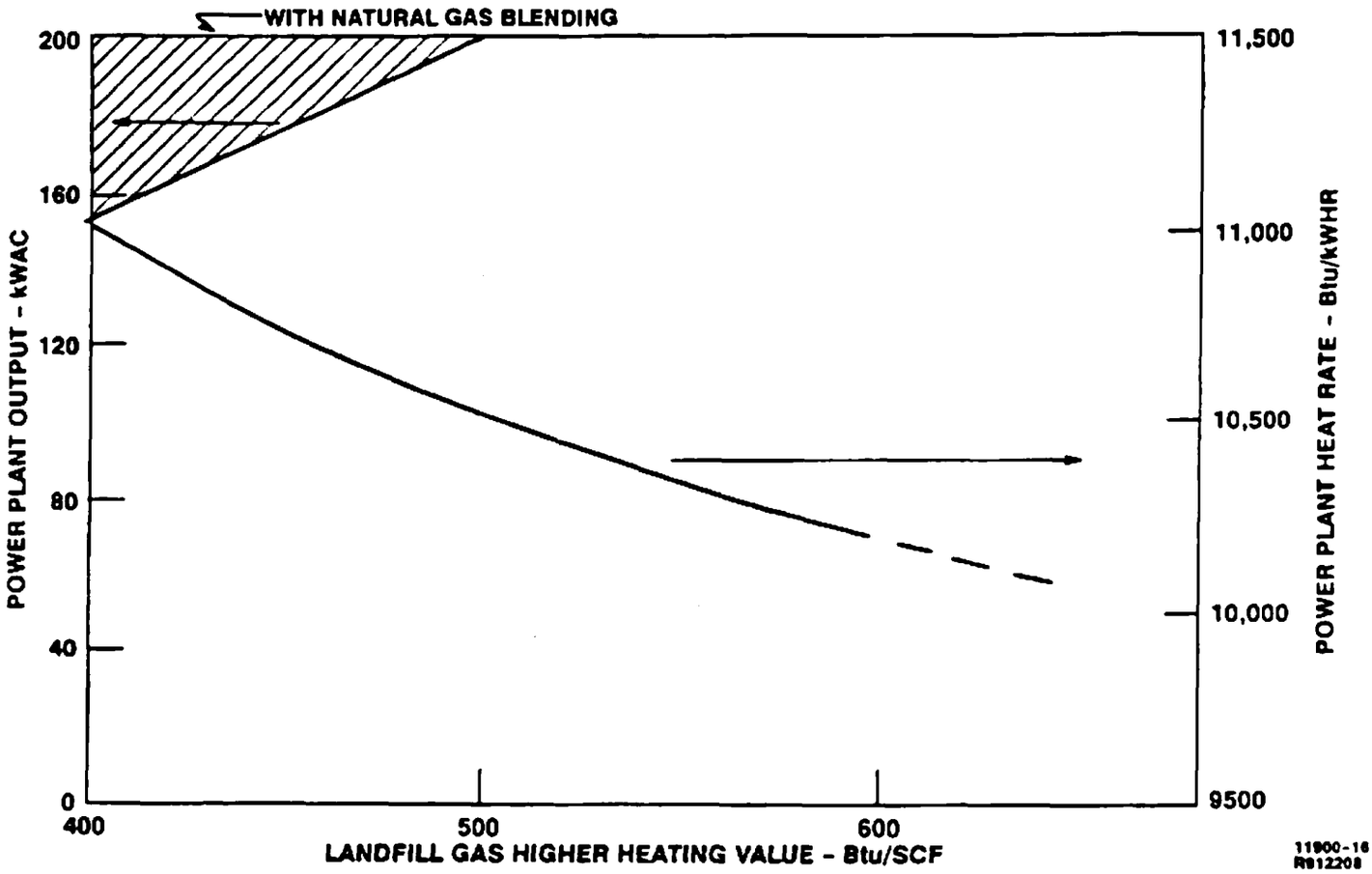

Figure 2.2-6. Impact of Landfill Gas Heating Value on Power Plant Power Output and Heat Rate

2.2.2 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 is selected. The site characteristics, shown in Table 2.2-5, assumed are the typical values discussed earlier. The site would produce approximately 434,000 standard cubic feet of landfill gas per day. The gas contains approximately 50 percent methane and has a gas heating value of 500 Btu per standard cubic foot.

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 2.2-5. Site Characteristics for Landfill Gas Assessment	
Landfill Gas Generation Rate	434,000 SCFD
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 ~ Btu/SCF	500

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 35.2 tons* per year of NO_x and 16.8 tons 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 severe environmental restrictions.

The environmental impact of application of the fuel cell concept to the potential market is shown in Table 2.2-6. The data show that both the flare and the fuel cell mitigate methane and NMOC, under the proposed standards and guidelines[2]. 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 2.2-6 Emissions Impact of Fuel Cell Energy Recovery from Landfill Gas

	Global Warming			Acid Rain and Health		
Abatement Technology	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

(*)1 ton = 907 kg

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.

The results of the analysis shown in Figure 2.2-7 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 2.2-7 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 ($2.92 per million Btu's). The value for the emission offset is $1000/ton 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 2.2-7. 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 $375 per million standard cubic fee of gas 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.

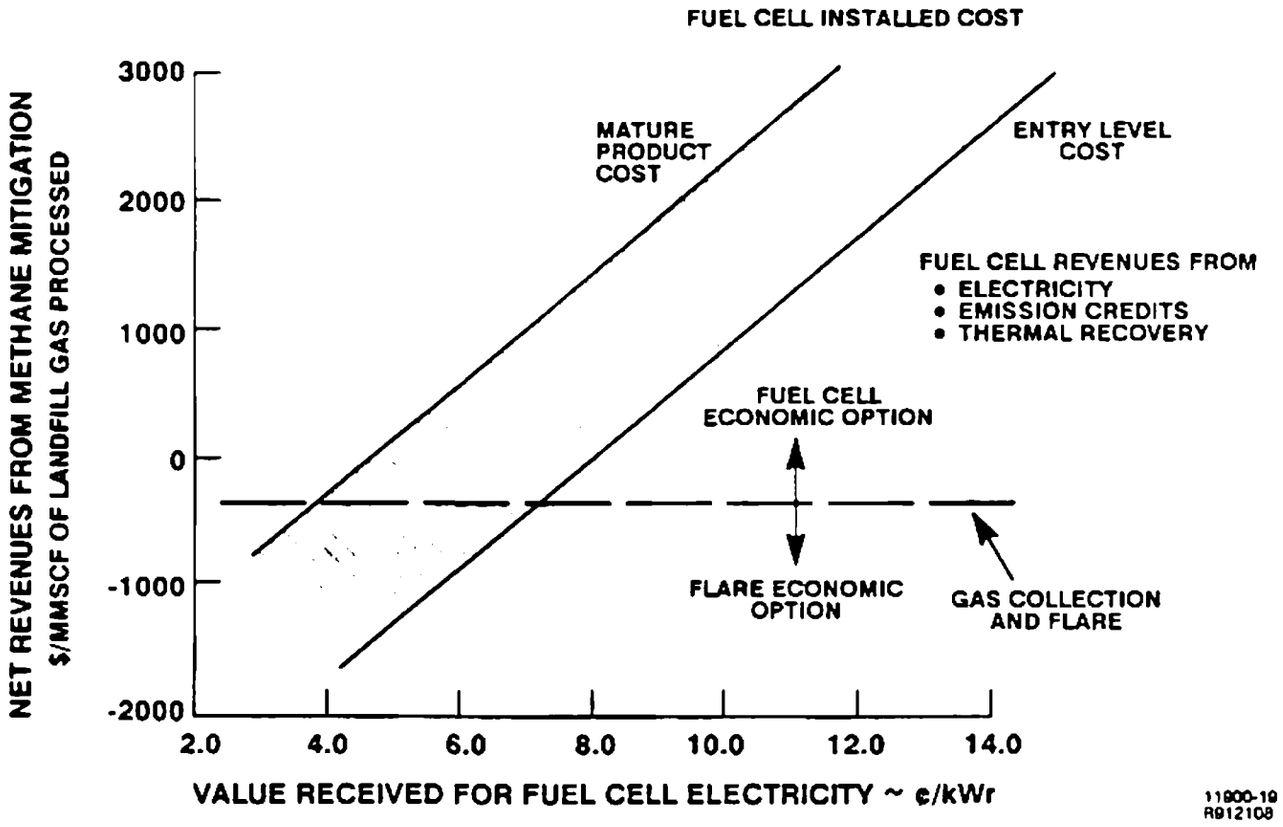

Figure 2.2-7. Comparison of Fuel Cell to Flare for Methane Mitigation Assuming Electric Revenues and Emission Credits

Figure 2.2-8 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 2.2-7.

Figure 2.2-9 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.

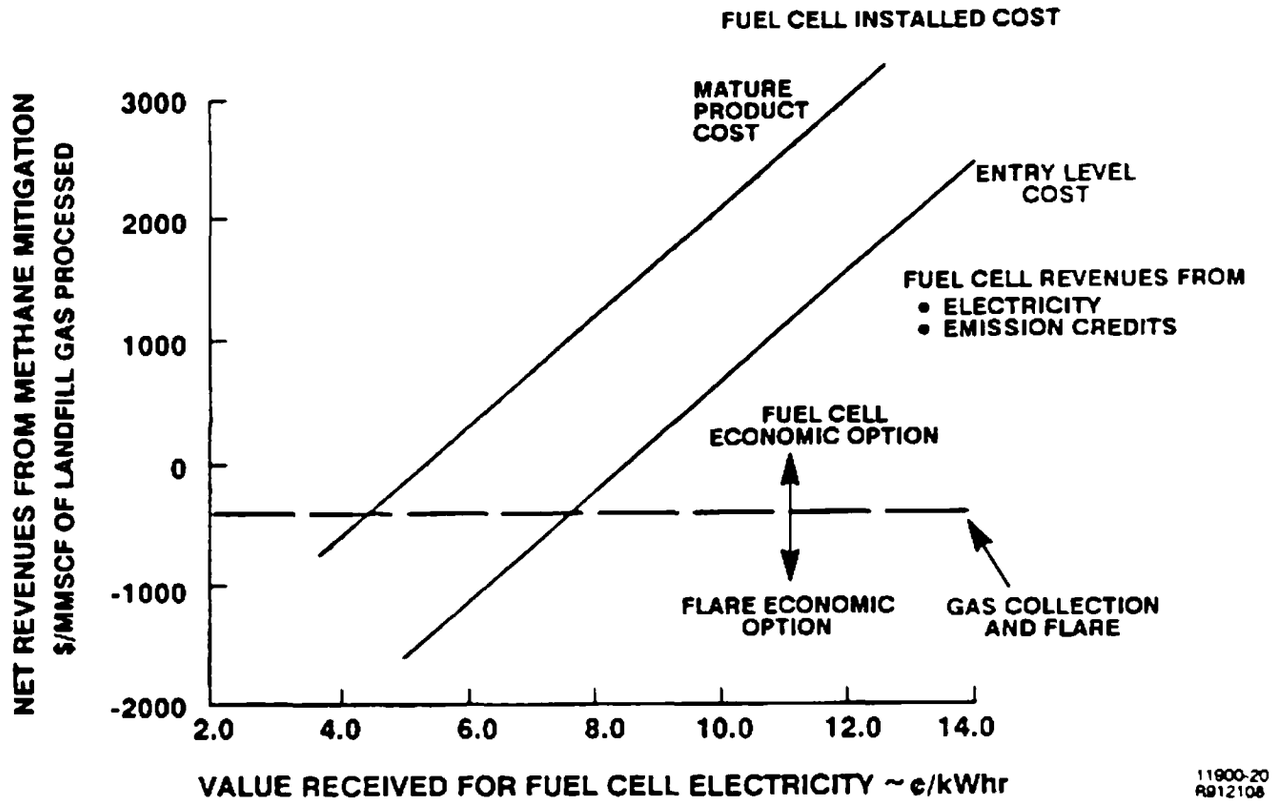

Figure 2.2-8. Comparison of Fuel Cell to Flare for Methane Mitigation Assuming Electric Revenues and Emission Credits

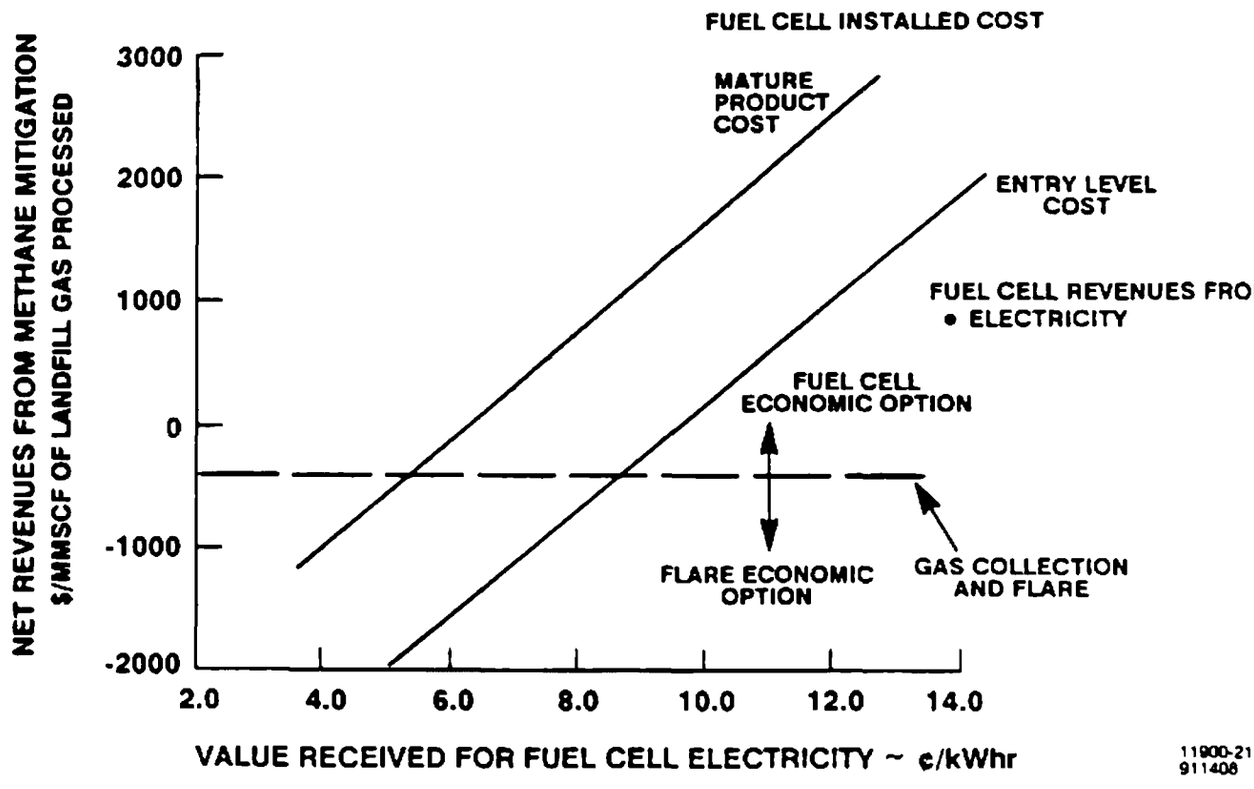

Figure 2.2-9. Comparison of Fuel Cell to Flare for Methane Mitigation Assuming Electric Revenues Only

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 2.2-10 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.

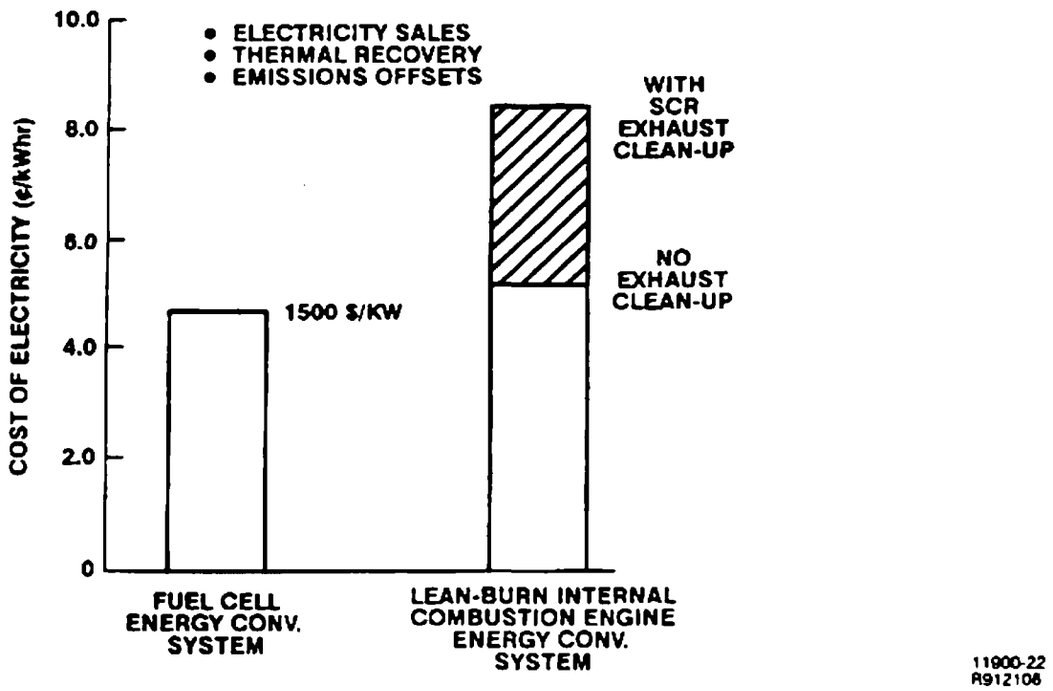

Figure 2.2-10. Comparison of Fuel Cell to Internal Combustion Engine Energy Conversion System

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.

2.2.3 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.

