USE OF FUEL CELLS ON WASTE METHANE GAS

by

Ronald J. Spiegel
National Risk Management Research Laboratory
United States Environmental Protection Agency
Research Triangle Park, North Carolina 27711

J. C. Trocciola and J. L. Preston
International Fuel Cells Corporation
195 Governors Highway
South Windsor, Connecticut 06074

ABSTRACT

Fuel cells convert the energy contained in fuels into electricity and useful heat. This conversion process is done in an efficient and environmentally superior manner. Fuel conversion efficiencies of up to 80% are possible with emission levels so low that fuel cells are exempt from air permitting requirements in many areas of the country. Fuel cells can operate on a variety of fuels including natural gas, propane, landfill gas, and anaerobic digester gas. Since many of these fuels may be produced from renewable sources, the fuel cell provides a method for conserving our natural resources. The U.S. Environmental Protection Agency (EPA) is currently demonstrating the operation of a commercial 200 kW fuel cell on waste methane gas produced by landfills. The project addressed two major issues: (1) the design, construction, and testing of a landfill gas cleanup system, and (2) a field test of the fuel cell power plant operating on the cleaned landfill gas. A summarization of the test results for the cleanup system and fuel cell operation are given.

INTRODUCTION

Performance standards for landfill gas control have been issued by the U.S. EPA [1]. The regulations relate to the emission of non-methane organic compounds (NMOCs), comprising some 100 varieties of volatile organic compounds and hazardous air pollutants (such as vinyl chloride and benzene) that are emitted in landfill gas. These emittants generally represent less than 1% of the total composition of landfill gas which in bulk is primarily methane (45-50%) and carbon dioxide (55-50%). This gas has a heating content that is roughly half that of natural gas.

According to this regulation, landfills emitting more than 55 tons (50 metric tons) per year of NMOCs will be required to install a gas collection system and a treatment system capable of destroying 98% of the NMOCs in the gas or reducing them to less than 20 parts per million (ppm). In this process the methane gas, which is a potent greenhouse gas, is also destroyed or utilized to produce electricity or heat. Once installed, the collection system must be operated until NMOC emissions are less than 55 tons per year. Monitoring requirements include quarterly tests with a methane analyzer to ensure that methane emissions are below 500 ppm on and around the landfill.

Landfill gas collection is a mature technology, and the usual method involves drilling 2-ft (0.6 m) diameter vertical holes into the landfill, spaced 50 to 300 ft (15 to 92 m) apart. A perforated pipe is inserted into each hole, the hole is backfilled with gravel, and a dirt cap is applied over the top. These pipes are connected to a manifold, leachate removal system, and gas pump. The collected gas can subsequently be flared, used to generate electricity and heat, or produce pipeline quality gas. Because landfill gas could produce over 1% of U.S. energy requirements, the EPA is encouraging energy production over methods (flaring) which merely destroy the NMOCs and methane.

These emission guidelines, therefore, may spur energy production from landfill gas because of the gas collection system requirement. The use of internal combustion engines (ICEs) to drive an electrical generator is the most common approach of producing energy from landfill gas. Today, in excess of 100 landfills are using ICEs to generate electricity, many of which were installed in the late 1970s and 1980s when the short term economic aspects of energy production were over estimated. Because of siting problems, maintenance requirements, noise, and air emissions (nitrogen oxides and carbon monoxide) associated with ICEs, it is desirable to seek other technologies that cannot only produce energy from landfill gas but also reduce air emissions and lower capital cost. Fuel cells are an emerging technology that may ultimately improve the outlook for clean, efficient, and economical energy use of landfill gas.

Early 1995 marked the completion of a major step toward establishing fuel cells as a promising new technology for utilizing landfill gas. The first demonstration using landfill gas in a commercially available phosphoric acid fuel cell power plant was successfully conducted at the Penrose Landfill in Sun Valley, California. This was the conclusion of a three-phase program which began in 1990 when EPA awarded International Fuel Cells Corporation (IFC) a contract to demonstrate landfill gas control with energy recovery. The project addressed two principal issues: (1) a landfill gas cleanup method to remove contaminants from the gas sufficiently for fuel cell operation, and (2) a demonstration test of a commercial fuel cell power plant operating on landfill gas.

