Fuel cell energy recovery from landfill gas*

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Abstract

International Fuel Cells Corporation is conducting a US Environmental Protection Agency (EPA) sponsored program to demonstrate energy recovery from landfill gas using a commercial phosphoric acid fuel cell power plant. The US EPA is interested in fuel cells for this application because it is the cleanest energy conversion technology available. This paper discusses the results of Phase I, a conceptual design, cost, and evaluation study. The conceptual design of the fuel cell energy recovery concept is described and its economic and environmental feasibility is projected. 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 a demonstration of the energy recovery concept.

Introduction

The US Environmental Protection Agency (EPA) has proposed standards and guidelines [1] for the control of air emissions from municipal solid waste (MSW) landfills. Although not directly controlled under the proposal, the collection and disposal of waste methane, a significant contributor to the greenhouse effect, would result from the emission regulations. 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 US 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. Work was initiated in Jan. 1991. This paper discusses the results of Phase I, a conceptual design, cost, and evaluation study, which addressed the problems associated with landfill gas as the feedstock for fuel cell operation.

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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 planed 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 a 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, CA. 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 Sept. 1991 and Phase III activities are scheduled to begin in Jan. 1993.

Landfill gas

Availability

The MSW landfills in the US were evaluated to determine the potential power output which could be derived using a commercial 200 kW fuel cell. Each fuel cell would consume 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 1992 [2a]. An estimated 4370 MW of power could be generated from the 7480 existing and closed sites identified. The largest number of potential sites greater than 200 kW occurs in the 400 to 1000 kW range. This segment represents a market of 1700 sites or 1010 MW.

The 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.

As a result of the assessment, the conceptual design of the commercial concept was required to be modular and sized to have the broadest impact on the market.

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 designs.

A summary of landfill gas characteristics is shown in Table 1. 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% by volume of the gas composition with a typical value of 50%. 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% but typical values are 5% or less. Oxygen concentrations are monitored closely and held low for safety reasons.

TABLE 1

Landfill gas characteristics

Characteristic	Range	Typical
Heating value (HHV) (Btu/ft^3)	350–600	500
CH_4 (%)	35–58	50
CO_2 (%)	40–55	45
N_2 (%)	0–15[a]	5
O_2 (%)	0–2.5[a]	<1% (for safety)
Sulfur as H_2S (ppmv)	1–700	21
Halides (ppmv)	N/A	132
Non-methane organic compounds (NMOCs) (ppmv)	237–14000	2700

[a]Highest values occur in perimeter wells.

Landfill gas constituent compounds reported by EPA [2b] indicate a typical value for the total non-methane organic compounds (NMOCs) of 2700 ppmv (expressed as hexane). 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 in 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 [2c]. 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.

Emissions requirements

Existing US regulations do not address methane emissions from landfills directly. Proposed new EPA regulations [1] would control NMOCs 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% 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, especially in areas identified as non-attainment regions. For instance, non-attainment regions for ozone may lead to strict requirements for secondary emissions including NO_x, carbon monoxide and NMOCs. The best known example of strict local emission requirements is the South Coast Air Quality Management District (SCAQMD) in southern California.

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 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 US. The complete system incorporates the landfill gas collection system, a fuel gas pretreatment system and a fuel cell energy conversion system. In the fuel gas pretreatment section, the raw landfill gas is treated to remove contaminants to a level suitable for the fuel cell energy conversion system. The fuel cell energy conversion system converts the treated gas to electricity and useful heat.

Landfill gas collection systems are presently in use in over 100 MSW landfills in the US. 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.

Overall system description

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

The commercial energy conversion system shown in Fig. 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 concentrations. The output from the fuel cell is utility grade a.c. electric power. It can be transformed and put into the electric grid, used directly at nearby facilities, or used at the landfill itself. The power plants are capable of recovering co-generation heat for nearby use or rejecting it to air.

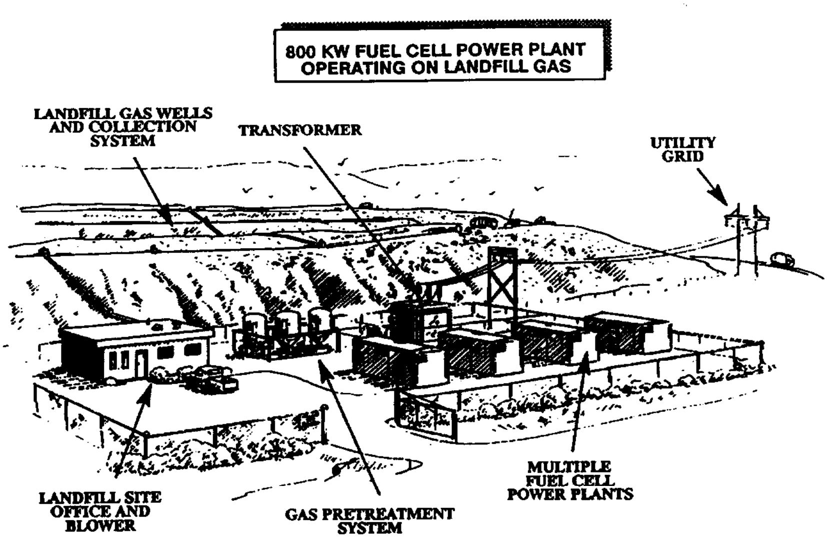

Fig. 1. Fuel cell energy recovery commercial concept.