2.3 FUEL CELL LFG-TO-ENERGY SYSTEM DEMONSTRATION

This section describes the results of the Phase I program activity to define the fuel cell landfill-gas-to-energy system demonstration. This activity includes the conceptual design of the fuel cell landfill gas to energy system demonstrator which will be designed and tested in Phases II and III, the selection of a landfill site for the demonstration, determination of the site specific requirements affecting the demonstrator design including codes, permitting requirements, site gas composition and clean up requirements, and establishment of the Phase II demonstration plan. This plan addresses the milestones and timing of the site specific final design of the landfill gas pretreatment system, the natural gas power plant modifications to accommodate landfill gas operation, and testing of the demonstrator to address the key economic and emission issues. The overall objectives for this Phase I program are summarized in Table 2.3-1.

Table 2.3-1. Overall Demonstration Phase I Objectives

- DEFINE AN OVERALL PRETREATMENT SYSTEM CONCEPTUAL DESIGN AND PC25 FUEL CELL MODIFICATIONS WHICH WILL ADDRESS THE KEY MARKETING AND TECHNICAL ISSUES AND LOW EMISSIONS OF A LANDFILL GAS TO ENERGY FUEL CELL METHANE MITIGATION SYSTEM AT A TYPICAL LANDFILL GAS SITE.
- SELECT A LANDFILL SITE TO MEET DEMONSTRATOR OBJECTIVES.
- ESTABLISH A LANDFILL GAS PRETREATMENT SPECIFICATION AND SITE SPECIFIC REQUIREMENTS FOR THE DEMONSTRATOR PRETREATMENT SYSTEM DESIGN.
- ESTABLISH THE PHASE II DEMONSTRATION PLAN.

2.3.1 Conceptual Design for Demonstrator

This section describes the demonstrator system and selected site, the fuel cell modifications to achieve satisfactory power rating and efficient operation on landfill gas, the landfill gas pretreatment system specification, site specific requirements, and the conceptual landfill gas pretreatment system design.

The conceptual design of the commercial system established key issues and system features requiring demonstration. Table 2.3-2 outlines the objectives for the conceptual design of the landfill gas pretreatment system and fuel cell modifications to allow operation on landfill gas. Introduction of these objectives at this point provides an introduction to the scope of the activities covered in this section. These objectives are discussed in detail in the sections describing the pretreatment and fuel cell systems. Meeting these objectives will lead to a demonstration which verifies the feasibility of the commercial product landfill gas methane and NMOC mitigation system. Therefore, the demonstrator will validate the basic elements of IFC's commercial fuel cell landfill gas to energy product concept.

Table 2.3-2. Conceptual Design Demonstrator Objectives

FUEL PRETREATMENT SYSTEM OBJECTIVES

PRODUCE A PRETREATMENT SYSTEM DESIGN WHICH BY DEMONSTRATION WILL:

- MEET LANDFILL GAS PRETREATMENT SYSTEM COMPONENT SPECIFICATIONS AND SITE SPECIFIC REQUIREMENTS
  - PERMITTING AND CODE REQUIREMENTS
  - CONTAMINANT LIMITS (FUEL CELL SUPPLY GAS)
  - OPERATING REQUIREMENTS (FLOWS, PRESSURES, STARTUP, SHUTDOWN, ETC.)
  - EMISSIONS (NO_X, NMOC DESTRUCTION, LIQUID AND SOLID PRODUCTS)
  - LIFE (MATERIALS, COMPONENTS)
- DETERMINE TYPICAL PRETREATMENT SYSTEM EXIT TOTAL HALIDE LEVELS TO ENABLE SIZING OF THE FUEL CELL HALIDE GUARD FOR THE COMMERCIAL PRODUCT.

FUEL CELL SYSTEM OBJECTIVES

DEFINE FUEL CELL MODIFICATIONS WHICH BY DEMONSTRATION WILL:

- VERIFY FUEL CELL DEMONSTRATOR PERFORMANCE ON CLEAN LANDFILL GAS.
- DEMONSTRATE OPERATION OF FUEL CELL HALIDE GUARD.
- DEMONSTRATE LOW AIR EMISSIONS ON LANDFILL GAS (NO_X, CO, H/C).

2.3.1.1 Overall System and Site Description

Figure 2.3-1 provides a simplified description of the overall demonstrator fuel cell landfill-gas-to-energy system and site. The demonstrator consists of the landfill gas wells and collection system, a modular gas pretreatment system and a PC25 natural gas fuel cell power plant modified for landfill gas operation. Landfill gas collected at the site is processed to remove contaminants in the pretreatment system. This clean medium Btu landfill gas fuels the fuel cell power plant to produce ac power for sale to the electric utility and cogeneration heat which, for the demonstration, will be rejected by an air cooling module. A simplified process description of the landfill gas pretreatment and fuel cell systems is provided in Figure 2.3-2. All pretreatment and fuel cell process functions are described in this section.

The demonstration site has a landfill gas collection system in place. The Penrose site, whose selection is described in Section 2.3.2, will provide compressed 85 psig gas to the gas pretreatment system, the conceptual design of which is described in detail in Section 2.3.1.4. Since collection and compression result in some condensed water, hydrocarbon and contaminants products, the existing site also has a condensate collection and treatment system.

A slipstream of landfill gas from the site will be supplied to the demonstrator at a pressure of 85 psig,* and will be regulated down to 10 psig. A first stage refrigeration condenser (~33°F) removes most of the water contained in the saturated landfill gas and, based on Bio Gas Development experience, some of the more easily removed heavier hydrocarbon and contaminant species in the gas. In the commercial application, this condensate is vaporized and incinerated to avoid all site liquid effluents. However, to avoid the extra cost and complexity for the demonstration we decided to return this condensate to the existing site condensate treatment system.

(*) 1 psig = 6.89 kPa

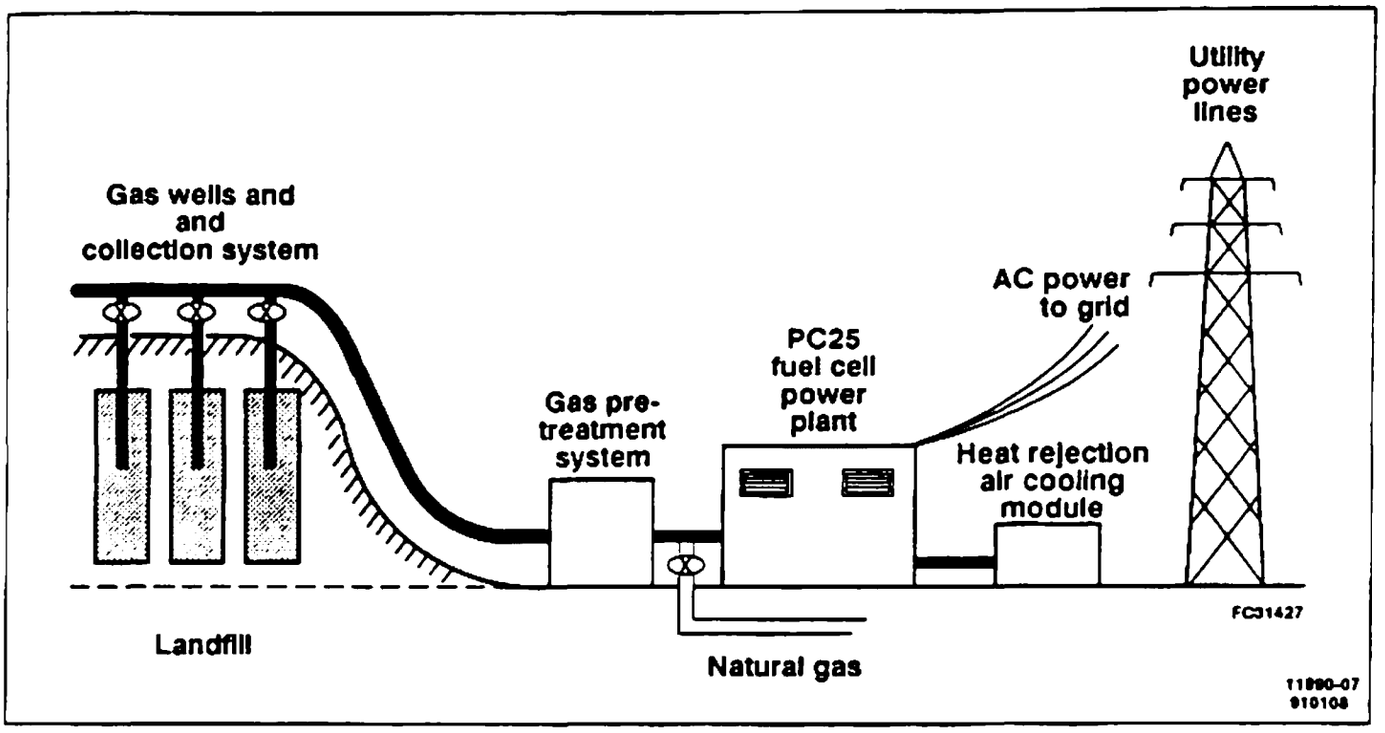

Figure 2.3-1. LFG Fuel Cell Demonstration Program

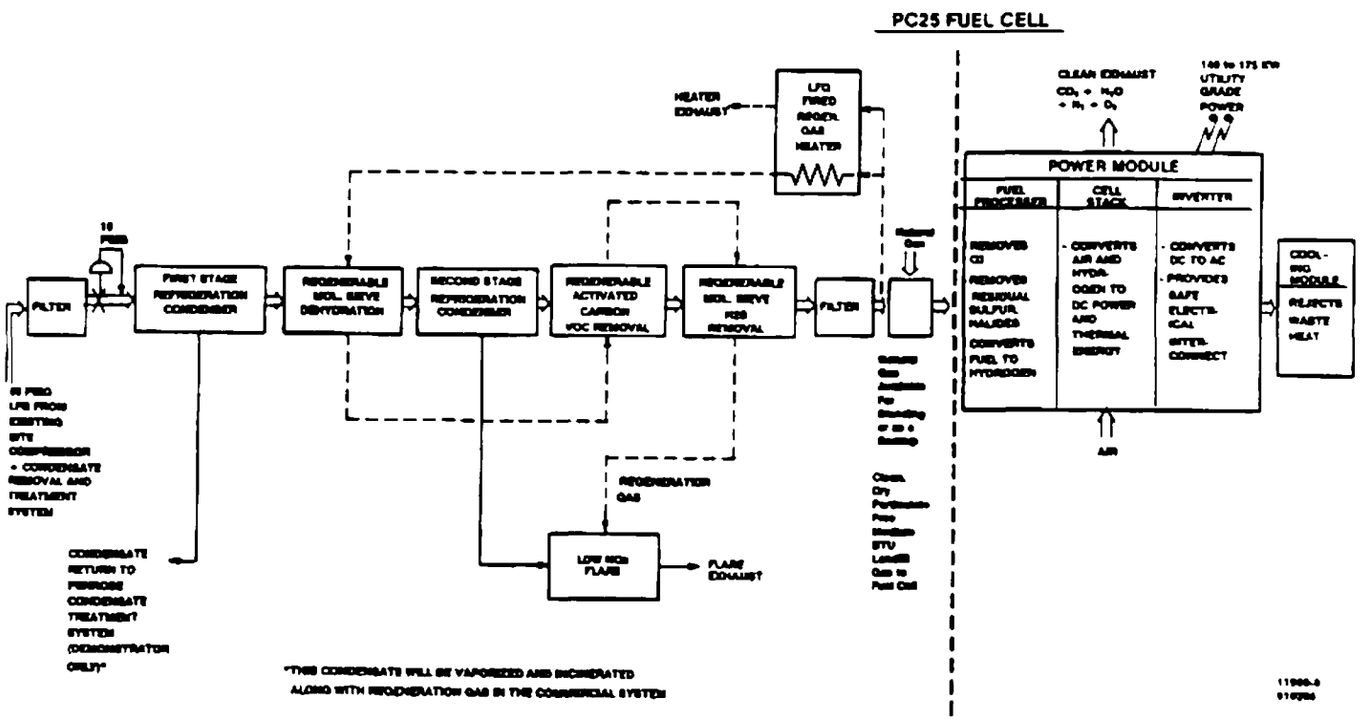

Figure 2.3-2. Demonstration Project Processes

Landfill gas exiting the first stage refrigeration condenser is then sent to a molecular sieve dehydration bed where the water content of the landfill gas is reduced to a -50°F dew point. This bed is periodically regenerated with heated clean landfill gas (heated by a separate clean LFG fired heater) to restore its dehydration function. During regeneration, a second fully regenerated bed takes over the function. The same gas is also used to regenerate two other beds, activated carbon for NMOC removal, and an H_2S-specific molecular sieve. The gas is subsequently incinerated in a low NO_x flare to destroy the NMOC's and combust the H_2S.

Following the molecular sieve dehydration step, the landfill gas proceeds to a second stage low temperature refrigeration condenser (-25°F) where, based on Bio Gas Development experience, additional high molecular weight NMOC species can be removed. The combination of first and second stage refrigeration condensers act as a bulk remover of NMOC species. This increases the flexibility of the pretreatment system to handle very high levels of landfill gas contaminants without need for modification or increasing the size of the regenerable adsorption beds. This makes the system an all-purpose LFG contaminant removal system. The effectiveness of the refrigeration condensate removal stages will be monitored during the pretreatment system acceptance test. A challenge test exposing the system to higher NMOC concentrations is being considered. The second stage refrigeration condenser also greatly enhances the operation of the downstream activated carbon NMOC adsorption and molecular sieve H_2S removal beds by reducing the gas temperature.

Next, the landfill gas proceeds to the activated carbon bed which adsorbs the remaining NMOC's including organic sulfur and halogen compounds. This is followed by a molecular sieve H_2S removal bed. The mol sieve for this bed will be selected and sized during the detail gas pretreatment system design in phase II, based upon literature and vendor capacity and selectivity data for H_2S versus CO_2. These beds are periodically regenerated as stated above with the regeneration gas being burned in a low NO_x flare. Second stage refrigeration condensate, which is easily vaporized, is incinerated along with the regeneration gas in the flare. The flare (an enclosed type) achieves greater than 98 percent destruction of all NMOC's by maintaining the combusted regeneration gas at a temperature of at least 1600°F for a residence time of at least one second.

In order to avoid the carryover of attrition products (dust) from the regenerable beds, the output gas is filtered through a submicron filter.. It is estimated that less than 20 lbs of attrited activated carbon and molecular sieve bed material will be collected by this filter over the one year demonstration period.

A clean, dry, particulate-free medium Btu landfill gas exits the filter for consumption in the fuel cell. A portion of this gas is extracted to provide regeneration gas. A backup natural gas supply is used to initially qualify the fuel cell power plant before operation on landfill gas. Natural gas is also available for blending with the landfill gas if needed to adjust the gas heating value for the demonstration test. It is estimated that approximately six percent natural gas blending will provide a heating value of 500 Btu/SCF (based on an average landfill gas heating value of 470 Btu/SCF on a dry basis).

Clean landfill gas is converted in the fuel cell power plant to ac power and heat. Details of the fuel cell preliminary design are described in Section 2.3.1.2. The general fuel cell system consists of three major subsystems - fuel processing, dc power generation in the fuel cell stack and dc to ac power conditioning by the inverter.

A halide guard will be added to the existing fuel processing system in the fuel cell power plant to scrub residual halides slipping by the pretreatment system. The addition of the halide guard to the fuel cell is an addition to the present capability of removing residual sulfur and any oxygen in the gas, and is significant because it simplifies the design of the pretreatment system. The added halide guard also

provides protection in the event of a system or site upset. The resulting fuel is steam reformed to produce hydrogen for the fuel cell stack.

The fuel cell converts hydrogen and the oxygen in air electrochemically to produce ac power and heat. The waste heat will be rejected by an air cooling module. The ac power will be transformed and delivered to the utility grid.

2.3.1.2 Fuel Cell System Preliminary Design

This section covers the modifications to the basic PC25 natural gas power plant to allow operation on clean medium Btu landfill gas. A photograph of the PC25 prototype power plant is shown in Figure 2.3-3. A functional schematic and listing of modification and improvement options to improve halide tolerance and increase rated power capability on landfill gas are provided in Table 2.3-3. These options will be reviewed in this section.

Table 2.3-3 identifies the changes to the 200 kW PC25 fuel cell power plant to allow operation and to increase rated power capability on landfill gas. Most of these changes are needed as a result of the lower heating value, higher gas density, and higher volumetric throughput and pressure drops associated with landfill compared to natural gas. The first three changes would only provide a capability of 80 kW on 500 Btu/SCF landfill gas compared to 200 kW on nominal Btu/SCF natural gas. An additional change of increasing the capacity of the inlet fuel controls increases the demonstrator power plant capability to 140 kW. These modifications can be made in the field, with minimum risk and cost following checkout and qualification of the fuel cell on natural gas. Changes 5 and 6 are required for 175 kW capability and require redesign of the fuel ejector and redesign of the burner fuel plumbing to reduce pressure drop. Changes 7 through 9 are more extensive and are required to achieve 200 kW capability. The changes to achieve 140 kW will be considered as the baseline, and the changes to achieve 175 kW will be carried as an option to be considered in Phase II of the program. If higher power levels above 175 kW are desired this could be accommodated in Phase III of the program by subsequent changes in additional fuel cell equipment

At a rating of 140 kW the heat rate of the PC25 fuel cell power plant operating on 500 Btu/SCF landfill gas is projected to be 10,200 Btu/kWh. Recoverable heat down to 160°F is estimated at 510,000 Btu/hr.