This paper will summarize some of the latest test results and the status of the project. Additional information can be found in EPA reports [2], [3].

LANDFILL GAS FUEL CELL

Overall System

Figure 1 provides a simplified description of the required components of a fuel cell landfill gas-to-energy system. The system consists of the landfill gas wells and collection system, a modular gas pretreatment unit (GPU), and a fuel cell power plant modified for landfill gas operation. The fuel cell power plant is an adaptation from the natural-gas-fueled PC25 fuel cell sold by ONSI Corporation, an IFC subsidiary. Landfill gas collected at the site is processed to remove contaminants in the GPU. The cleaned medium heat content landfill gas is then used to fuel the fuel cell power plant to produce alterating current (AC) for sale to the electric utility. The clean cogeneration heat produced by the fuel cell may also be utilized if a requirement for heat exists at the site. If not utilized, it is rejected by the air cooling module.

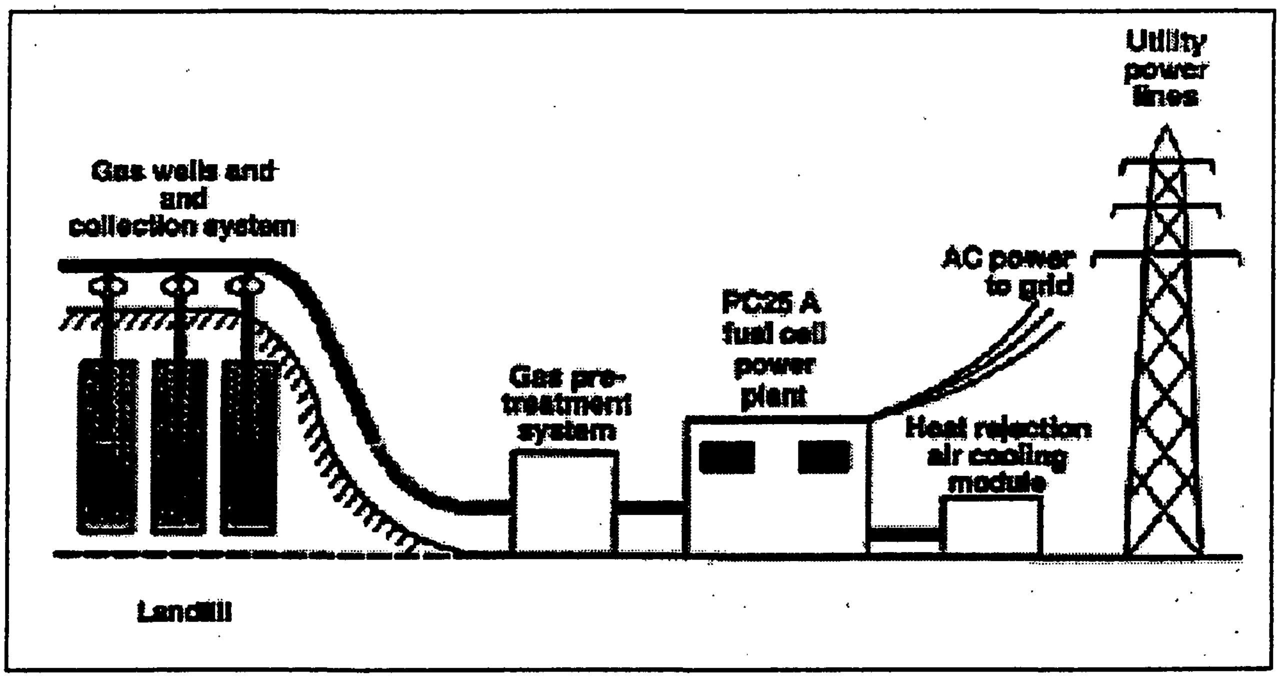

FIGURE 1. FUEL CELL LANDFILL GAS ENERGY RECOVERY

Fuel Cell Power Plant

A simplified functional schematic of the 200 kW fuel cell power unit is shown in Figure 2. Major sections of the system, include the fuel processing system, fuel cell stack, and the thermal management system. In the fuel processing section treated landfill gas is converted to hydrogen (H_2) and carbon dioxide (CO_2) for introduction into 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 H_2 and CO_2.