As configured in Fig. 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 Fig. 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 significantly reduces the water content and removes the bulk of the heavier hydrocarbons from the landfill gas. This step provides flexibility to accommodate varying landfill characteristics by delivering a relatively narrow cut of hydrocarbons for the downstream beds in the pretreatment system. The second refrigeration step removes additional hydrocarbons by a proprietary process 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 a single site varying with time.

The three adsorbents are regenerated by using heated gas from the process stream. Each 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 Fig. 2. A small portion of the treated landfill gas (approximately 8%) is heated by regeneration with the incinerator gases and then passes through the beds in the sequence shown. 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 98% destruction of the NMOCs 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 cell power plant in an efficient, economic, and environmentally acceptable manner.

The pretreatment system design provides flexibility for operation on a wide range of landfill gas compositions, it has minimal solid wastes, high thermal efficiency, and low parasite power requirements. The pretreatment system is based upon modification of an existing system and utilizes commercially available components. The process train and operating characteristics need to be validated by demonstration. Key dem-

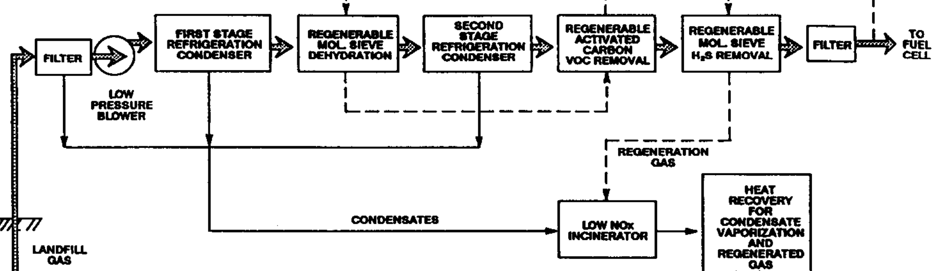

Fig. 2. Simplified block diagram of commercial landfill gas pretreatment system.

onstrations in Phase II will include: the achievement of low total halide contaminant levels in the treated gas; effectiveness of the regeneration cycle as affected by regeneration time and temperature; durability of the regenerable beds; and low environmental emissions.

The fuel pretreatment system described above was analyzed to estimate the overall thermal efficiency, internal electric power requirements and maintenance characteristics. The estimated thermal efficiency is 92% with the balance of thermal energy used for regeneration, vaporization of the condensate and incineration of regeneration gases. Electric power is used for pumping the gases and the refrigeration stages 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 and replacement of fully regenerated spent bed materials on an annual basis.

The pretreatment system was evaluated to define anticipated air emissions, and liquid and solid effluents. The incinerator is designed for 98% destruction of all NMOCs and NO_x emissions of less than 0.06 pounds per million Btu of fuel consumed. 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 factory and treatment by an approved reclamation processor.

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 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% 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.

Environmental and economic assessment of the fuel cell energy conversion system

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% methane with a heating value of 500 Btu per standard cubic foot.

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 NMOCs from the landfill gas system. For the example site considered, the methane elimination is essentially complete for both systems and 98% of the NMOCs 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% 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 kW h of electricity per year, with a net reduction of NO_x of 35.2 tons per year and a reduction of SO_x of 16.8 tons per year. 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. The data show that both the flare and the fuel cell mitigate methane and NMOCs under the proposed standards and guidelines [2]. However, the flare merely converts these emissions to CO_2, and rain and other unhealthy pollutants. The fuel cell can provide a net reduction in global pollution by offsetting energy production from coal.

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.

Economics

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 kW h to a low of 2.71 cents per kW h. The median rate in the US is approximately 7 cents per kW h. The rates charged to industry are generally

TABLE 2

Emissions impact of fuel cell energy recovery from landfill gas

Abatement technology	Global warming			Acid rain and health		
	Methane (Mg/yr.)	NMOC (Mg/yr.)	CO_2 (Mg/yr.)	SO_2 (Mg/yr.)	NO_x (Mg/yr.)	CO (Mg/yr.)
Venting [2] only	1.8×10^7	52100				
Flare	0	−10200	$+4.94\times10^7$	+2972	+29720	+14860
Fuel cell	0	−10200	-6.45×10^7	−53500	−259000	−8620

lower and are closer to the fully burdened avoided cost for the utility. These rates range from 10.0 cents per kW h to a low of 1.64 cents per kW h with the mean value of approximately 5 cents per kW h. 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 studied 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%. For this analysis, two levels of fuel cell installed costs were considered. The lower level 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 represents a price level when the power plant is being introduced into the marketplace, and is produced on a moderate and continuous basis.