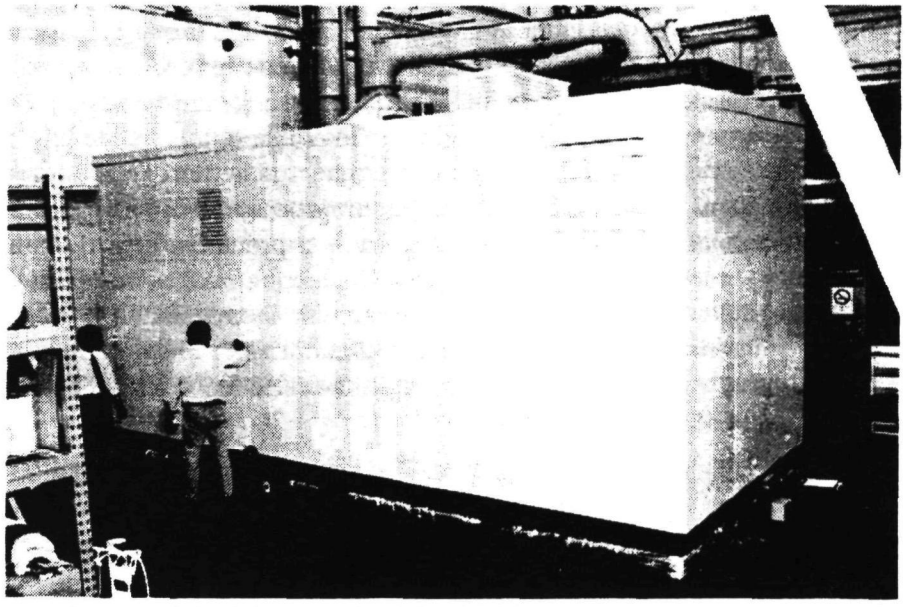

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Figure 2.3-3. Photograph of the PC25 Prototype Power Plant

Table 2.3-3. Improvements to PC25 Landfill Gas Power Plant

ACHIEVEMENT OF INCREASED RATED POWER CAPABILITY

140 kW

80 kW

1. MODIFY CONTROL SOFTWARE (SWITCH FROM NATURAL GAS TO HIGHER DENSITY, LOWER HEATING VALUE LFG)
2. CHANGE CATHODE EXIT ORIFICE (REDUCE PRESSURE DROP)
3. CHANGE FUEL PROCESSING SYSTEM RECYCLE ORIFICE (REDUCE PRESSURE DROP)
4. LARGER CAPACITY INLET FUEL CONTROLS (REDUCE PRESSURE DROP)

175 kW

5. HIGHER HEAD RISE EJECTOR (PUMP HIGHER DENSITY, LOWER HEATING VALUE LFG AND OVERCOME HIGHER PRESSURE DROP)
6. LOW PRESSURE DROP REFORMER BURNER FUEL INLET NOZZLE (REDUCE PRESSURE DROP)

200 kW

7. HIGHER HEAD RISE AIR BLOWER (OVERCOME INCREASED PRESSURE DROP)
8. LARGER ANODE EXIT NOZZLE AND PIPE (REDUCE PRESSURE DROP)
9. LARGER ANCILLARY COOLANT PUMP (INCREASING COOLING TO MAINTAIN 95°F DAY WATER RECOVERY CAPABILITY)

IMPROVED HALIDE TOLERANCE

10. ADD HALIDE GUARD TO LOW TEMPERATURE FUEL PREPROCESSOR (ALLOW HIGHER PRETREATMENT SYSTEM EXIT HALIDE SLIP TO REDUCE DEMANDS ON PRETREATMENT SYSTEM)

START UP ON LANDFILL GAS

11. MODIFY START BURNER (ALLOWS HEAT UP ON LOWER HEATING VALUE LFG - NOT REQUIRED FOR DEMONSTRATOR WHICH WILL USE NATURAL GAS FOR START BURNERS

Figure 2.3-4 demonstrates the impact of landfill gas halide level on PC25 fuel processor life. A pretreatment system would have to be designed to achieve total halide removal down to 0.15 ppm_v to ensure a one year fuel processor life. This does not include contingency for the possibility of upsets of the site, the collection system or pretreatment system. To mandate this halide level or lower would impose a severe complexity and cost burden on the pretreatment system. The addition of a conventional commercial halide guard bed to the existing fuel preprocessor will provide increased fuel processor protection. A commercial halide guard is typically a promoted activated alumina material which has a high affinity for hydrogen and halogens. Trace light halogen compounds such as vinyl chloride or freons, exiting the pretreatment system are readily hydrogenated to HCL and HF in the fuel preprocessor and absorbed on the commercial guard material down to low parts per billion levels in the gas. This same process has been validated in naphtha-fueled fuel cell power plants where organic chloride contamination of the fuel is a concern.

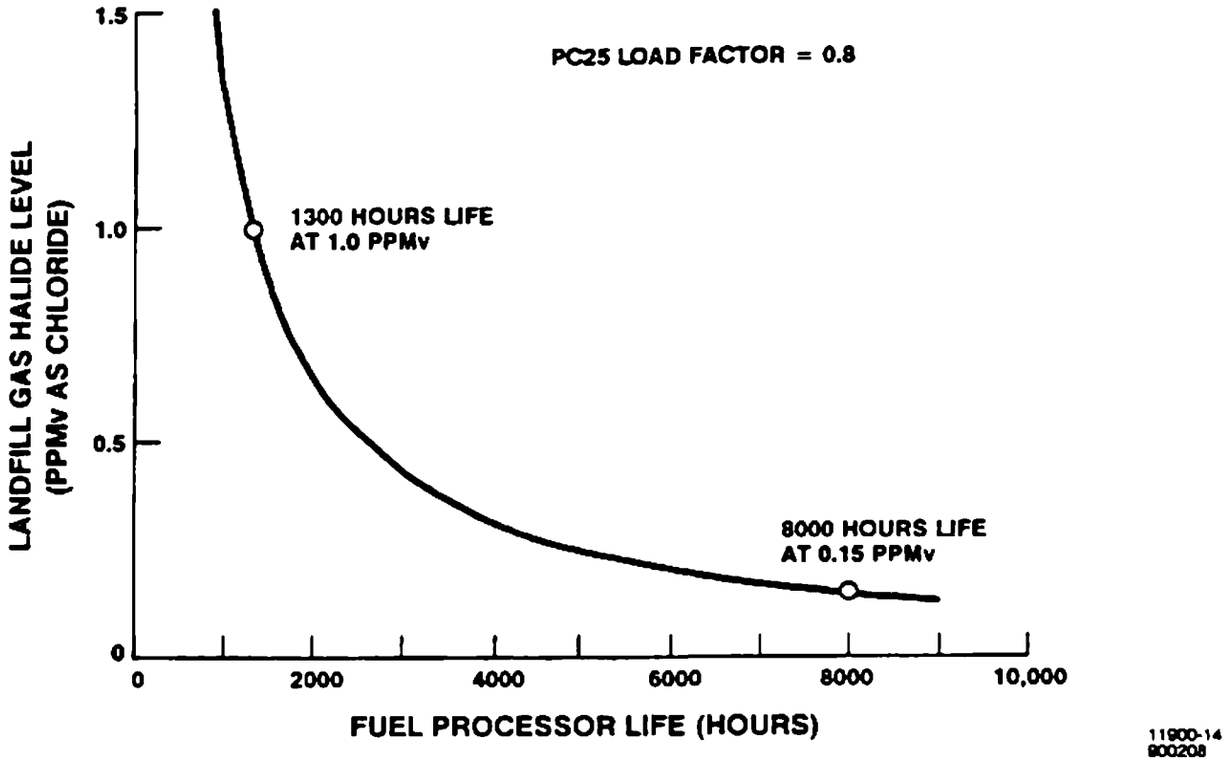

Figure 2.3-4. Fuel Processor Life vs. Landfill Halide Level

Halide protection can be accomplished by removing approximately 1/3 of the present sulfur absorption guard material (which is currently designed for 3 ppm_v average sulfur for 5 year life) and replacing it with sufficient halide guard material to remove 3 ppm_v halide from LFG for one year. This can be accomplished while leaving sufficient sulfur absorption capacity for the one year demonstration in Part III. Another option is to place a separate bed of halide guard material after the fuel preprocessor. Final selection of the best halide guard placement option will be decided in the Phase II Site Specific Design. If the pretreatment system is capable of achieving total halide levels below 0.5 ppm_v this same halide guard volume would protect the fuel processor for up to five years; this equals the fuel processor catalyst life for the commercial power plant. Conversely, at higher pretreatment halide exit levels a larger halide guard can be designed to provide longer life.

2.3.1.3 Landfill Gas Pretreatment System Specification and Site Specific Requirements

The landfill gas pretreatment system specification establishes the technical requirements for guiding the Bio-Gas Development Inc. pretreatment demonstrator design. The complete gas pretreatment system component specification (FCCS 5736) can be found in Appendix A. This specification includes applicable standards, state and local codes, all technical requirements, and quality assurance requirements. The technical requirements include output gas quality to the fuel cell, operating conditions including start-up/shutdown/normal operation, pressure regulation, contaminant disposal, life, permitting, design and construction, and documentation requirements.

The output gas requirements are summarized in Table 2.3-4. These requirements include allowable sulfur and halide limits, particulate levels, dew point and operating flows, and the pressure and temperature of the landfill gas supplied to the fuel cell. The allowable limits on total sulfur and halides provide a readily achievable requirement which should result in a lower cost commercial pretreatment system.

Table 2.3-4. Output Gas Requirements to Fuel Cell Power Plant			
	Minimum	Maximum	Units
Flow	0	5000	SCFH
Pressure	4	14	Inches of Water Column
Temperature	30	130	°F
Dew Point	—	20	°F
Total Sulfur	—	3	PPM_v
Total Halides	—	3	PPM_v
Particulates	—	Particulates removal of 100% at 1 micron or larger and 98% removal at 0.4 microns or larger	

Two final elements have been added. These include a summary of the local permitting requirements so that the pretreatment system can be permitted at the Penrose site with minimum difficulty and an expanded analysis of trace contaminants in the gas at Penrose for fine tuning the demonstrator pretreatment system preliminary design.

Table 2.3-5 lists the local permits presently required at the Penrose site. This list shows 30 permits which have been obtained from the South Coast Air Quality Management District, the City of Los Angeles, Los Angeles County, the State of California, and the U.S. EPA. In addition, a list of preliminary permit requirements is being developed based on the Bio-Gas pretreatment system preliminary design (See Section 2.3.1.4) including equipment, size and weight, interface requirements, utilities, and the expected gaseous, liquid and solid wastes anticipated to result from the demonstration. This list will be utilized to make contacts with various permitting agencies to define the final permitting requirements for this demonstration in Phase II.

Table 2.3-6 lists the range of landfill gas constituents at the Penrose site which can provide a number of optional gas mixtures from both Penrose and adjacent sites. Sulfur compounds, volatile priority pollutants including halogenated species, and major hydrocarbon species are listed. This tabulation is based on data taken recently at Penrose and adjacent sites (see Appendix B). A complete characterization of the landfill gas will be repeated for the pretreatment system acceptance test during Phase II using EPA and SCAQMD approved methods.

Table 2.3-5. List of Permits for Penrose Site				
Agency	Type of Permit	Permit Number	Object Permitted	Date Issued
SCAQMD (043535)	Air Pollution	155945	Cond. Accum.	7-18-88
SCAQMD	Air Pollution	156443	#1 Eng.	10-13-88
SCAQMD	Air Pollution	158444	#2 Eng.	10-13-88
SCAQMD	Air Pollution	158445	#3 Eng.	10-13-88
SCAQMD	Air Pollution	156446	#4 Eng.	10-13-88
SCAQMD	Air Pollution	156447	#5 Eng.	10-13-88
SCAQMD	Air Pollution	156448	#6 Eng.	10-13-88
SCAQMD	Air Pollution	155951	#1 Flare	
SCAQMD	Air Pollution	155950	#2 Flare	
SCAQMD	Air Pollution	155849	#3 Flare	
SCAQMD	Air Pollution	155948	#4 Flare	
SCAQMD	Air Pollution	155947	#5 Flare	
SCAQMD	Air Pollution	161452	Cool. Ywr.	
SCAQMD	Air Pollution	152625	Gas Chill.	
SCAQMD	Air Pollution	155946	Used Oil Tnk.	
LA City	Ind. Safety	A-76778	Air Tank	8-1-86
LA City	Ind. Safety	A-77143	Air Tank	7-10-86
LA City	Ind. Safety	A-77144	Air Tank	7-10-85
LA City	Industrial Waste	W-441246	Ind. Waste	1-1-85
LA City	Occ. Cart.	LA08723/85	Facility	6-30-86
LA City	Fire Dept.	66024	Vapor Rec. Sys.	5-8-90
LA City	Fire Dept.	66025	Vapor Rec. Sys.	5-8-90
LA County	Fire Dept.		Haz. Materials	11-1-89
LA City	Public Health Lic.	509222	Haz. Waste	2-2-89
LA City	Fire Dept.	558299-25	Haz. Material	8-24-87
LA City	Fire Dept.	66024	Industrial Processing System	
LA City	Fire Dept.	66025	Industrial Processing System	
State of Calif.	Bd. Equalization	HYHQ36-0202150005		
EPA	Haz Waste Gen. ID#	CAD 981 460 892		

Table 2.3-6. Range of LFG Constituents at Penrose	
Sulfur (ppm_v)	
H_2S	103.0
Methyl Mercaptan	3.0
Ethyl Mercaptan	0.5
Dimethyl Sulfide	8.0
Dimethyl Disulfide	0.02
Carbonyl Sulfide	< 0.5
Carbon Disulfide	< 0.5
Total Sulfur, as H_2S (ppm_v)	114.5
Volatile Priority Pollutants (ppm_v)	
Dichloroethene	0–33
Dichloroethane	0–0.25
Benzene	0.4–2.0
Chlorobenzene	0.1–1.0
Ethylbenzene	3.5–13.0
Methylene Chloride	0–12.0
Styrene	0–0.5
Trichloroethene	0.6–2.8
Trichlorofluoromethane	0–0.6
Toluene	4.7–35.0
Tetrachloroethene	1.0–6.3
Vinyl Chloride	0.4–1.4
Xylene Isomers	6.9–22.0
CIS–1, 2–Dichloroethane	4.1–5.1
Major Hydrocarbon Species (vol %, dry)	
Methane	41–48
Ethane	0
Propane	0
Isobutane	0–0.01 (100 ppm_v)
N–Butane	0
Isopentane	0–0.097 (970 ppm_v)
N–Pentane	0–0.018 (180 ppm_v)
Hexanes	0.0040–0.039 (390 ppm_v)
Total Chloride as CL (ppm_v)	**14.5–67.1**
Total Volatile Priority Pollutants (ppm_v)	**21.7–105.3**

2.3.1.4 Gas Pretreatment Conceptual Design

This section covers the specific details of Bio Gas Development Inc. conceptual design of the landfill gas pretreater for the demonstrator. The conceptual design is based on the requirements set forth in the landfill gas pretreatment system specification and on the experience gained with the commercial landfill gas cleanup system designed for the 12 MW Johnston, R.I. landfill site. The demonstrator design (and future commercial designs) incorporate improvements which will minimize liquid and solid wastes and provide enhanced capability for handling a wide range of varying contaminant concentrations at different landfills.

Figure 2.3-5 shows the features of the Johnston, R.I. landfill gas cleanup system. Table 2.3-7 lists the full range of improvements that would be incorporated in going from the R.I. cleanup system to a commercial concept pretreatment system to the pretreatment system for the demonstrator. Changes from the R.I. system will include reducing the scale of process flow from 12 MW to a nominal 200 kW, and reducing operating pressure from 60 psig to 7 psig to minimize landfill gas pumping parasite power.

The sources of solid waste products in the R.I. system will be eliminated. The non-regenerable zinc oxide and permanganate beds are being replaced with regenerable molecular sieve beds.

A very significant change is the addition of two landfill gas refrigeration and condensing stages to significantly reduce water and heavy NMOC loading on the regenerable desiccant and activated carbon beds. The second colder condensing stage is a proprietary process which not only allows the activated carbon and H_2S removal regenerable beds to be operated at a low temperature to optimize their performance but also provides a means to reduce the concentration of high molecular weight compounds such as siloxanes which are not removed in the first condensing unit. Total parasite power of the commercial pretreatment system including the landfill gas blower and the two refrigeration stages is estimated to be about two percent of the fuel cell net power.