In the fuel cell stack, H_2 from the process fuel stream is combined electrochemically with oxygen from the air to produce direct current (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.

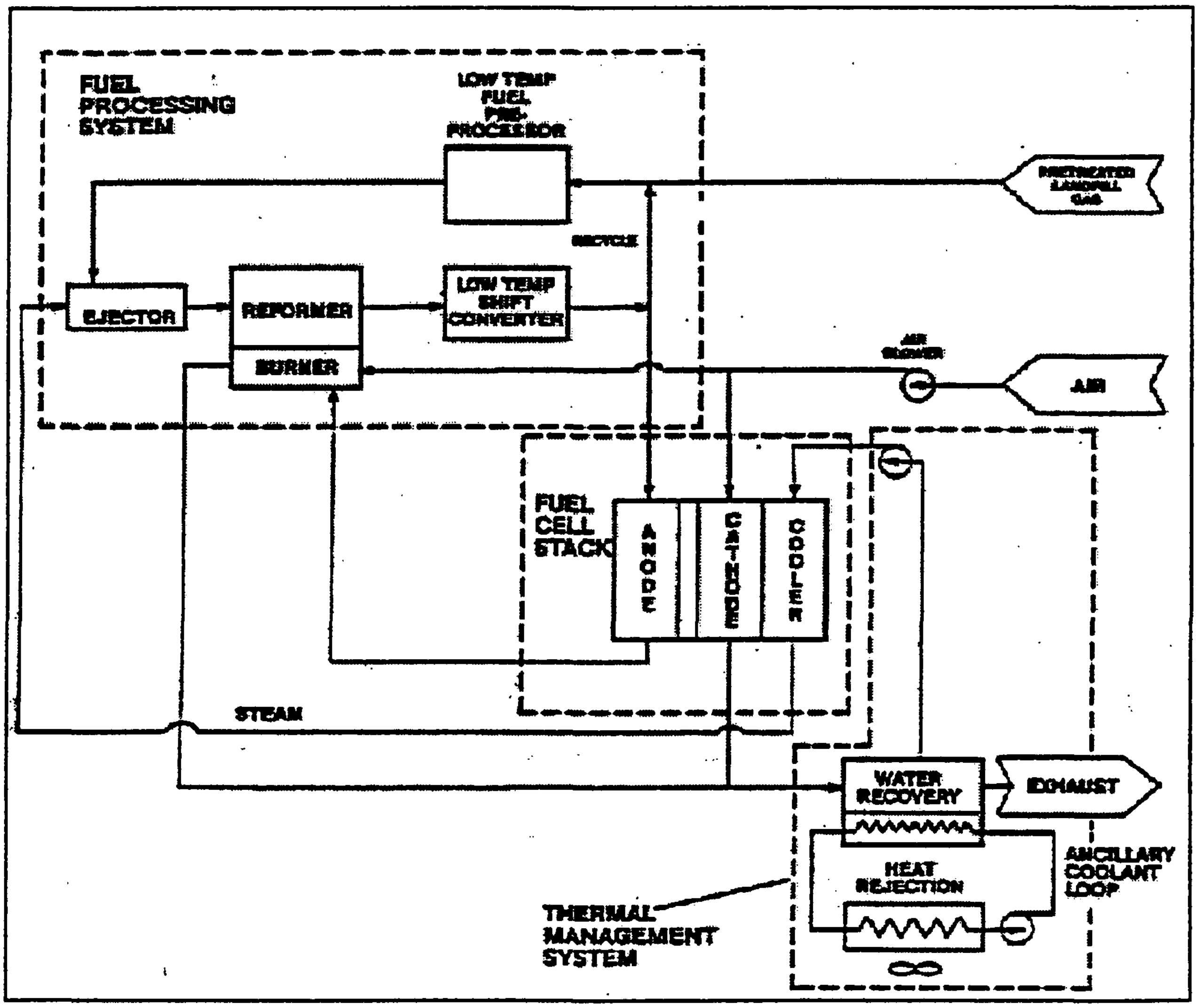

FIGURE 2. FUNCTIONAL SCHEMATIC FUEL CELL LANDFILL GAS POWER UNIT

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 operating on natural gas. A primary issue is to protect the fuel cell from sulfur and halide compounds in the landfill gas. A second issue is to provide mechanical components in the reactant gas supply systems to accommodate the large 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% above that anticipated from operation on natural gas. This is a result of the inefficiency of using the dilute methane fuel. The efficiency 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 fuel 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 1.