Figure 3 shows the fuel cell revenues for the most stringent application situation (no emission credits or thermal energy utilization). 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 the mature product installed cost. At the entry cost the fuel cell is economical in those areas where the value of electricity is 9 cents per kW h or higher. This would primarily be areas such as California, New York, and other parts of New England. With the potential for revenue from thermal energy or emission offset credits, the economics become more competitive. Thus the applicability of the concept would become attractive to a broader market.

Other energy conversion systems could also produce electric and/or thermal energy. Both the internal combustion engine and the gas turbine engine have been suggested as options for methane mitigation at landfill sites. For the landfill size selected for

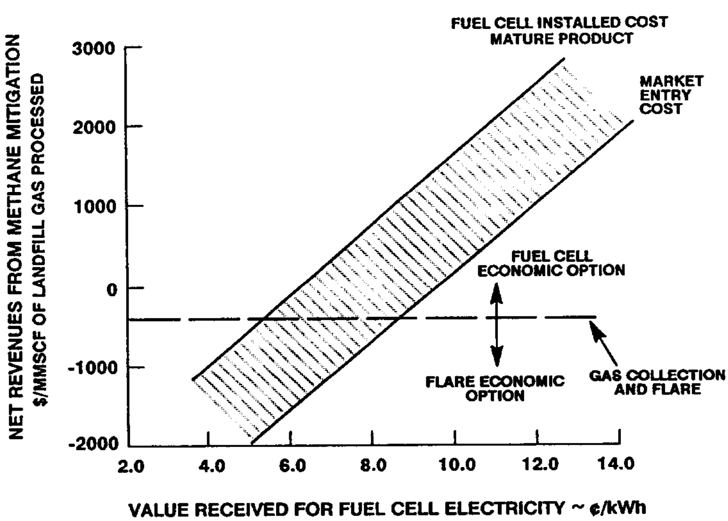

Fig. 3. Comparison of fuel cell to flare for methane mitigation assuming electric revenues only.

this analysis, the internal combustion engine is more effective than the gas turbine options for cleanup. This is used as the basis for the comparisons provided here. 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 NO_x emissions than a fuel cell unless special precautions are taken to clean the exhaust. For our analysis two cases were considered. The first case assumes no cleanup of the internal combustion engine exhaust, and the second assumes that the exhaust is cleaned with selective catalytic reduction (SCR). Since the SCR employs a catalyst in the cleanup system, the landfill gas will have to be pretreated in a manner similar to the fuel cell system. For those cases with a SCR cleanup system, a pretreatment system has also been included as part of the total system cost.

Figure 4 shows the results of the economic analysis for the fuel cell system and the internal combustion engine system. Since both systems can provide electricity, the comparison between the systems is based on the cost of electricity generated from the energy conversion system with appropriate credit for thermal sales and/or emission offsets. The fuel cell is competitive at the full mature price when no exhaust cleanup is required with the internal combustion engines. However, the operation of the internal combustion engine at the landfill site would be quite dirty, and significant amounts of NO_x 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 exhaust cleanup option is required. Consequently, the fuel cell option would be fully competitive with the internal combustion engine option for most cases where on-site cleanup of the internal combustion engine is required. In areas where a SCR would be employed to clean up an internal combustion engine exhaust, the fuel cell concept is competitive at entry level cost.

Based on the analysis of both the flare option 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.

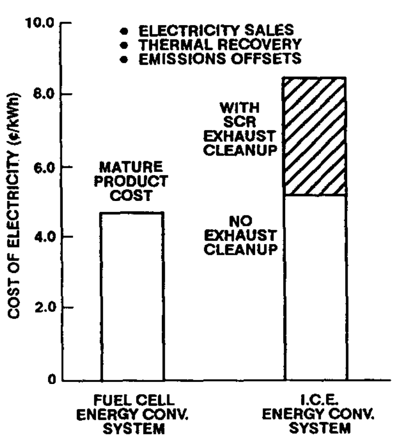

Fig. 4. Comparison of fuel cell to internal combustion engine energy conversion system.

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 a net reduction in total emissions while simultaneously mitigating the methane from the landfill gas.
- Fuel cells will be competitive at initial product prices on landfill sites located in high electric cost areas or where the thermal energy can be utilized. The fuel cell will also be attractive where there is a credit for the environmental impact of fuel cell energy conversion.
- 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 landfill owners. This could, in the long term, result in methane mitigation without additional cost to the ultimate consumer.

References

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