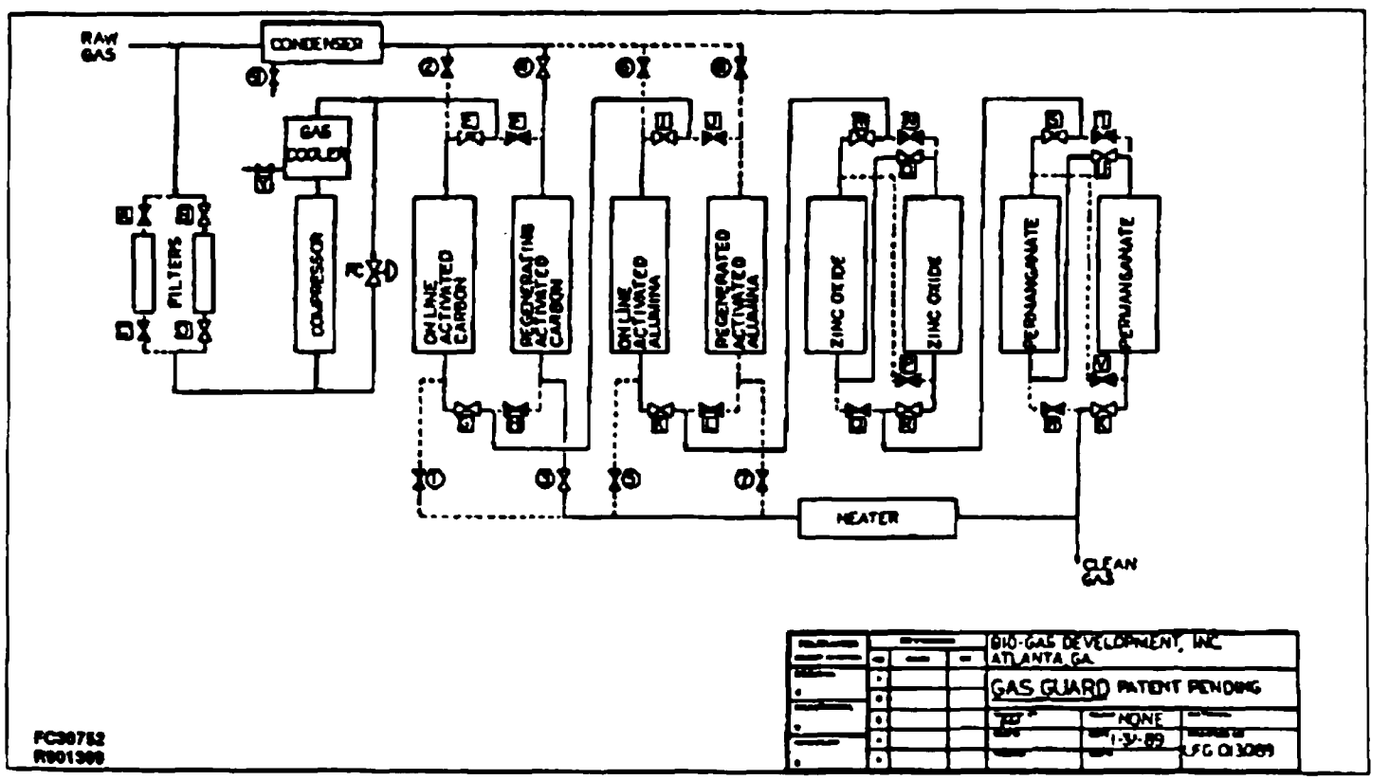

Figure 2.3-5. Commercial Landfill Gas Cleanup in Rhode Island

TABLE 2.3-7. PRETREATMENT SYSTEM MODIFICATIONS

COMMERCIAL CONCEPT

- SCALE FROM 12 MW TO 800 KW.
- REDUCE DESIGN PRESSURE FROM 60 PSIG TO 7 PSIG NOMINAL.
- ELIMINATE CONDENSING AND STORAGE OF ALL DESORBED CONTAMINANTS. ADD LOW NO_X INCINERATION OF ALL DESORBED CONTAMINANTS, AND VAPORIZE AND INCINERATE ALL LIQUID PRODUCTS.
- ELIMINATE NON REGENERABLE (SOLID WASTE) ABSORBENT ZINC OXIDE AND PERMANGANATE BEDS AND ADD REGENERABLE MOLECULAR SIEVE H_2S REMOVAL BEDS.
- ADD TWO LFG REFRIGERATION AND CONDENSING STAGES TO ENHANCE WATER, VOC, HALIDE AND SILICON COMPOUND REMOVAL.
- INTEGRATE INCINERATOR AND REGENERATION GAS HEATER FUNCTIONS. RECOVER HEAT FROM INCINERATOR.

DEMONSTRATOR

- RETURN WATER AND HYDROCARBON CONDENSATE (99.5%/H_2O) FROM FIRST STAGE REFRIGERATION CONDENSER TO EXISTING SITE LANDFILL GAS COMPRESSOR AND COOLING CONDENSATE TREATMENT SYSTEM TO ELIMINATE NEED FOR REVAPORIZATION HEAT RECOVERY UNIT.
- UTILIZE SEPARATE LOW NOx FLARE AND CLEAN LANDFILL GAS FIRED REGENERATION GAS HEATER.

Overall thermal efficiency of the commercial pretreatment system will be enhanced by using a heat recovery unit to extract heat from the incineration exhaust and provide energy for preheating of regeneration gas and vaporizing liquid refrigeration condenser products. It is estimated that the thermal efficiency of the commercial version of the pretreatment system (heating value of gas delivered to the fuel cell vs. heating value of raw landfill gas supplied to the pretreater will be approximately 92%). About 8 to 16 percent of the clean landfill gas processed by the pretreater will be used for regeneration and will provide by incineration the energy for regeneration gas preheating and condensate vaporization.

The smaller nominal 200 kW demonstrator pretreatment system incorporates all of the major features of a commercial system except in those areas where it is expedient to simplify the design to reduce the cost of the demonstrator without sacrificing verification of critical features of the commercial system. Table 2.3-7 lists these simplifications which eliminate the need to incorporate an integrated incinerator and heat recovery unit, allowing the use of a smaller enclosed low NOx ground flare. Figure 2.3-6 shows a process flow diagram of the demonstrator landfill gas pretreatment system. Since the Penrose site has an existing and permitted condensate collection and pretreatment system, this will be used to treat the condensate from the first refrigeration condenser only (the smaller condensate from the second condenser is easily vaporized and will be incinerated in the flare). The use of a separate landfill gas fired heater to heat regeneration gas rather than energy recovery will result in a lower pretreatment thermal efficiency than in the commercial system. Specific design details and performance of the demonstrator pretreatment system design are discussed later in this section. The resultant system is de-

signed to meet the requirements of the pretreatment specification and should allow through its actual demonstration, verification of the design and meeting of the key objectives of this program.

The pretreatment system is a demand system providing a regulated supply of clean landfill gas of up to 5000 SCFH (120,000 SCFD) at 4 to 14 in. H_2O to the fuel cell. A continuous and uninterrupted gas supply is guaranteed by completing the required regeneration of the beds in a shorter time (approximately 7 hours) than the adsorption cycle (approximately 8 hours). This allows the adsorbing bed and the freshly regenerated bed to be put on line in parallel flow (adsorption mode) prior to switch over and beginning the regeneration of the depleted adsorbing bed. Pretreatment system operating supply pressure is sufficient to overcome all system pressure drops in the pretreatment system ensuring an adequate gas supply to the fuel cell. The pretreatment system supply pressure is approximately 10 psig. This would be reduced by further optimization to seven psig in the commercial version.

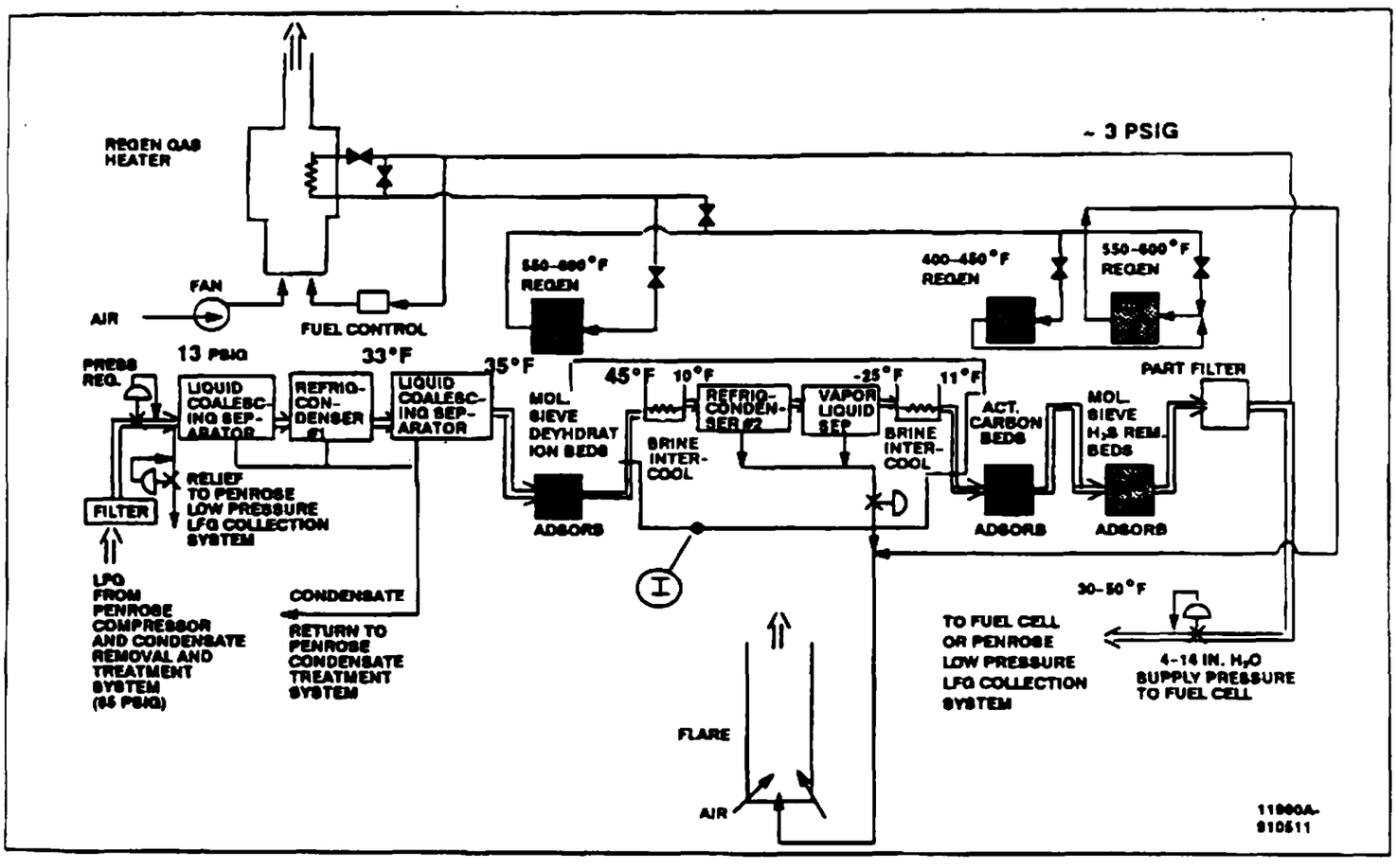

Figure 2.3-6. Demonstrator LFG Pretreatment System

A dew point of approximately -50°F is achieved in the gas by means of the first refrigeration condenser and regenerable molecular sieve dehydration bed. The condenser also reduces the water loading in the dehydration bed increasing overall effectiveness and minimizing dehydration bed size. The combined action of the two condensing stages in removing the bulk of the NMOC's and the substantial reduction in temperature makes the activated carbon bed an effective polishing bed for minimizing halides and organic sulfur compounds. Effectiveness of the molecular sieve H_2S removal bed is also enhanced greatly by its low operating temperature to ensure that the specification allowable contaminant levels for sulfur will not be exceeded. A final particulate filter ensures the meeting of specification particulate limits. Lastly, heating by ambient air will increase the temperature of the clean landfill gas supplied to the fuel cell to within specification limits.

Although incineration of pretreatment by-products will be combined with heat recovery in a commercial system, a separate enclosed flare and regeneration gas heater will be used in the demonstrator. The flare will be designed for low NOx meeting South Coast design specifications. It will also be designed to preclude dioxin formation and have a destruction efficiency consistent with South Coast design specifications.

Bio-Gas Development Inc. has completed a conceptual design of the demonstrator landfill gas pretreatment system. They provided: a P&ID drawing showing all process, valving instrumentation and safety equipment; a system mass balance describing process temperatures, pressures, major and contaminant species; heat balances at major process steps; process calculations; and an equipment list including all major process components, valves, and instrumentation including qualified manufacturers, materials of construction and size where applicable.

The overall pretreatment package would consist of a skid-mounted modular assembly approximately ten feet * in length by eight feet in width by nine feet in height weighing approximately 10,000 lbs. ** An enclosed flare, approximately two feet in diameter by 18 feet in height above ground, would be shipped horizontally and erected as part of the pretreatment package at the site. All equipment is self contained and is readily accessible for inspection and maintenance as required.

The pretreatment system will be installed at the site and receive raw landfill gas from the existing Penrose supply. This gas has been filtered and undergone compression and cooling to 80–100°F (and the removal of condensate). The supply feeds both the existing internal combustion engines at Penrose and the fuel cell demonstrator at the site. This compares with a commercial version of this system where landfill gas would be collected, undergo some condensate removal, be filtered and compressed to about seven psig by a blower, and supplied to the pretreatment fuel cell system. The landfill gas is regulated to the pretreatment system inlet pressure of 10 PSIG (13 psig maximum working pressure). Pressure losses in the pretreater lower the pressure to about three psig where it is then regulated to the fuel cell supply pressure of 4–14 inches H_2O gage.

The system consists of seven major subsystems:

1. First stage refrigeration condenser and condensate removal.
2. Molecular sieve dehydration regenerable beds.
3. Second stage refrigeration condenser.
4. Activated carbon hydrocarbon and NMOC polisher regenerable beds, H_2S removal molecular sieve regenerable beds, and particulate filter.
5. Regeneration gas heater and regeneration valving subsystem.
6. Enclosed flare.
7. Refrigeration system to provide coolant to condensers.

The first refrigeration condenser consists principally of a liquid coalescing separator for removing condensate which may be formed during expansion of the inlet raw landfill gas from 85 psig to 10 psig, the first stage refrigeration condenser and another coalescing separator for removing condensate entrained in the gas leaving the condenser. Water and hydrocarbon removed from these devices is collected in a condensate blowdown tank for transfer to the existing Penrose condensate collection and treatment system. Also included in the subsystem is a cold brine circulation loop which rejects heat from the condenser to the refrigeration subsystem.

(*) 1 ft = 0.3 m
(**) 1 lb = 0.45 kg

The molecular sieve dehydration beds remove the remaining water in the gas to less than -50°F dew point and protect downstream equipment from freezing. Removal of water by condensation in the first stage condenser reduces the water loading on this molecular sieve allowing the design of a smaller bed.

The second stage refrigeration condenser subsystem together with the first stage condenser, removes many of the heavy NMOC's from the landfill gas and enhances the capability of the overall system to remove difficult light halogenated species and silicon compounds. Also included in this subsystem is a cold brine loop which rejects heat from the condenser to the refrigeration subsystem.

The remaining low temperature dry process units, the regenerable activated carbon beds, the regenerable molecular sieve beds and the particulate filter complete the gas cleanup process by respectively polishing the remaining NMOC's including organic sulfur and halogen compounds, removing H_2S, and preventing fine and attritted material from these beds from reaching the fuel cell. Total sulfur as H_2S exiting the pretreatment system is estimated to be less than 3 ppm_v. Total halide, as chloride, is estimated to be negligible exiting the activated carbon bed (approximately 5 ppm_v entering the bed). These values are all subject to verification in Phase II of this demonstration program.

Final sizing and selection of specific adsorbent bed materials will be made in the Phase II demonstrator pretreatment final design process. Final bed sizing, bed material selection, adsorption and regeneration cycle length will be based on vendor calculations (plus a factor of safety) for the specific adsorbent material heat capacity and properties and the specific environmental working conditions during the adsorption and regeneration cycles. One specific issue that has been raised is the interference of CO_2 in the H_2S removal molecular sieve. Vendor experience will be used in the selection and sizing of the molecular sieve to minimize potential interference and to calculate the required molecular sieve bed volume to compensate for any interference. The allowable fuel cell sulfur specification of 3 ppmV also allows for a significant sulfur slip from the pretreatment system to ease the requirements placed on the molecular sieve bed. Verification of adsorbent bed effectiveness will be done by gas analysis during the Phase II pretreatment system acceptance testing. A challenge test exposing the beds to higher than usual contaminant levels and an extended cycle test to determine potential breakthrough (or lack thereof) of specific contaminants is being considered.

Regeneration of the molecular sieve dehydration beds, activated carbon beds and H_2S removal molecular sieve beds is achieved by diverting approximate 16 percent of the clean landfill gas counterflow and in series through these respective beds. A preliminary staged regeneration sequence was described earlier in Section 2.2.1, Figure 2.2-3. Sample calculations of bed regeneration thermal requirements and heat balances are provided in Appendix C. In the larger commercial fuel cell version only about eight percent of the clean landfill gas will be required for regeneration. During the first half of the regeneration period (approximately four hours), this regeneration gas is heated by the regeneration gas heater to approximately 550°F to heat up and regenerate the beds. The regeneration gas heater is fired with one percent of the clean landfill gas during this period. As the beds successively reach their desired regeneration temperature, the regeneration gas flow can be bypassed around that bed so as not to overheat the bed. For the next four hours, the regeneration gas heater is bypassed (heater also turned off) to cool the adsorbent beds. Following cooldown, the freshly regenerated beds are slowly brought back to operating pressure (equalized) by opening small bleed valves between each bed and its twin adsorbing bed. Both beds are operated in parallel flow for a few minutes before beginning the regeneration cycle on the depleted adsorbent bed which will have been in the adsorbing mode for about eight hours. The timing and sequencing of all pneumatically activated valves is controlled by a programmable computer which provides high flexibility in fine tuning and adjusting the system.

Regeneration gas and vaporized condensate from the second stage refrigeration system is burned in an enclosed flare. The flare is rated at greater than 99 percent NMOC destruction efficiency.

Cooling of the first and second stage refrigeration condensers is provided by a single refrigeration system which removes heat from the cold brine loops in the first and second stage condenser subsystems. Total power requirement of the pretreatment system including the refrigeration compressor is estimated at about 6 kW or about three percent of a nominal 200-kW fuel cell. This compares with about a two percent parasite load projected for an optimized 800 kW commercial landfill gas to energy fuel cell system.

The remainder of the Bio-Gas landfill pretreatment system details provide for manual startup of the unit, automatic monitoring of unattended operation, both manual and automatic shutdown in response to out of limits pressure and temperature conditions and safety systems including pressure reliefs to protect the system from over pressure (13 psig maximum working pressure).

Early in Phase II of the program, a specific pretreatment system checkout, commissioning and verification test program will be developed to document pretreatment system performance later in Phase II including contaminant removal and air emissions. A challenge test will be devised to verify pretreatment system performance at higher raw landfill gas contaminant levels. It is envisioned, at this time, that this challenge test will consist of subjecting the pretreatment unit to increased levels of a known light easily handled, but difficult to remove, halogenated freon compound.

2.3.1.5 Overall Demonstrator Performance

This section presents a preliminary prediction of the overall performance of the demonstrator landfill-gas-to-energy fuel cell conversion system. The case selected is for a net fuel cell output of 140 kW. The raw landfill gas flows have been scaled to be consistent with the lower fuel cell demand of 69,000 SCFD of clean gas. Regeneration gas flows are based on 16 percent of the landfill gas flow for regeneration gas and one percent for regeneration gas heating.