TABLE 1. PERFORMANCE COMPARISON FOR NOMINAL 200 KW OUTPUT

	Natural Gas Power Plant	Landfill Gas Power Plant
Fuel	Natural Gas	Landfill Gas
Electrical Efficiency (LHV) - %	40	36.4
Heat Rate (HHV) -kcal/kWhr	2,390	2,620
Available Heat - kcal/hr	192,000	208,000
Ambient Temperature for Fuel Water Recovery - °C	35	35
Startup Fuel	Natural Gas	Natural Gas

Landfill Gas Cleanup

Landfill gases consist primarily of CO_2, methane (CH_4), and nitrogen (N_2), plus trace amounts of hydrogen sulfide (H_2S), organic sulfur, organic halides, and non-methane hydrocarbons. N_2 is not a true constituent of landfill gas, but is drawn into the mix when vacuuming gas into the collection system. The concentration varies widely, with highest concentrations occurring from the landfill's perimeter wells. The specific contaminants in the landfill gas of concern to the fuel cell are sulfur and halides. Both of these components can "poison" and, therefore, reduce the life of the power plant's fuel processor. The fuel processor is the unit which converts CH_4 in the landfill gas into H_2 and CO_2 in an endothermic reaction over a catalyst bed. The catalyst in this bed can react with the halides and sulfides and lose its activity. This reaction, when it occurs, is irreversible.

The GPU, designed to remove fuel cell contaminants, is shown in Figure 3. H_2S is first removed by adsorption on a packed bed. The material which performs this function is a specially treated carbon, activated to catalyze the conversion of H_2S into elemental sulfur which is deposited on the bed. The reactions for the conversion of sulfur, the Claus reactions, are:

$$H_2S + 3/2\ O_2 \rightarrow H_2O + SO_2$$

$$SO_2 + 2H_2S \rightarrow 2H_2O + 3S$$

The bed is not regenerable on site, but must be removed to another site if regeneration is desired.