Figure 2.3-7 summarizes the estimated overall performance of the demonstrator including raw landfill gas input flows based on a 500 Btu/SCF methane, CO_2 mixture and 1745 ppm NMOC's which is the maximum possible contaminant level at the Penrose site, net electrical output, available thermal energy, pretreatment and fuel cell exhaust flows and air, liquid and solid effluents. Overall performance is similar to a scaled down version of the commercial system presented in Section 2.2. Very low air emissions and solid products are generated as in the commercial system. No sulfur or halide solid products are handled on site since all bed refurbishment is done at the factory as discussed earlier in this section. The only exception to the commercial system is the return of the pretreatment first stage refrigeration condenser liquid products (mostly water) to the existing Penrose condensate treatment system.

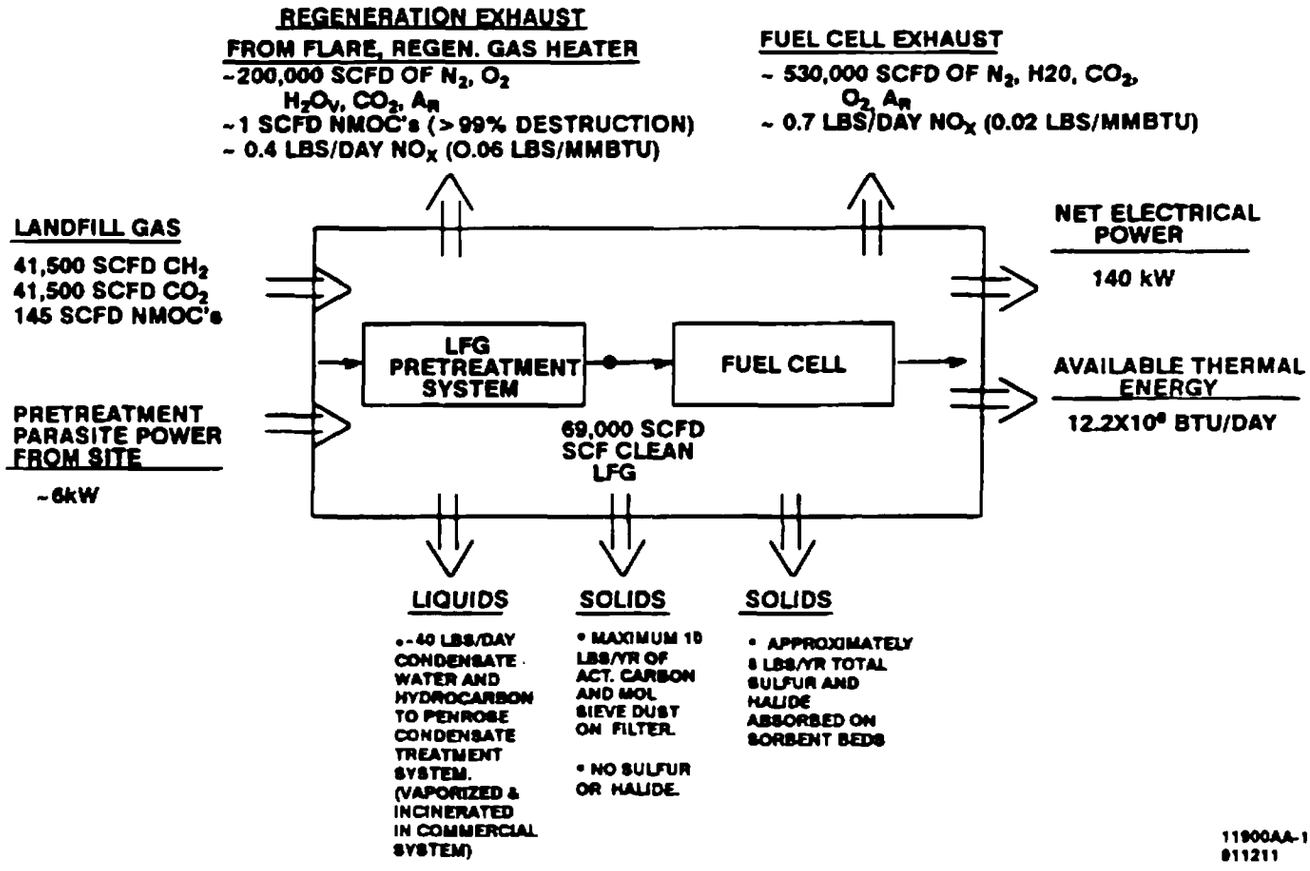

Figure 2.3-7. Overall Performance Estimate for Demonstrator Fuel Cell Landfill Gas To Energy Conversion System (1 Year Demonstration)

2.3.2 SELECT LANDFILL SITE TO MEET DEMO OBJECTIVES

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.

2.3.2.1 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 1992 and the fuel cell demonstration in 1993.

2.3.2.2 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 2.3-8. 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 2.3-9 and 2.3-10 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.

Table 2.3-8. 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 2.3-9. Assessment of Candidate Sites vs. Evaluation Criteria

ASSESSEMENT OF CANDIDATE SITES
VS.
EVALUATION CRITERIA

	TYPICAL USA	PENROSE	TOYON	OAKLAND	OTAY
I. SELECT SITE REPRESENTATIVE OF U.S. LANDFILLS SO DEMONSTRATION WILL BE RELEVANT TO A LARGE PORTION OF THE U.S. MARKET (COMPARE LANDFILL TO RANKS FOR U.S. LANDFILLS).					
• Gas Heat Content (BTU/FT^3 HHV)	500 BTU/ft^3	440	470-550	550-670	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%	38%	43%
• Gas Contaminants					
• Total NMOC (PPM)	274	130-474	35-130	36 - 60	Not Available
• Total Sulfur (PPM)	21	150	14-24	Not Available	27-63
• Total Halides (PPM)	132	78-86	7-68	Not Available	Not Available
• Local codes and regulations - is demonstration at this site likely to be accepted at other local sites (yes/no)?		Yes	Yes	Yes	Yes
• Name of local regulatory agency		SCAQMD	SCAQMD	Ventura APCD	San Diego APCD
• Geographic/market potential - is demonstration 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	2.7 MW	1.8 MW
II. SUITABILITY OF SITE FOR DEMONSTRATION TEST					
• Multiple Landfill Gas Sources		Yes	No	Yes	No
• Site, set-up for LFG-to-energy?		Yes	Yes	Yes	Yes
• Collection system in-place (yes/no)		Yes	Yes	Yes	Yes
• Gas compressed (yes/no)		Yes	Yes	Yes	Yes
• Permits in place (yes/no)		Yes	Yes	Yes	Yes
• Power equipment in place (yes/no)		Yes	Yes	Yes	Yes
• Space available for demonstration (yes/no)		Yes	Yes	Yes	Yes
• Excess Gas availability for demonstration (at least 84 SCFM)		Yes	No	Yes	Yes
• Natural Gas Service Available		Yes	Yes	No	No
• Opportunity to Demonstrate Thermal Utilization (NOTE: Note 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 Equipment		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		4 Closed	1 Closed	2 Closed 1 Open	1 Open

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Table 2.3-10. 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)

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 84 SCFM 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.

2.3.2.3 Description of Selected Site

A detailed description of the selected site is given in Figures 2.3-8 and 2.3-9. 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.

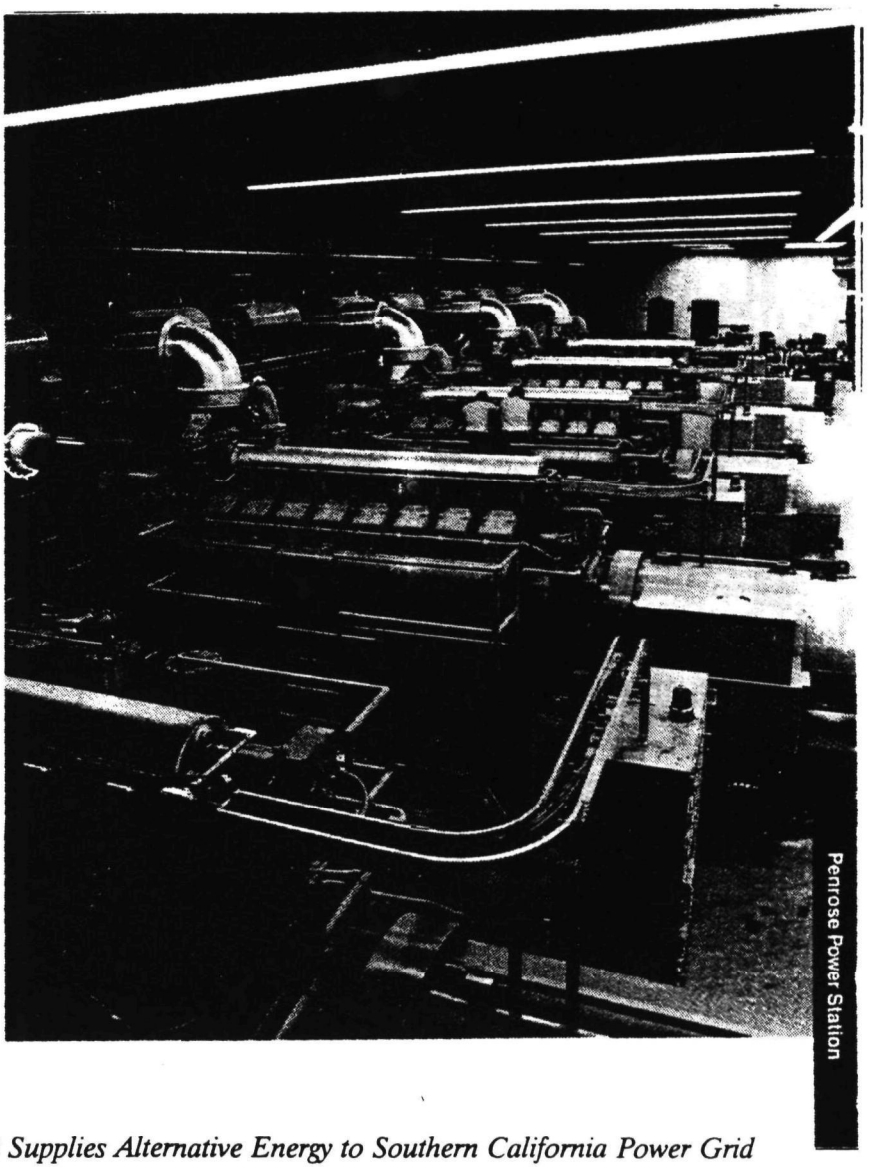
Figure 2.3-10 shows an aerial photograph of the Penrose Station which is located off Tujunga Avenue along the edge of the Penrose landfill. Site potential locations for the demonstration are identified on the aerial photograph. The relative merits of these will be assessed early in Phase II, prior to making a final selection.

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 2.3-8. Penrose Plant Supplies Alternative Energy to Southern California Power Grid
(Courtesy of Pacific Energy)

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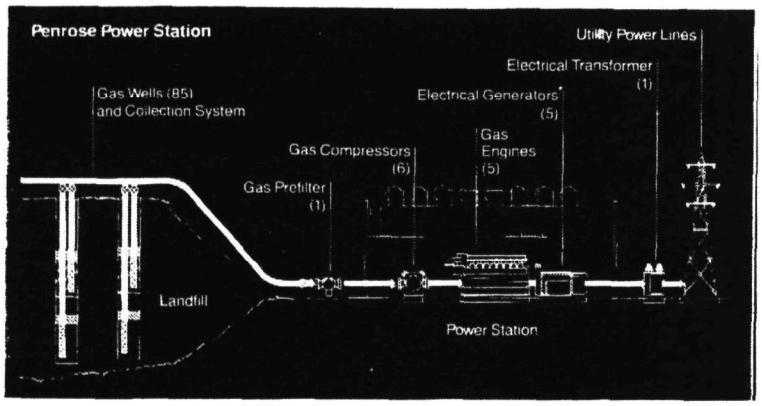
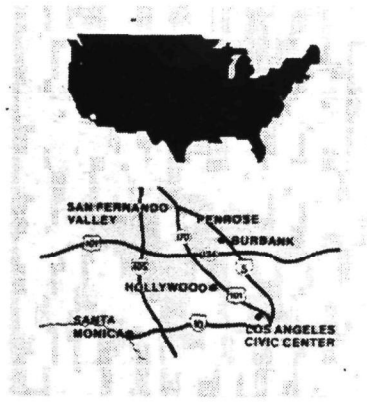
Landfill Gas to Electric Power





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.

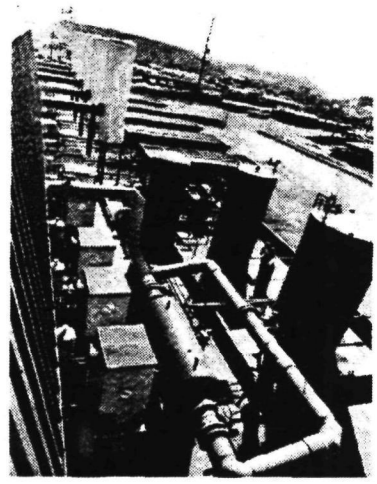
Power Station Description

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.



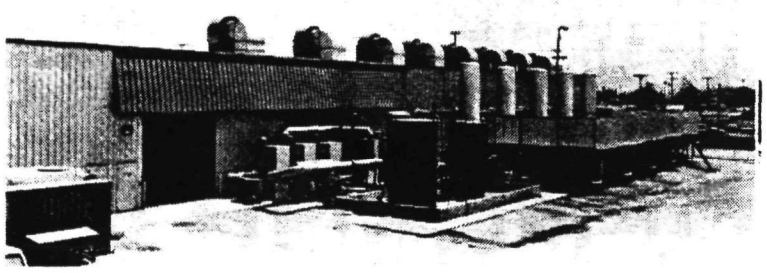
Key Project Data

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

Figure 2.3-9. Landfill Gas to Electric Power
(Courtesy of Pacific Energy)

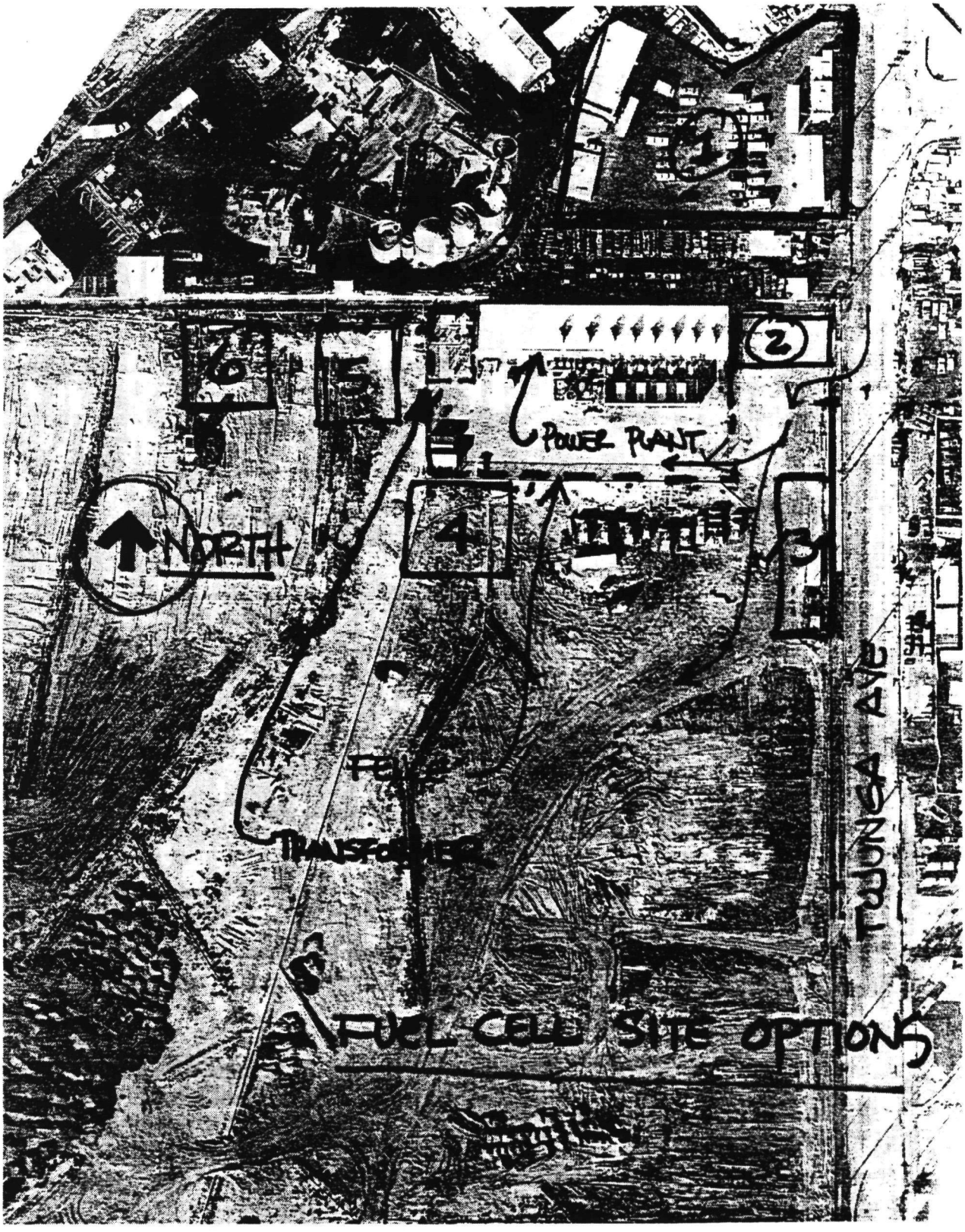


Figure 2.3-10. Fuel Cell Site Options
(Courtesy of Pacific Energy)

2.3.3 PHASE II PLAN

The goal for this demonstration project is to demonstrate recovery of energy from landfill gas in an economical and environmentally effective manner, using a commercial phosphoric acid fuel cell. In the program we will determine the feasibility of using landfill methane as a commercial fuel cell fuel; define the amount of pretreatment needed to render the LFG suitable for the fuel cell; and document the emission characteristics of the fuel cell energy recovery system.