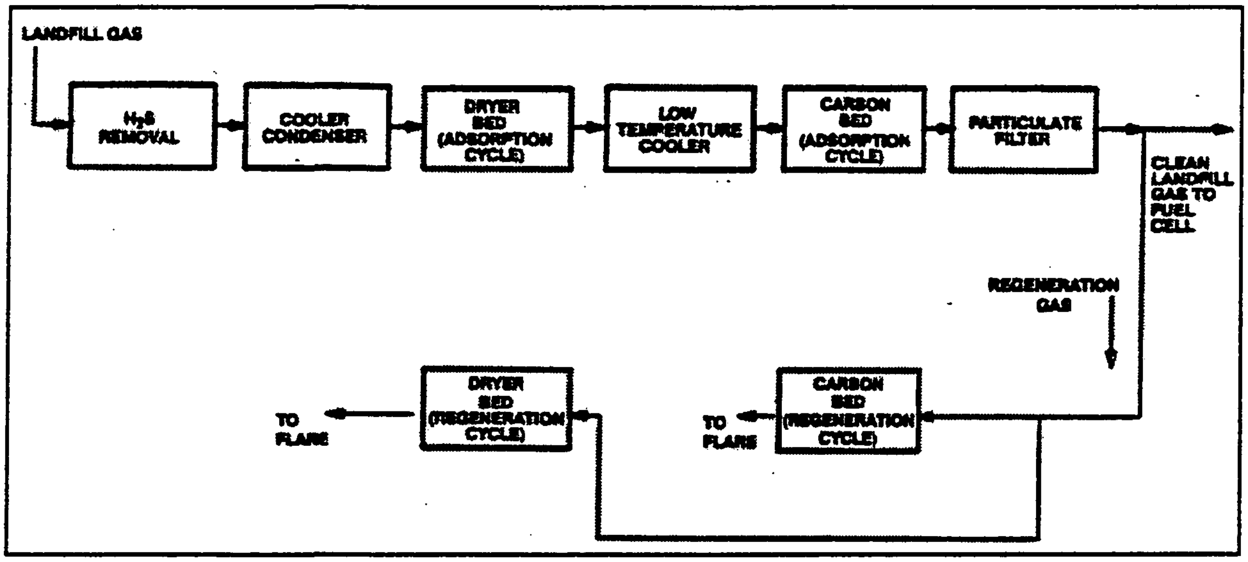

FIGURE 3. LANDFILL GAS PRETREATMENT SYSTEM

The first stage cooler removes water, some heavy hydrocarbons, and sulfides which are discharged as condensate to the landfill plant's existing water condensate treatment system. Most of the contaminant halogen and sulfur species are lighter and remain in the landfill gas to be treated in the pretreatment unit. Remaining water in the landfill gas, as well as some sulfur and halogen compounds, are removed in a regenerable dryer bed which has a high capacity for adsorbing the remaining water vapor in the landfill gas. There are two dryer beds so that one remains operational while the other is being regenerated.

The dry landfill gas is then fed to the second stage cooler. This cooler can be operated as low as -32°C and potentially can condense additional hydrocarbons if present at sufficient concentrations. The second stage cooler also reduces the temperature of the carbon bed, thereby enhancing its adsorption performance [4]. The downstream hydrocarbon adsorption unit, which has its temperature controlled by the second stage cooler, is conservatively sized to remove heavy hydrocarbon, sulfur, and halogen contaminant species in the landfill gas. This unit consists of two beds of activated carbon so that one remains operational while the other is being regenerated. Both the regenerable dryer and hydrocarbon removal beds operate on a nominal 16-hour cycle, with each set of beds operating in the adsorption mode for 8 hours and in the regeneration mode for 8 hours.

The gas then passes through a particulate filter and is warmed indirectly by an ambient air, finned-tube heat exchanger to attain a temperature above 0°C before being fed to the fuel cell unit.

GPU TEST RESULTS

The GPU depicted in Figure 3 has been successfully tested. Detailed results of the tests, along with the test plan, are contained in an EPA report [3]. The results of those tests will be summarized here.

After completing 216 hours of continuous operation and a total of 616 hours since the first GPU startup, performance testing was conducted over a 3 day period at the beginning, middle, and end of the regenerative cycle to evaluate performance over the normal 8-hour cycles on each of the two regenerative beds (dryer bed and carbon bed). At specific times in the regeneration cycles, Tedlar bag samples were collected from sampling manifolds located at the GPU inlet and outlet as well as at the flare inlet and outlet. These bag samples were analyzed off-site using gas chromatography/mass spectrometry (GC/MS) analysis for the volatile organic compounds (VOCs) and gas chromatography/flame photometric detection (GC/FPD) analysis for sulfur compounds. Additionally, sulfur compounds were measured at the GPU's inlet and outlet using on-line GC/FPD. No on-line or on-site measurements were utilized for VOCs because it was found that the landfill gas matrix could bias the results. This was determined via an audit using certified cylinder gases.

The results from one of the cycles are summarized in Table 2. All the measurements demonstrated that the GPU was very effective in removing the target sulfur compounds and VOCs. For sulfur compounds, the GPU outlet concentrations were either below detection limits (0.01 ppm for the on-line method and 0.004 ppm for the off-site analyses) or in the parts per billion concentration range. Likewise halogenated and other VOCs were below 0.002 ppm with the exception of methylene chloride, which was detected in trace levels of less than 0.02 ppm.

The fuel test data for the GPU flare have been summarized elsewhere [3]. It suffices to state that the flare destruction of VOCs and sulfur compounds exceeded 99%. Nitrogen oxides and carbon monoxide concentrations at the flare outlet average 10.4 and 3.0 ppm, respectively, over three test periods. Particulate matter averaged 0.03 mg/m^3.