Phase I activities were focused on defining the critical issues impeding implementation of the commercial concept and requiring resolution prior to conducting the demonstration. The issues can be categorized as follows: Those related to the amount of pretreatment needed to render LFG suitable for use in a fuel cell; and those related to achieving rated power in the commercial fuel cell with the dilute methane fuel.

Phase II program logic is shown in Figure 2.3-11. We plan to conduct two tasks, one to verify the Bio-Gas pretreatment system renders LFG suitable for fuel cell use, and a second task to generate a site specific design which includes modifications to the PC25 fuel cell to maximize its power output on LFG.

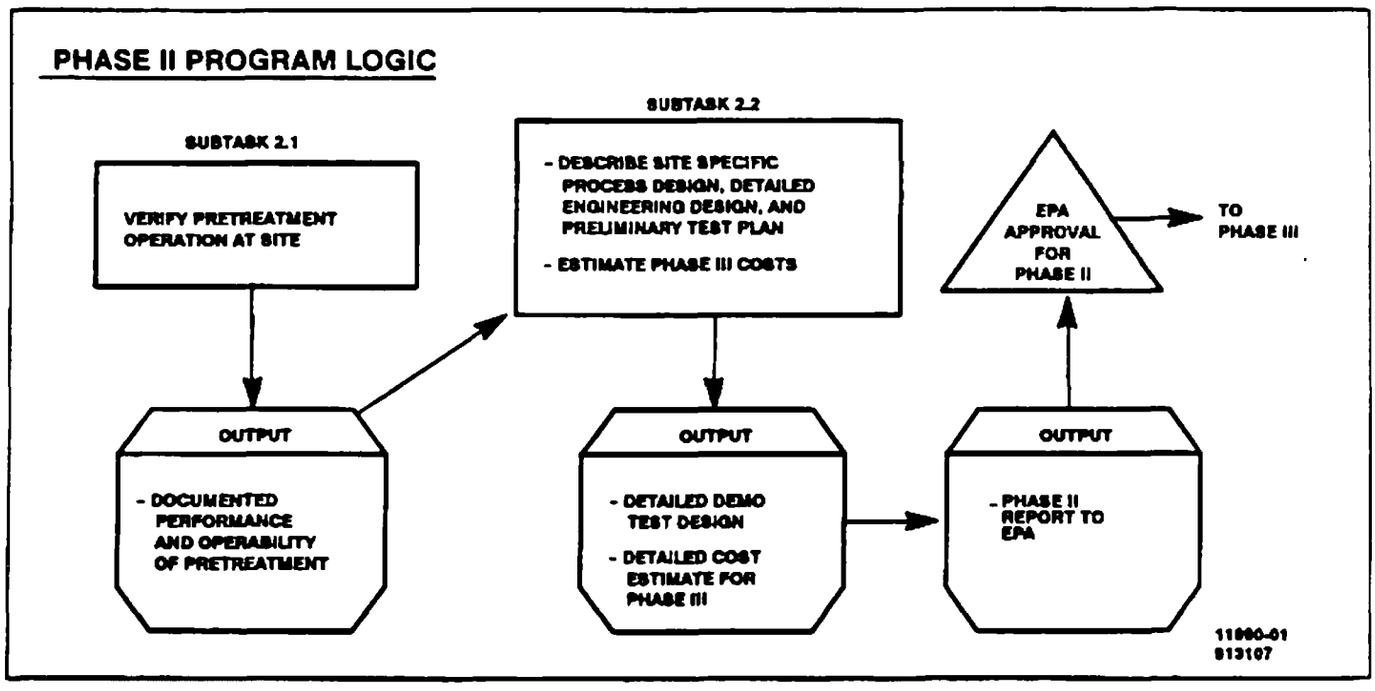


Figure 2.3-11. Phase II Program Logic

Task 2.1 Verify Pretreatment System Operation

There are two objectives in Task 2.1. Our main focus will be to demonstrate that the performance and operability of the LFG pretreatment system is suitable for operation with the PC25 fuel cell at Penrose. A secondary objective is to verify the Bio-Gas System's ability to accommodate contaminant levels from various landfill conditions. This is important to show the applicability of the pretreatment process in the commercial concept.

The major milestone schedule for this task is shown in Figure 2.3-12. The initial activity is to complete the design of pretreatment system and fabricate the demonstration hardware. Concurrently, IFC will work with Pacific Energy to obtain all necessary permits pertaining to local fire, safety, and building codes and state and local requirements for air, water and noise emissions. Upon receipt of the neces-

sary permits, we will prepare the site to receive the gas pretreatment system. These activities are planned to be completed by February 1992.

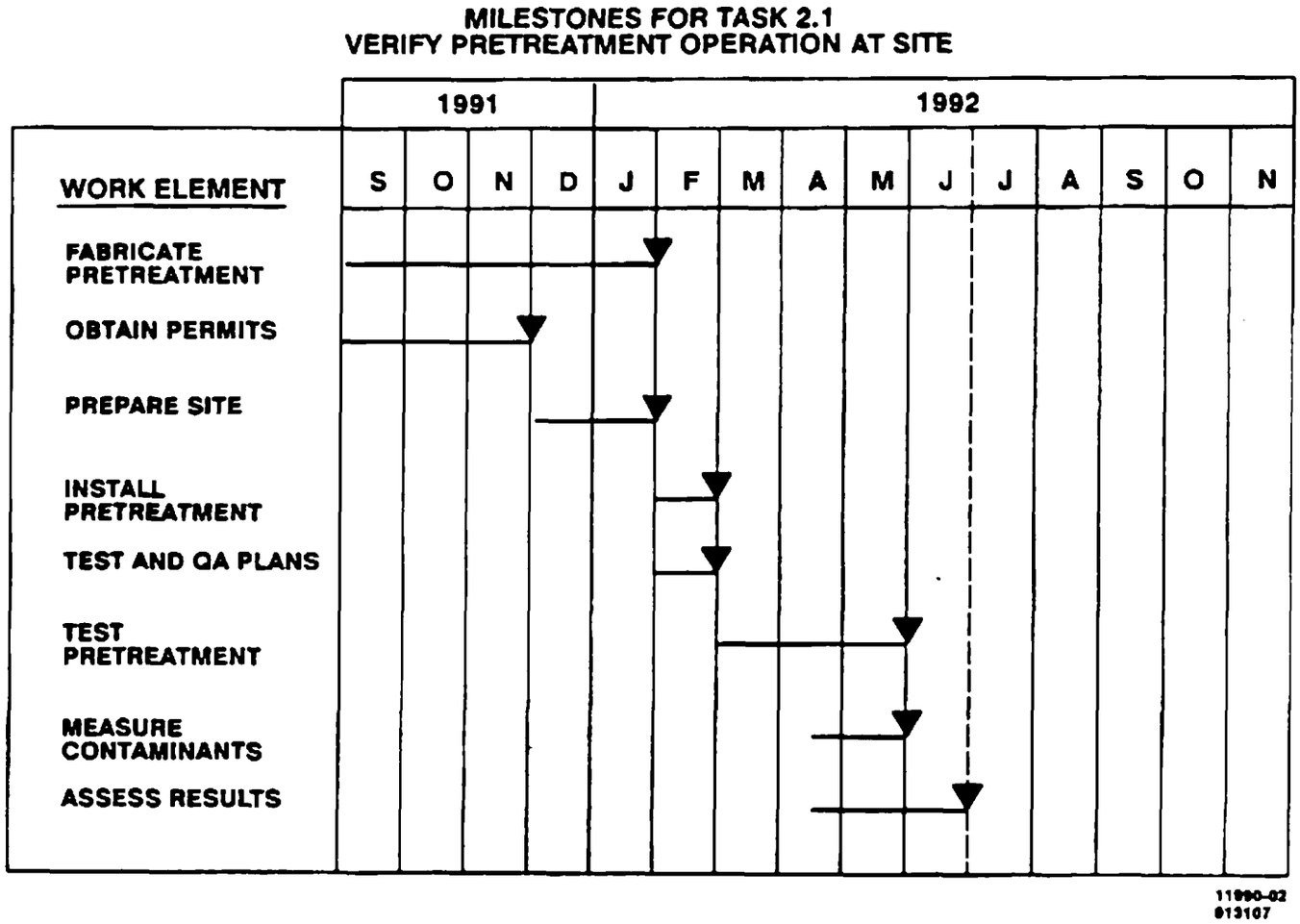


Figure 2.3-12. Task 2.1 Major Milestone Schedule

Quality Assurance and Test Plans will be prepared in February 1992 for the verification testing of the Bio-Gas pretreatment system. The plans will be submitted to EPA for review and approval prior to initiating the Pretreatment Unit Test.

Bio-Gas will install and check out the pretreatment system at the Penrose site. We will confirm that the operation of all electrical, mechanical and control functions meet the design requirements. Bio-Gas will then transfer operation of the system to Pacific Energy when the unit is checked out. Operating and maintenance manuals for the pretreatment unit will be provided to Pacific Energy by Bio-Gas.

The verification test of the gas pretreatment unit will be conducted for up to 500 hours. During the test, an overall mass and energy balance will be defined. Landfill gas analyses of the feed gas and output will define the effectiveness of the pretreat unit to clean up the LFG. Emissions tests of flare exhaust and condensate streams will confirm that design emission levels have been achieved. This testing will include a performance challenge test which will determine the ability of the gas pretreatment system to remove sulfur and halogenated compounds. We plan to dope the input landfill gas to simulate levels representative of a worse case landfill contamination level. This test is intended to verify the ability of the pretreatment unit to operate effectively in commercial concept.

IFC will assess the results of the performance and operability test to determine the impact on the demonstration to be conducted in Phase III. If contaminant levels are judged too high, IFC will consider modifications to the pretreatment unit, the fuel cell or both to resolve the issue. Solutions will be proposed to EPA for their consideration.

We anticipate the activities of this task will be competed by July 1, 1992. IFC will provide a complete description of the pretreatment system including operation and maintenance manuals to the EPA in a Topical Report.

Task 2.2 Demonstration Test Site Specific Design

The objective of this effort is to define the site specific design for the Phase III demonstration, and estimate the cost of the demonstration phase of the program. A major focus of the design effort will be on defining the modifications to the PC25 fuel cell which maximize power output on landfill gas at minimum demonstration cost.

During Phase I, IFC identified modifications to the PC25 which would increase power output on landfill gas (see Section 2.3.1). Modifications which would yield an output power rating of approximately 140 kW are the basis of the proposed program, however, additional modifications which could yield 175 kW rated power output were identified. These additional modifications will be studied further to assess the cost impact to the program and to judge the benefit to the demonstration. A complete list of modifications to achieve 200 kW will be provided to EPA.

The major milestone schedule for Task 2.2 is provided in Figure 2.3-13. IFC will generate a detailed engineering design of the demonstration test hardware at the selected site. A process design will establish the requirements for site facilities, gas supply, demonstration hardware, and electrical, mechanical and thermal interfaces. From these requirements we will design the demonstration hardware, installation interfaces and demonstration test plan to accomplish the goals of the program.

An outline for the Q/A Plan and Test Plan required in Phase III will be generated to enable an accurate cost estimate of the Phase III effort. IFC, with input from Pacific Energy, TRC, and Southern California Gas Company, will prepare a detailed cost estimate for Phase III from the site specific design, the Q/A Plan and Test Plan.

A Phase II Final Report will be prepared in October of 1992 describing the site specific design, the proposed demonstration test and the anticipated costs. The report will be submitted for EPA approval in November 1992.

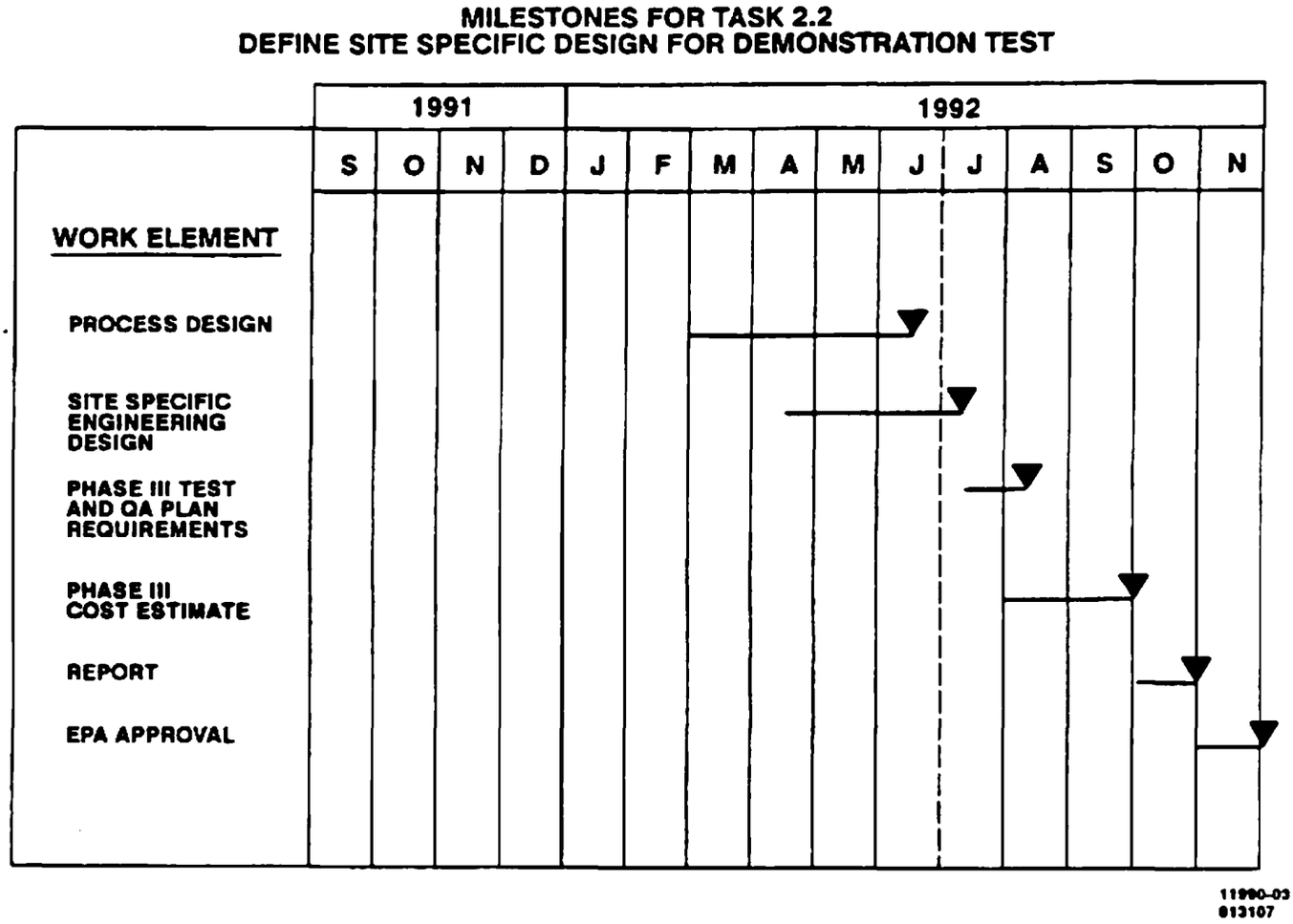


Figure 2.3-13. Task 2.2 Major Milestone Schedule

References:

1. U.S. Federal Register, May 30, 1991, Part III Environmental Protection Agency, 40 CFR Parts 51, 52 and 60; Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources; Municipal Solid Waste Landfills; Proposed Rule, Guideline and Notice of Public Hearing.
2. 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.
3. Solid Waste & Power, "Will Gas-To-Energy Work at Your Landfill?," Greg Maxwell, June 1990, p.44.
4. 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 3-23.
5. Ibid, Table 3-6 pages 3-25 through 3-28.

APPENDIX A

LANDFILL GAS PRETREATMENT SYSTEM COMPONENT SPECIFICATION

International Fuel Cells

TITLE:

LANDFILL GAS PRETREATMENT SYSTEM COMPONENT SPECIFICATION

REV LTR	AUTHOR	RELEASE NO.	DATE
—	J.L. PRESTON	D91PL233	5-3-91

PRODUCT FILE ADDRESS:

POWER PLANT/PROGRAM	SYSTEM & TAG NO.	PART NO.	DOCUMENT NO.
PC25/LANDFILL	FPRS		FCCS 5736
			PAGE 1 OF 8

FORM NO. 0054 REV 10-88

IFC FORM 0054, B.01.01

REVISION RECORD

(DASH No.) LTR	REL NO.	LTR	DESCRIPTION	DATE
			ORIGINAL ISSUE	5/15/91

DOCMT. NO.	
FCCS 5736	
REVISION	PAGE 2

FC FORM NO. 0054A 1/88

1.0 SCOPE AND DESCRIPTION:

This specification defines the requirements for a landfill gas pretreatment system (pretreatment system) for an EPA landfill-gas-to-energy demonstration utilizing a commercially available 200kW fuel cell power plant. The pretreatment system will remove sulfur and halide contaminants, water, and particulates present in raw landfill gas. Removal of the landfill gas diluents, including carbon dioxide, nitrogen, and oxygen, are not required.

The pretreatment system shall include means for contaminant removal, on-site destruction of contaminants removed from the system, delivery pressure regulation of pretreated landfill gas fuel to the fuel cell power plant, and all controls. It is anticipated that the system will be a complete skid-mounted and truck-transportable unit designed for exposed weather installation and unattended operation with safety controls to provide automatic shutdown. It is desirable to apply a process operating at a pressure as close to atmospheric as possible.

2.0 APPLICABLE DOCUMENTS:

At the time of contract, the latest version of the applicable documents with any amendments shall apply.

2.1 NATIONAL STANDARDS:

This system must be suitable for siting in an industrial setting in the city of Los Angeles. It therefore must be designed and built to recognize industrial standards such as ANSI B31 Code for Pressure Piping, ASME Boiler and Pressure Vessel Code, NFPA, FM, AGA and NEMA.

2.2 STATE AND LOCAL CODES:

City of Los Angeles Unified Building Code,

City of Los Angeles Electrical Code,

City of Los Angeles Bureau of Fire Prevention Code,

City of Los Angeles Health Department Code,

California State Industrial Code: Title 8,

South Coast Air Quality Management District, Rules & Specifications

3.0 REQUIREMENTS:

3.1 SUMMARY:

The gas pretreatment system will accept compressed raw landfill gas available at 80 to 95 psig from an existing site supply and will supply clean landfill gas of an appropriate temperature, pressure, humidity, and contaminant specification limit to the fuel cell on demand at a flow rate of up to 120,000 standard cubic feet per day (5000 SCFH). The system will provide the functions of water and particulate removal, contaminant removal, contaminant incineration, and supply pressure regulation on an automatic basis once operation is initiated.

3.2 INTERFACES:

3.2.1 Input Gas

The landfill gas feed to the pretreatment system will be available at up to 84 SCFM (5000 SCFH) and will have the following nominal properties:

- Temperature 80-100°F
- Pressure 80-95 PSIG
- CH4 42-50%
- CO_2 38-48%
- N_2 10-20%
- Oxygen at less than or equal to 1%
- Water vapor: saturated at nominal delivery conditions
- Heating value 425-510 BTU/SCF on a higher heating value basis
- Total non-methane organic compounds (NMOC) of 862 ppmv

For the pretreatment system design the total halides as chloride is 264 ppmv and total sulfur of 42 ppmv. These values are based on two times the EPA average compositional analysis for 48 quantifications at 23 different sites shown in Appendix A. Detailed compositional analysis for these values is given in Appendix B.

3.2.2 Output Gas Requirements to Fuel Cell Power Plant

	Min	Max	Units
Flow	0	5000	SCFH
Pressure	4	14	Inches of Water (Column W.C.)
Temperature	30	130	°F
Dew Point	--	20	°F
Total Sulfur	--	3	PPMv
Total Halides	--	3	PPMv
Particulates	--	Particulate removal of 100% at 1 micron or larger and 98% removal at 0.4 microns or larger	

3.2.3 Other Site Interfaces

- Location: Los Angeles, CA
- Site Services Available
  - Landfill Gas Supply
  - Electricity
  - Natural Gas
  - Water
  - Other site services to be defined by Pretreatment System Supplier

3.3 OPERATING CONDITIONS:

3.3.1 Start-Up

The pretreatment system design should be compatible with eventual automatic start-up. Manual start-up is acceptable for the demonstration program. Start-Up Time: 1 shift.

3.3.2 Shutdown

Normal shutdown can be accomplished manually.

In the event of malfunction in the fuel pretreatment system, the pretreatment system shall have provisions for automatic shutdown which protects the pretreatment system and does not exceed any site emissions limitations.

3.3.3 Normal Operation

The operation of the pretreatment system shall not be linked with the fuel cell power plant except that it can accept a shutdown signal from the fuel cell power plant. The pretreat system should be capable of checkout and operation without the fuel cell. A landfill gas pipeline operating at subatmospheric pressure (10 to 60 inches W.C. vacuum) is available to accept pretreated landfill gas during trials without the fuel cell.

3.4 PRESSURE REGULATION:

Provide to the fuel cell power plant on demand pretreated landfill gas at up to 120,000 SCFD (5000 SCFH) on a continuous, and uninterrupted basis at a delivery pressure of 4 to 14" of W.C. Pretreatment system shall provide rapid flow response to changes in the fuel cell demand. Delivery pressure shall not fall below 4" W.C. during increased demand from 0 to 5000 SCFH in 15 seconds.

3.5 CONTAMINANT DISPOSAL:

The pretreatment system shall not collect and store hazardous contaminants on site for later shipment off site. All contaminants regenerated from the pretreatment system shall be disposed of on-site using an incinerator which shall preclude dioxin formation, and shall be consistent with the current South Coast Air Quality Management District design specifications.

3.6 LIFE:

The pretreatment system adsorbents and absorbents shall be designed for a minimum life of 1 year. Quarterly filter replacement is allowable only if this can be accomplished without shutdown of the unit. Active components (solenoid valves, pumps, etc.) may be serviced on an annual basis.

3.7 PERMITTING:

The design specifications and stampings of the pretreatment system shall be consistent with all national, state and local codes and regulations as listed in Section 2.

3.8 DESIGN AND CONSTRUCTION:

The pretreatment system shall be modular, self-contained, and skid mounted. Materials of construction should be compatible with the operating environment and operating schedule to insure a minimum of two years of uninterrupted service. The system shall be designed to operate outdoors in the Los Angeles, California area.

3.9 DOCUMENTATION:

- Installation Manual and Drawings including Point of Connection Interface Locations
- Operating Manual
- Overhaul and Maintenance Manual
- P&I Diagram
- Electrical Diagram
- Process Flow Diagram
- Equipment Drawings
- Vendor Supplied Literature for Purchased Equipment
- Foundation Loading Calculation Document

4.0 QUALITY ASSURANCE:

4.1 QUALITY CONTROL SYSTEM:

The supplier shall have a Quality Control System that will ensure that parts are manufactured to the requirements of this specification. IFC reserves the right to review the supplier's system prior to contract award and to inspect parts and witness tests during manufacture and prior to shipment. IFC or its representatives will act as the authorized inspector required by ANSI B31 Codes for Pressure Piping.

4.2 TESTING:

All testing required by applicable codes (e.g., ASME Code vessel pressure testing) will be identified upon completion of the design, including a 24 hour pneumatic static test at 100% of rated pressure.

4.3 REPORTS:

All test and code required documentation will be provided to IFC prior to delivery of the pretreatment system.

5.0 PREPARATION FOR DELIVERY:

5.1 IDENTIFICATION:

The pretreatment system shall have a metal identification plate attached with the following information at a minimum:

- LANDFILL GAS PRETREATMENT SYSTEM
- IFC FCCS-5736
- vendor part number
- vendor serial number
- property of U.S. EPA under contract 68-D1-0008

6.0 APPENDICES:

A. Landfill Gas Contaminant Composition for Pretreatment System Design

B. EPA Average Landfill Gas Contaminant Composition Analysis

APPENDIX B

GAS ANALYSES FROM PENROSE LANDFILL

LANDFILL GAS OPERATING SCENARIES

Landfill Gas Flow Rates (scfm) *

Run #1 - Penrose, Sheldon, Bradley Blend

Penrose =	1325	scfm
Sheldon =	403	scfm
Bradley =	1650	scfm

Run #2 - Penrose, Bradley Blend

Penrose =	1525	scfm
Bradley =	1650	scfm

Run #3 - Penrose, Natural Gas Blend

Penrose =	1724	scfm
Natural Gas =	325	scfm

Run #4 - Penrose, Sheldon, Natural Gas Blend

Penrose =	1611	scfm
Sheldon =	544	scfm
Natural Gas =	155	scfm

Run #5 - Penrose, Sheldon, Bradley, Natural Gas Blend

Penrose =	1611	scfm
Sheldon =	450	scfm
Bradley =	1650	scfm
Natural Gas =	195	scfm

* Operating scenarios ran at Penrose Power Station on 5/31/91. Landfill gas blend sample taken for sulfur compound analysis for each scenario.

R. Rolfe
6/11/91

1

ZALCO LABORATORIES, INC.

Analytical & Consulting Services

B.C. Analytical
1255 Powell Street
Emeryville, CA 94608

Lab. No.: 027113_001
Received: Apr 10, 1991
Reported: Apr 10, 1991

Attention: Scott Chestnut

Sample Description: Penrose 8:52 4/10/91

* CHROMATOGRAPHIC ANALYSIS (Z 1610) *

Components	Mole %	Wt %	G.P.M.
Carbon Dioxide	39.475	60.175	
Oxygen	.330	365	
Nitrogen	14.013	13.597	
Carbon Monoxide	0.000	0.000	
Methane	46.080	25.606	
Ethane	0.000	0.000	
Propane	0.000	0.000	0.000
IsoButane	0.000	0.000	0.000
N-Butane	0.000	0.000	0.000
IsoPentane	.097	.243	.035
N-Pentane	0.000	0.000	0.000
Hexanes+	.004	.013	.002
Totals =	100.000	100.000	.037

	SPECIFIC GRAVITY (Air = 1)	.9989
*	SPECIFIC VOLUME, cu.ft./lb	13.12
*	GROSS CALORIFIC VALUE, BTU/cu.ft.	463.50
**	GROSS CALORIFIC VALUE, BTU/cu.ft.	471.52
**	GROSS CALORIFIC VALUE, BTU/lb	6184.74
*	NET CALORIFIC VALUE, BTU/cu.ft.	417.43
**	NET CALORIFIC VALUE, BTU/cu.ft.	424.65
	COMPRESSIBILITY FACTOR 'Z' (60 F,1 ATM)	.9977

* Water Saturated ** Dry Gas @ 60 F, 14.73 psia

Maryann W. Benoit
Organics Supervisor

Richard L. Penner
Laboratory Director

4309 Armour Avenue Bakersfield, California 93308

(805) 395-0539 FAX (805) 395-3069

(2)

ZA TORIES, INC.

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B.C. Analytical
1255 Powell Street
Emeryville, CA 94608

Lab. No.: 027113_003
Received: Apr 10, 1991
Reported: Apr 10, 1991

Attention: Scott Chestnut

Sample Description: Bradley 5:17

* CHROMATOGRAPHIC ANALYSIS (Z 1610) *

Components	Mole %	WL %	G.P.M.
Carbon Dioxide	40.786	60.489	
Oxygen	.418	.450	
Nitrogen	17.722	16.729	
Carbon Monoxide	0.000	0.000	
Methane	41.015	22.173	
Ethane	0.000	0.000	
Propane	0.000	0.000	0.000
IsoButane	.010	.020	.003
N-Butane	0.000	0.000	0.000
IsoPentane	0.000	0.000	0.000
N-Pentane	.011	.026	.004
Hexanes+	.039	.113	.017
Totals *	100.000	100.000	.024

	SPECIFIC GRAVITY (Air = 1)	1.0268
*	SPECIFIC VOLUME, cu.ft./lb	12.76
*	GROSS CALORIFIC VALUE, BTU/cu.ft.	411.49
**	GROSS CALORIFIC VALUE, BTU/cu.ft.	418.61
**	GROSS CALORIFIC VALUE, BTU/lb	5341.87
*	NET CALORIFIC VALUE, BTU/cu.ft.	370.57
**	NET CALORIFIC VALUE, BTU/cu.ft.	376.97
	COMPRESSIBILITY FACTOR 'Z' (60 F,1 ATM)	.9978

* Water Saturated ** Dry Gas @ 60 F, 14.73 psia

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Emeryville, CA 94608

Lab. No.: 027113_005
Received: Apr 10, 1991
Reported: Apr 10, 1991

Attention: Scott Chestnut

Sample Description: Sheldon-Post-Chiller 9:34

^ CHROMATOGRAPHIC ANALYSIS (Z 1610) ^

Components	Mole %	Wt %	G.P.M.
Carbon Dioxide	38.872	59.997	
Oxygen	.485	.544	
Nitrogen	12.633	12.411	
Carbon Monoxide	0.000	0.000	
Methane	47.992	27.002	
Ethane	0.000	0.000	
Propane	0.000	0.000	0.000
IsoButane	0.000	0.000	0.000
N-Butane	0.000	0.000	0.000
IsoPentane	0.000	0.000	0.000
N-Pentane	.018	.046	.007
Hexanes+	0.000	0.000	0.000
Totals =	100.000	100.000	.007

	SPECIFIC GRAVITY (Air = 1)	.9868
*	SPECIFIC VOLUME, cu.ft./lb	13.28
*	GROSS CALORIFIC VALUE, BTU/cu.ft.	479.25
**	GROSS CALORIFIC VALUE, BTU/cu.ft.	487.53
**	GROSS CALORIFIC VALUE, BTU/lb	6473.77
*	NET CALORIFIC VALUE, BTU/cu.ft.	431.53
**	NET CALORIFIC VALUE, BTU/cu.ft.	438.99
	COMPRESSIBILITY FACTOR 'Z' (60 F,1 ATM)	.9977

* Water Saturated ** Dry Gas @ 60 F, 14.73 psia

Maryann W. Benoit
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ZALCO LABORATORIES, INC.

Analytical & Consulting Services

B.C. Analytical
1255 Powell Street
Emeryville, CA 94608

Lab. No.: 027113_007
Received: Apr 10, 1991
Reported: Apr 10, 1991

Attention: Scott Chestnut

Sample Description: Tuxford 10:56

* CHROMATOGRAPHIC ANALYSIS (Z 1610) *

Components	Mole %	Wt %	G.P.M.
Carbon Dioxide	33.090	50.582	
Oxygen	.577	.641	
Nitrogen	28.250	27.487	
Carbon Monoxide	0.000	0.000	
Methane	38.054	21.205	
Ethane	0.000	0.000	
Propane	0.000	0.000	0.000
IsoButane	0.000	0.000	0.000
N-Butane	0.000	0.000	0.000
IsoPentane	0.000	0.000	0.000
N-Pentane	.011	.027	.004
Hexanes+	.019	.057	.008
Totals *	100.000	100.000	.012

	SPECIFIC GRAVITY (Air = 1)	.9959
*	SPECIFIC VOLUME, cu.ft./lb	13.16
*	GROSS CALORIFIC VALUE, BTU/cu.ft.	380.57
**	GROSS CALORIFIC VALUE, BTU/cu.ft.	387.15
**	GROSS CALORIFIC VALUE, BTU/lb	5093.58
*	NET CALORIFIC VALUE, BTU/cu.ft.	342.70
**	NET CALORIFIC VALUE, BTU/cu.ft.	348.62
	COMPRESSIBILITY FACTOR 'Z' (60 F,1 ATM)	.9982

* Water Saturated ** Dry Gas @ 60 F, 14.73 psia

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Analytical Report

(5)

LOG NO: G91-04-168

Received: 09 APR 91

Mailed: APR 17 1991

Mr. Scott Chesnut
BC Analytical, Air Monitoring Program
2000 Powell Street
Emeryville, California 94608

Project: 4798-11

REPORT OF ANALYTICAL RESULTS

C NO	SAMPLE DESCRIPTION, VAPOR OR AIR SAMPLES	DATE SAMPLED
-168-1	Penrose	09 APR 91
-168-2	Bradley-Sheldon	09 APR 91
-168-3	Bradley	09 APR 91
-168-4	Sheldon-Pre-Chiller	09 APR 91
-168-5	Sheldon-Post-Chiller	09 APR 91

AMETER	04-168-1	04-168-2	04-168-3	04-168-4	04-168-5
.Pri.Poll. (EPA-8240)					
te Analyzed	04/11/91	04/12/91	04/12/91	04/10/91	04/10/91
lution Factor, Times 1	5	5	5	1	1
1,1-Trichloroethane, ppb	<250	<250	<250	<50	<50
1,2,2-Tetrachloroethane, ppb	<250	<250	<250	<50	<50
1,2-Trichloroethane, ppb	<250	<250	<250	<50	<50
1-Dichloroethane, ppb	<250	3300	3300	<50	<50
1-Dichloroethene, ppb	<250	250	<250	<50	<50
2-Dichloroethane, ppb	<250	<250	<250	<50	<50
2-Dichlorobenzene, ppb	<250	<250	<250	<50	<50
2-Dichloropropane, ppb	<250	<250	<250	<50	<50
3-Dichlorobenzene, ppb	<250	<250	<250	<50	<50
4-Dichlorobenzene, ppb	<250	<250	<250	<50	<50
Chloroethylvinylether, ppb	<250	<250	<250	<50	<50
Hexanone, ppb	<250	<250	<250	<50	<50
etone, ppb	<250	<250	<250	<50	<50
rolein, ppb	<250	<250	<250	<50	<50
rylonitrile, ppb	<250	<250	<250	<50	<50
omodichloromethane, ppb	<250	<250	<250	<50	<50
omomethane, ppb	<250	<250	<250	<50	<50
nzene, ppb	2000	1400	1200	400	400
omoform, ppb	<250	<250	<250	<50	<50
lorobenzene, ppb	1000	<250	<250	100	90
rbon Tetrachloride, ppb	<250	<250	<250	<50	<50

01 Western Avenue
Glendale, CA 91201

818/247-5737
Fax: 818/247-9797

BCA B C Analytical

Analytical Report

LOG NO: G91-04-168

Received: 09 APR 91

Mr. Scott Chesnut
BC Analytical, Air Monitoring Program
2000 Powell Street
Emeryville, California 94608

Project: 4798-11

REPORT OF ANALYTICAL RESULTS

LOG NO	SAMPLE DESCRIPTION, VAPOR OR AIR SAMPLES	DATE SAMPLED
04-168-1	Penrose	09 APR 91
04-168-2	Bradley-Sheldon	09 APR 91
04-168-3	Bradley	09 APR 91
04-168-4	Sheldon-Pre-Chiller	09 APR 91
04-168-5	Sheldon-Post-Chiller	09 APR 91

PARAMETER	04-168-1	04-168-2	04-168-3	04-168-4	04-168-5
Chloroethane, ppb	<250	<250	<250	<50	<50
Chloroform, ppb	<250	<250	<250	<50	<50
Chloromethane, ppb	<250	<250	<250	<50	<50
Carbon Disulfide, ppb	<250	<250	<250	<50	<50
Dibromochloromethane, ppb	<250	<250	<250	<50	<50
Ethylbenzene, ppb	13000	5600	4300	3400	3500
Freon 113, ppb	<250	<250	<250	<50	<50
Methyl ethyl ketone, ppb	<250	<250	<250	<50	<50
Methyl isobutyl ketone, ppb	<250	<250	<250	<50	<50
Methylene chloride, ppb	<250	11000	12000	<50	<50
Styrene, ppb	<250	<250	500	<50	<50
Trichloroethene, ppb	600	2900	2800	<50	<50
Trichlorofluoromethane, ppb	<250	600	600	<50	<50
Toluene, ppb	35000	36000	33000	4800	4700
Tetrachloroethene, ppb	1000	6600	6300	<50	<50
Vinyl acetate, ppb	<250	<250	<250	<50	<50
Vinyl chloride, ppb	400	1500	1400	<50	<50
Total Xylene Isomers, ppb	22000	13000	11000	6500	6900
cis-1,2-Dichloroethene, ppb	4100	5100	5100	60	<50
cis-1,3-Dichloropropene, ppb	<250	<250	<250	<50	<50
trans-1,2-Dichloroethene, ppb	<250	<250	<250	<50	<50
trans-1,3-Dichloropropene, ppb	<250	<250	<250	<50	<50
Other Vol.Pri.Poll. (EPA-8240)	---	---	---	---	---