TABLE 2. GPU INLET/OUTLET EMISSION TEST DATA

	1800-1900 Hour 1		1900-0100 Hours 2-7		0100-0200 Hour 8
Sampling Location	GPU Inlet	GPU Outlet	GPU Inlet	GPU Outlet	GPU Outlet
Reduced Sulfur Compounds (ppm)					
Sample Type	bag	bag	bag	on-line	on-line
hydrogen sulfide	92.7	<0.004	107	<0.01	<0.01
carbonyl sulfide	0.197	0.017	0.164	0.035	0.026
methyl mercaptan	2.91	<0.004	2.96	<0.01	<0.01
ethyl mercaptan	0.48	<0.004	0.47	<0.01	<0.01
dimethyl sulfide	6.51	<0.004	6.52	<0.01	<0.01
carbon disulfide	<0.07	<0.002	<0.07	<0.01	<0.01
dimethyl disulfide	<0.07	<0.002	<0.07	<0.01	<0.01
Total Reduced Sulfur - see note 1	104	0.017	118	0.035	0.026
Volatile Organic Halogens - GC/MS Analysis (ppm)					
Sample Type	bag	bag	bag	bag	bag
Compound					
dichlorodifluoromethane	0.83	<0.002	0.95	<0.002	<0.002
vinyl chloride	1.1	<0.002	1.2	<0.002	<0.002
methylene chloride	6.6	0.016	11	<0.002	<0.002
cis- 1,2-dichloroethene	4.3	<0.002	5.9	<0.002	<0.002
1,1-dichloroethane	1.9	<0.002	2.7	<0.002	<0.002
trichloroethene	1.3	<0.002	1.8	<0.002	<0.002
tetrachloroethene	2.7	<0.002	3.6	<0.002	<0.002
chlorobenzene	0.91	<0.002	1.4	<0.002	<0.002
Total Halogens (as halide) - see note 2	46.7	0.032	66.6	<0.002	<0.002
Volatile Organic Compounds - GC/MS Analysis (ppm)					
benzene	1.1	<0.002	1.4	<0.002	<0.002
toluene	28	0.005	36	<0.002	<0.002
xylenes	14.9	<0.002	21.2	<0.002	<0.002
ethyl benzene	6.1	<0.002	9	<0.002	<0.002
styrene	0.6	<0.002	0.81	<0.002<0.0	<0.002
acetone	<1.2	0.01	18	05	<0.005
2-butanone	5.2	<0.004	6.6	<0.004	<0.004
ethyl acetate	8.1	<0.002	10.8	<0.002	<0.002
ethyl butyrate	6.3	<0.002	8.4	<0.002	<0.002
alpha-pinene	10.8	<0.002	18	<0.002	<0.002
d-limonene	12.6	<0.002	36	<0.002	<0.002
tetrahydrofuran	1.3	<0.002	1.6	<0.002	<0.002

NOTES:
1. Total reduced sulfur is calculated as the sum of target compound concentrations as sulfur, plus the sum of any unknown sulfur compounds quantified as hydrogen sulfide.

2. Total halogen is calculated as follows: multiply each compound concentration by the number of halide atoms and total.

FUEL CELL TESTING

Fuel Cell Performance

The power plant used in the demonstration is a commercial ONSI PC25 200-kW phosphoric acid fuel cell. The power plant, designed to operate on pipeline natural gas, was shipped to and installed at the Penrose Landfill during 1994. The field test began on December 7, 1994, and ended on February 19, 1995, with eight operational test runs. During this period, the fuel cell operated for 707 hours on landfill gas. Power produced by the unit was fed into the electrical grid for sale to the local electrical utility, the Los Angeles Department of Water and Power (LADWP). It was the first fuel cell ever connected to the LADWP grid. The revenue produced by the sale of electricity was used to help offset program costs.

Because landfill gas has approximately half the heat content of natural gas, this fuel cell power plant cannot produce 200 kW of net power when operated on landfill gas. To increase the net power, higher flows of landfill gas would be required to obtain an equivalent natural gas fuel content and heating value. However, the required modifications to achieve fuel rated power were not accomplished for this project. The only modifications to the fuel cell were those that could be field installed under the direction of an IFC engineer, from modification kits designed and fabricated by IFC. The modifications included a larger fuel control valve and fuel flow venturi, a new process fuel recycle orifice, a new cathode exit orifice, and a new redundant start fuel shut-off valve. Additionally, there were modifications to the control software.