801 Western Avenue
Glendale, CA 91201

818/247-5737
Fax: 818/247-9797

BCA B C Analytical

Analytical Report

(7)

LOG NO: G91-04-168

Received: 09 APR 91

Mr. Scott Chesnut
BC Analytical, Air Monitoring Program
2000 Powell Street
Emeryville, California 94608

Project: 4798-11

REPORT OF ANALYTICAL RESULTS

LOG NO	SAMPLE DESCRIPTION, VAPOR OR AIR SAMPLES	DATE SAMPLED
04-168-6	Toyon	09 APR 91
04-168-7	Tuxford	09 APR 91
04-168-8	Blank	09 APR 91

PARAMETER	04-168-6	04-168-7	04-168-8
Vol.Pri.Poll. (EPA-8240)			
Date Analyzed	04/10/91	04/10/91	04/10/91
Dilution Factor, Times 1	1	1	1
1,1,1-Trichloroethane, ppb	<50	<50	<50
1,1,2,2-Tetrachloroethane, ppb	<50	<50	<50
1,1,2-Trichloroethane, ppb	<50	<50	<50
1,1-Dichloroethane, ppb	70	<50	<50
1,1-Dichloroethene, ppb	<50	<50	<50
1,2-Dichloroethane, ppb	<50	<50	<50
1,2-Dichlorobenzene, ppb	<50	<50	<50
1,2-Dichloropropane, ppb	<50	<50	<50
1,3-Dichlorobenzene, ppb	<50	<50	<50
1,4-Dichlorobenzene, ppb	<50	<50	<50
2-Chloroethylvinylether, ppb	<50	<50	<50
2-Hexanone, ppb	<50	<50	<50
Acetone, ppb	19000	<50	<50
Acrolein, ppb	<50	<50	<50
Acrylonitrile, ppb	<50	<50	<50
Bromodichloromethane, ppb	<50	<50	<50
Bromomethane, ppb	<50	<50	<50
Benzene, ppb	2000	400	<50
Bromoform, ppb	<50	<50	<50
Chlorobenzene, ppb	200	<50	<50
Carbon Tetrachloride, ppb	<50	<50	<50
Chloroethane, ppb	<50	<50	<50
Chloroform, ppb	<50	<50	<50

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BCA B C Analytical

Analytical Report

LOG NO: G91-04-168

Received: 09 APR 91

Mr. Scott Chesnut
BC Analytical, Air Monitoring Program
2000 Powell Street
Emeryville, California 94608

Project: 4798-11

REPORT OF ANALYTICAL RESULTS

LOG NO	SAMPLE DESCRIPTION, VAPOR OR AIR SAMPLES	DATE SAMPLED
04-168-6	Tovon	09 APR 91
04-168-7	Tuxford	09 APR 91
04-168-8	Blank	09 APR 91

PARAMETER	04-168-6	04-168-7	04-168-8
Chloromethane, ppb	<50	<50	<50
Carbon Disulfide, ppb	<50	<50	<50
Dibromochloromethane, ppb	<50	<50	<50
Ethylbenzene, ppb	5100	1000	<50
Freon 113, ppb	<50	<50	<50
Methyl ethyl ketone, ppb	13000	<50	<50
Methyl isobutyl ketone, ppb	<50	<50	<50
Methylene chloride, ppb	300	<50	<50
Styrene, ppb	<50	<50	<50
Trichloroethene, ppb	200	<50	<50
Trichlorofluoromethane, ppb	<50	<50	<50
Toluene, ppb	8900	600	<50
Tetrachloroethene, ppb	300	<50	<50
Vinyl acetate, ppb	<50	<50	<50
Vinyl chloride, ppb	100	200	<50
Total Xylene Isomers, ppb	7200	1700	<50
cis-1,2-Dichloroethene, ppb	400	200	<50
cis-1,3-Dichloropropene, ppb	<50	<50	<50
trans-1,2-Dichloroethene, ppb	<50	<50	<50
trans-1,3-Dichloropropene, ppb	<50	<50	<50
Other Vol.Pri.Poll. (EPA-8240)	---	---	---

Jeffrey A. Erion, Laboratory Manager

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BCA B C Analytics

APPENDIX C

GAS PRETREATMENT SYSTEM MASS AND ENERGY BALANCE PRELIMINARY DESIGN CALCULATIONS

BIO-GAS DEVELOPMENT, INC. PROCESS CALCULATIONS

PAGE 1A OF

PROJECT LANDFILL GAS PRETREATMENT AS FUEL CELL FEED STOCK

SHEET NO. OF

JOB NO. 110-I

SUBJECT IFC - PRELIMINARY DESIGN ~ ENERGY BALANCES

MADE BY DWM DATE 07.25.91

PENROSE LANDFILL L.A. CTY. CALIFORNIA, LFG

CHKD. BY DATE

REFERENCE: ① PENROSE GAS ANALYSIS - BGD. PG. 18

② BGD MATERIAL BALANCE TABULATION ~ 07/26/91

Ⓐ STREAM (2) IS CHILLED IN THE 1ST STAGE REFRIGERATION CONDENSER WHEREBY WATER AND HYDROCARBONS ARE CONDENSED AND SEPARATED FROM THE GAS PHASE.

PROCESS GAS = 506.4 lb/hr. T_{IN} = 100°F T_{EXIT} = 32°F

	BTU/HR.
SENSIBLE HEAT OF LFG =	9938.
LATENT HEAT OF CONDENSED H_2O =	1957.
SENSIBLE HEAT OF WATER =	101.
SENSIBLE HEAT OF ORGANICS/S =	.4.
LATENT HEAT OF ORGANICS/SULF. =	100.
TOTAL Q_I =	12,100. BTU/HR

Ⓑ GLYCOL IS FED TO THE 1ST STAGE REFRIGERATION CONDENSER AT 32°F

BRINE FLOW = 110. GPM C_p = 0.55

Q_S = SENSIBLE HEAT OF BRINE = 12,100. BTU/HR

AVERAGE $\Delta T = T_{EXIT} - T_{IN}$ = 0.4 °F

STREAM (6) IS CHILLED IN THE 2ND STAGE INTERCOOLER (A) PRIOR TO PASSAGE THRU THE 2ND STG. CONDENSER.

Ⓐ PROCESS GAS @ T_1 = 45°F FROM H_2S MOLE SIEVE BEDS

PROCESS GAS FLOWRATE = 500.2 lb/hr.

T_{INLET} = 45°F

T_{EXIT} = +10°F

Q_S = SENSIBLE HEAT LOSS OF LFG = 5250. BTU/HR.

Ⓑ GLYCOL (BRINE) IS FED TO THE INTERCOOLER (A) +10°F = T_B

BRINE FLOW = 20. GPM C_p = 0.53 $T_{B\text{-}IN}$ = 10°F ; $T_{B\text{-}OUT}$ = 11°F

Q_S = SENS HT. OF BRINE = 5400. BTU/HR.

STREAM (8) IS HEATED IN THE 2ND STAGE INTERCOOLER (B-SECTION) UTILIZING THE SAME BRINE STREAM FROM INTERCOOLER - A-SECTION ABOVE

Ⓐ PROCESS GAS @ T_{IN} = -25°F FROM 2ND STAGE REFRIG. CONDSR.

PROCESS GAS FLOWRATE = 500.75 lb/hr.

T_{INLET} = -25°F

T_{EXIT} = +11°F

Q_S = SENSIBLE HEAT LOSS OF LFG (CLEAN) = 5250. BTU/HR.

Ⓑ GLYCOL (BRINE) IS FED TO THE (B-SEC.) INTERCOOLER AT T_B = 11°F

BRINE FLOW = 20. GPM T_{BIN} = 11°F T_{BOUT} = 10°F

Q_{SB} = SENS. HT. DUTY OF BRINE = 5400. BTU/HR.

Reference: Penrose Gas Analysis

V STREAM (7) IS ROUTED THRU THE 2ND STAGE INTERCOOLER WHEREBY SMALL QUANTITIES OF VOCS ARE CONDENSED AND SEPARATED. THE GAS IS CHILLED TO -25°F AND THEN REHTD. TO +11°F IN THE INTERCOOLER.

(A) PROCESS GAS @ T_{IN} = +10°F
PROCESS GAS FLOW = 500.8 lb/HR.

T_{IN} = +10°F ΔT = 35°
T_{OUT} = -25°F

Q_s = SENSIBLE HEAT LOSS TO LFG = 500.8 × C_p × ΔT = 9250. → Q_{TOTAL} ≅ 9250. BTU/HR.
Q_L = LATENT HT. OF VOC'S = ZERO

(B) BRINE (GLYCOL) IS FED TO THE 2ND STAGE CONDENSER AT: T_B = -26°F
BRINE FLOW = 100. GPM C_p = 0.50

Q_s = SENSIBLE HEAT GAIN TO GLYCOL = 51,000. × .50 × ΔT = 9250. BTU/HR.

∴ ΔT = 0.36°F

I STREAM (10) IS FED THRU THE REGENERATION GAS HEATER COILS WHEREBY IT IS HEATED TO +600°F PRIOR TO BEING ROUTED TO THE 3-PAIRS OF ADSORPTION BEDS.

(A) REGENERATION GAS FLOW = 85.1 lb/hr. $C_{p_{AIR}}$ ≅ 0.33
T_{INLET} = 11°F ΔT = 539°F
T_{OUTLET} = 550°F

Q_s = SENSIBLE HEAT GAIN TO REG. GAS = 15136. BTU/HR.

(B) COMBUSTION GAS FLOW = 72. lb/hr
T_{INLET} = 1450°F ΔT = 750°F $C_{p_{AVG}}$ ≅ 0.270 BTU/lb°F
T_{OUT} = 700°F

Q_s = SENSIBLE HEAT LOSS TO COMBUSTION GAS = 15,200 BTU/HR. = $MC_p\Delta T$

VII STREAM (12); HOT REGENERATION GAS AT 600°F IS ROUTED TO THE DEHYDRATION MOLE-SIEVE BEDS. THE TWO BEDS ARE ARRANGED IN A PARALLEL FLOW MODE. ONE BED IS ALWAYS ON-LINE WHILE THE OTHER BED IS IN REGENERATION MODE. THE REGENERATION CYCLE LASTS A TOTAL OF 8 HOURS, THIS, DIVIDED INTO A COOLING (CYCLE) PHASE AND A HEATING PHASE. THE REGEN. MODE BEGINS WHEN ONE BED, HAVING COMPLETED 8 HRS. ON-LINE, IS SWITCHED BY VALVES OFF-LINE. HOT REGEN. GAS IS ROUTED TO THE BEDS' BOTTOM DISTRIBUTOR AND EXITS THE MEDIA BED VIA THE TOP DISTRIBUTOR/COLLECTOR ASSY.

DATA:

A. INITIAL TEMP. OF SS. VESSEL, INTERNALS + MEDIA = T_i = 35°F

B. WEIGHTS: VESSEL + INTERNALS: 1.5' DIA. × 1.85' TALL ≅ 0.09 ft³ + 0.05 ft³ + 0.005 ft³ ≡ [illegible]

MEDIA (MOLE SIEVES): 150. lbs. WEIGHT

(A)

① HEAT REQUIRED TO INCREASE VESSEL + MEDIA TEMP. FROM 35°F TO 600°F

$Q_1 = (75 \times 0.12 \times 565) + (150. \times 0.20 \times 565) \equiv 5085. + 16{,}950. = 22{,}035.$ BTUS

② HEAT REQUIRED TO INCREASE TEMP. OF ADSORBED WATER (AS VAPOR) TO 535° °F FROM 35°F.

$Q_2 = \dot{m}_{AW} \times C_p \times \Delta T = 11.80\ lb \times 1.0 \times 200. + 11.80 \times .40 \times 300 = 2365 + 1416 = 3778.$ BTUS

③ HEAT REQUIRED TO VAPORIZE WATER – N/A

$Q_3 = \dot{m}_{AW}\, \lambda_{AW} = N/A$

④ TOTAL HEAT INPUT TO BED + MEDIA ≡ $Q_{TOTAL} = [22{,}035. + 3778.] = 25{,}813.$ BTUS

(B) REGENERATION GAS FLOW = 80.21 lb/hr.
INLET GAS TEMP. = 600°F
OUTLET GAS TEMP. (A.16.) = 275°F

Q_{RGS} (T = 150 MINS.) = 25,751. BTUS (ENTHALPY DIFFERENCE)

II STREAM (13) HOT REGENERATION GAS AT 600°F IS ROUTED TO THE CARBON ADSORPTION BEDS AFTER 30 MINS TO THE MOLE-SIEVE BEDS.

DATA: BASIS

A. INITIAL TEMP. OF S.S VESSEL + INTERNALS + MEDIA = T_I = 40°F

B. FLOWRATE OF H/C CONTAMINANTS = 0.4 lb/HR = 0.00667 lbs/MIN

C. TOTAL QTY. OF VOCS ADSORBED ON CARBON = 0.4 x 8 = 3.2 lbs. x $\frac{\text{lbmole}}{130 \text{ lbs}}$ = 0.0246 lbmoles (IN 8 HRS)

HEAT OF DESORPTION = 14,700 $\frac{\text{cal}}{\text{gmole}}$ = 26,460 $\frac{\text{BTU}}{\text{lbmole}}$

D. TOTAL WEIGHT OF CARBON = 3.2 x $\frac{1}{0.10}$ = 32.0 lbs (10% BY WEIGHT)

E. VOLUME OF CARBON = 32 lb. x $\frac{\text{ft}^3}{30 \text{ lbs}}$ = 1.067 ft³ ACTUAL VOLUME OF CARBON = 1.0656 x 1.25 = 1.333 ft³ = [illegible]

VESSEL DIMENSIONS = 1.25 ft DIA. x 1.25 ft S-S

F. VESSEL + INTERNALS : WEIGHT = 50. lbs SP HT OF CARBON = C_p = 0.25 BTU/lb°F

HEAT REQUIRED TO RAISE BED AND VESSEL FROM 40°F TO 450°F

$Q_{cap} = \dot{m}_s C_{p,m} \Delta T + \dot{m}_c C_{p_c} \Delta T$ = 50. x 0.12 x 410. + 46.0 x .25 x 410. = 2460 + 4715. = 7175 BTUS

HEAT REQUIRED TO DESORB VOCS FROM CARBON = Q_{DES} = 26,460 $\frac{\text{BTU}}{\text{lbmole}}$

Q_{DES} = 26,460. $\frac{\text{BTU}}{\text{lbmole}}$ x 0.0246 lbmoles = 650 BTUS

TOTAL BTUS REQ'D TO REGENERATE = 7175. + 650 = 7825 BTUS

NOTE: REGENERATION OF CARBON IS DONE IN ___ STEP :

1ST: EXIT GAS FROM DAB - MOL.SIEVE BEDS @ T_{AVG} ≅ 250°F IS FED TO THE CARBON BEDS FOR 30 MINS (FROM 40°F → 540°F)

$Q_{REG.I}$ = 30.21 lb/hr. x 0.29 x 220° ≅ 5000. BTUS/HR.

Q_{REGI} = 5000 BTU/HR x 2.5 HRS = 12,500 BTUS

∴ REGENERATION OF CARBON BEDS IS FINISHED IN 2HRS FROM START OF DAB-BEDS REGENERATION

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IX STREAM (14) HOT REGENERATION GAS AT 600°F IS ROUTED TO THE MOLE-SIEVE BEDS – 3AB – AFTER 2.5 HOURS OF FLOW TO THE 1ST MOLE SIEVE BEDS AND CARBON BEDS

DATA:

A. INITIAL TEMP. OF S.S. VESSEL + INTERNALS = T_S = 40°F

B. TOTAL RATE OF H_2S ADSORBED PER HOUR = 0.06 lbs./HR. CAPACITY OF MOLE SIEVES = $\frac{0.06 \text{ lbs } H_2S}{1.0 \text{ lb MOLE SIEVE}}$

C. WEIGHT OF MOLE-SIEVES FOR 8-HR. CYCLE = 9.6 lbs. ρ_{MS} = 45 lb/ft³

D. VOLUME OF MOLE-SIEVES = 0.2133 ft³ ACTUAL VOLUME =

E. DIMENSIONS OF ADSORPTION BED: 0.75 ft. DIA x 0.75 ft. S-S. VOLUME OF MEDIA = 0.33 ft³ + 9" DIA

F. WEIGHT OF VESSEL + INTERNALS: WGHT = 0.04 + .02 + .0025 = 0.0627 ft³ ≅ 35. lbs.

A. REQ'D. HEAT INPUT

① HEAT REQUIRED TO RAISE VESSEL + MEDIA FROM 40°F TO 525°F

$$Q_I = (35. \times .12 \times 485.) + (15. \times .20 \times 485.) = 2037. + 1455. = 3492. \text{ BTUS}$$

② HEAT REQ'D TO INCREASE TEMP OF ADSORBED H_2S VAPOR FROM 40°F TO 525°F

$$Q_{II} = (0.48 \text{ lbs} \times 0.50 \times 485) = 116.4 \text{ BTUS}$$

③ TOTAL HEAT REQ'D. = 3492. + 116.4 = 3608. BTUS.

B. REGEN. GAS

① INLET GAS TEMP. = 500°F

② OUTLET GAS TEMP = 275°F (AVG.)

$Q_{REG.}$ (T = 25 MINS.) = 4000. BTUS (ENTHALPY DIFFERENCE

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