The fuel cell was operated at up to 137 kW, which is 3 kW below the goal for operation on the Penrose Landfill gas. An-endurance operating condition of 120 kW was selected for the bulk of the field test operations to provide a margin for steady fuel cell operation during periods of sub-standard gas quality, which occur periodically due to upsets in gas quality from the active landfill (Bradley) which supplies gas to the Penrose site. The fuel cell efficiency was calculated over two periods during the field test. The first period covered 6 days from January 24 through 30, 1995. Efficiency during this 6-day period of continuous operation was 37.1%. The second period covered 8 days from February 9 through 17, 1995. Average efficiency for this 8-day period, which included a brief shutdown, was 36.5%.

Table 3 presents results of emission testing of the PC25 power plant at the Penrose Landfill conducted during February 1995. The emission levels indicate that fuel cells can operate on landfill gas while maintaining the low emission levels characteristic of natural-gas-based fuel cells.

TABLE 3. EMISSION TEST* RESULTS FROM FUEL CELL OPERATING ON LANDFILL GAS

Pollutant	Fuel Cell Emission
Sulfur Dioxide (SO_2)	Non-detect**
Nitrogen Oxides (NO_x)	0.12 ppm, avg.
Carbon Monoxide (CO)	0.77 ppm, avg.

*Tests used EPA Methods 6c, 7e, and 10.
**Detection limit for SO_2 was 0.23 ppm; all data are dry measurements corrected to 15% O_2.

GPU Operation

The GPU consistently removed total halides (as HCl) from inlet levels of 45 to 60 ppm in the raw landfill gas to very low or undetectable levels at the outlet. During seven tests conducted between January 19 and February 17, 1995, there were no detectable halides (individual species detection limits range from 0.001 to 0.020 ppm). The results are consistent with the data contained in Table 2.

Total sulfur (as H_2S) was reduced from about 110 ppm (about 10 ppm from organic sulfur, plus 100 ppm H_2S) to between non-detectable and 0.385 ppm. The only sulfur species detected was carbonyl sulfide. The elevated levels of 0.173 to 0.385 ppm of cabonyl sulfide measured on February 9 and 10, 1995, are believed due to a slight increase in H_2S exiting the non-regenerable H_2S removal bed, since H_2S at the H_2S bed exit was measured at 1.0 to 2.7 ppm on February 14. Earlier laboratory work at IFC showed that H_2S is converted to carbonyl sulfide over the activated alumina in the downstream drier bed by the reaction $H_2S + CO_2 = COS + H_2O$, due to the removal of the product water by the alumina. The resulting carbonyl sulfide is not readily removed by the low temperature carbon bed. The non-regenerable H_2S removal bed was switched over to a fresh bed on February 15, 1995, and the exit H_2S level returned to non-detectable. The carbonyl sulfide level measured shortly after, on February 17, also fell to just 0.061 ppm.

DISCUSSION AND CONCLUSIONS

Emissions from landfills are potential contributors to global warming and hazardous air pollutants. Conventional methods to mitigate these emissions, such as flaring, produce other greenhouse gases, such as CO_2. Operating a fuel cell at a landfill site can eliminate CH_4, hazardous air pollutants, and other universal secondary emissions (CO, SO_2, NO_x), lowers total CO_2 emissions, and can permit efficient generation of electric power. In order to operate a fuel cell on landfill gas, the gas must be sufficiently purified. A landfill gas cleanup pretreatment module designed, constructed, and tested in this demonstration was successful. The combined gas cleanup system and power plant produced electrical power with low levels of air pollution.

Currently, the fuel cell/GPU is located on a landfill in Groton, Connecticut, as a follow-up to the earlier demonstration of the technology at the Penrose Landfill. This demonstration is scheduled to run for approximately 18 months during which time a significant amount of operating data will be acquired. Additionally, research will be conducted to refine the design of the GPU in order to simplify the required equipment. This demonstration is a partnership between EPA, the Town of Groton, and Connecticut Light and Power, with technical support from IFC.

It is expected that at least 1.6 million kWh of electricity will be generated over the test period. The fuel cell has produced a record 165 kW from the Groton Landfill gas, but the system is being operated at a conservative 140 kW to minimize inadvertent shutdown due to gas heat fluctuations.

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a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Electricity	Pollution Control	13B	20C
Fuel Cells	Heat	Stationary Sources	10B	20M
Methane		Gas Cleaning	07C	
Exhaust Gases			21B	
Earth Fills			13C	
Electric Power Plants				

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