EPA-600/R-98-021

EMERGING TECHNOLOGIES FOR THE MANAGEMENT AND UTILIZATION OF LANDFILL GAS

by

Stephen Roe
Joel Reisman
Randy Strait
Michiel Doorn
E.H. Pechan & Associates, Inc.
2880 Sunrise Blvd., Suite 220
Rancho Cordova, CA 95742

EPA Contract No. 68-D30035
Work Assignment No. 3-109

Project Officer

Susan A. Thorneloe
Air Pollution Prevention and Control Division
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Prepared for:

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

January 1998

ABSTRACT

In October 1993, President Clinton released the U.S. Climate Change Action Plan, a blueprint for reducing emissions of greenhouse gases (GHGs) in the U.S. (Clinton and Gore, 1993). The plan is designed to reduce emissions of GHGs in the U.S. to 1990 levels by the year 2000 in a cost-effective manner. For landfills, the plan includes actions for increasing the stringency of landfill regulations to control emissions, an outreach program, and expansion of research and development (R&D) for methane (CH_4) recovery from landfills.

The U.S. Environmental Protection Agency (EPA) finalized regulations for new landfills, and guidelines for existing landfills, to reduce landfill emissions on March 12, 1996 (61 FR 49, 1996). However, the regulations do not require the utilization of landfill gas (LFG) to produce energy or other products. The EPA's Air Pollution Prevention and Control Division (APPCD) is conducting ongoing research to provide information on options for managing and utilizing LFG as a means of assisting landfill owners/operators that may be affected by the regulations. This report presents information on emerging technologies that are currently ready for commercialization (Tier 1), undergoing R&D [e.g., field- or bench-scale demonstrations (Tier 2)], or are being considered as potentially applicable (Tier 3) for: 1) the utilization of landfill-derived CH_4 and carbon dioxide (CO_2); or 2) the management of landfills to reduce emissions of CH_4 and other pollutants.

The technologies that are considered to be Tier 1 technologies include (1) phosphoric acid fuel cells (PAFCs), (2) conversion of CH_4 from LFG to compressed landfill gas (CLG) for vehicle fuel or other uses, and (3) use of CH_4 from LFG as a fuel for landfill leachate evaporation. International Fuel Cells Corporation (IFC) was awarded a contract by EPA to demonstrate energy recovery from LFG using a commercial PAFC. Major advantages of this technology are its high energy efficiency, minimal by-product emissions, and minimal labor and maintenance. The technical feasibility of CLG production for use as vehicle fuel has been commercially demonstrated using different processes in the U.S. and abroad by the Los Angeles County Sanitation Districts (LACSDs) and a French firm (the SITA Group). The economic feasibility of the technologies employed in the U.S. has hinged on the availability of a sufficient user vehicle fleet. LFG is also being used in the U.S. to evaporate landfill leachate and LFG condensate.

Technologies that are undergoing R&D and presented here at the Tier 2 level include operation of landfills as either anaerobic or aerobic bioreactors, production of methanol from LFG, production of CO_2 from LFG, and use of LFG to provide heat and CO_2 to greenhouses. Operation of landfills as bioreactors is considered to be LFG management technologies, although energy production can also be enhanced during operation of landfills as anaerobic bioreactors. The overall objective of both bioreactor approaches is to enhance waste degradation to stabilize the waste over a much shorter time-frame.

A major advantage of methanol production (as well as CLG production) is that LFG could be utilized as a resource to produce clean vehicle fuels that provide significantly lower emissions relative to gasoline and diesel fuels. At the same time, the air quality and human health impacts associated with flaring LFG are minimized. Technologies are developing to produce high-purity liquid CO_2 and liquefied landfill gas (LLG) from raw LFG. This technology offers a unique opportunity for controlling both CH_4 and CO_2 from LFG to produce commercial products. LFG is also being used at sites in the U.S. and Canada to produce heat in commercial greenhouses. For the Canadian project, LFG is also being used to enhance CO_2 levels (for optimizing plant growth) in commercial greenhouses.

Technologies that are considered as potentially applicable for LFG (Tier 3) include the Stirling and Organic Rankine Cycle (ORC) engines. These two technologies could potentially use waste heat from flares used to control landfills to generate mechanical energy. However, they have not yet undergone field demonstration at a landfill to determine if they are technically and economically feasible.

TABLE OF CONTENTS

(Continued)

TABLE OF CONTENTS (Cont.)

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

This report was prepared by Stephen Roe and Joel Reisman of E.H. Pechan & Associates, Inc., Rancho Cordova, CA and Randy Strait and Michiel Doorn of E.H. Pechan & Associates, Inc., Durham, NC (M. Doorn is currently with Acurex Corporation). The work was sponsored by the U.S. Environmental Protection Agency's Air Pollution Prevention and Control Division and Control Technology Center. The authors are particularly grateful for the guidance provided by the EPA Project Officer, Susan Thorneloe. The authors would also like to acknowledge the assistance of the following individuals in both the public and private sector who provided technical data and/or provided a review of the information presented in this report:

William Beale, Sunpower, Inc., Athens, OH
William Brown, Acrion Technologies, Inc., Cleveland, OH
John Comas, Commonwealth of Massachusetts, Boston, MA
William Ernst, Mechanical Technology, Inc., Latham, NY
Lewis Goodroad, South Carolina Energy Research and Development Center, Clemson, SC
Elson Hanson, E.H. Hanson Engineering Group, Ltd., Delta, BC
Mark Hudgins, American Technologies, Inc., Aiken, SC
Steve Maguin, Los Angeles County Sanitation Districts, Whittier, CA
John Pacey, EMCON Associates, San Mateo, CA
Phillip Tracy, Gas Resources Corporation, Englewood, CO
John Trocciola, International Fuel Cells Corporation, South Windsor, CT
Mike Walker & Larry Connor, Pacific Energy, West Plains, MO
Ed Wheless, Los Angeles County Sanitation Districts, Whittier, CA
Ramin Yazdani, Yolo County Department of Public Works and Transportation, Davis, CA

ABBREVIATIONS

AGA	American Gas Association
APPCD	Air Pollution Prevention and Control Division
ASE	Automotive Stirling engine
ATI	American Technologies, Incorporated
BOD	Biological oxygen demand
CARB	California Air Resources Board
CLG	Compressed landfill gas
CNG	Compressed natural gas
COD	Chemical oxygen demand
CONEG	Coalition of Northeast Governors
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FC	Fuel cell
GFI	Gaseous fuel injection
GHG	Greenhouse gas
GMC	General Motors Corporation
GPU	Landfill gas pretreatment unit
GRC	Gas Resources Corporation
IFC	International Fuel Cells Corporation
IHC	International Harvester Company
LACSD	Los Angeles County Sanitation Districts
LES	Leachate Evaporation System
LEV	Low-emission vehicle
LFG	Landfill gas
LLG	Liquefied landfill gas
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether
MTI	Mechanical Technology Incorporated
NGV	Natural gas vehicle
NMHC	Non-methane hydrocarbon
NMOC	Non-methane organic compound
O&M	Operation and maintenance
ORC	Organic Rankine Cycle
OWT	Organic Waste Technologies, Inc.
PAFC	Phosphoric acid fuel cell
PEI	Perennial Energy, Inc.
R&D	Research and development
REPI	Renewable Energy Production Incentives
RFG	Reformulated gasoline
RIC	Reciprocating internal combustion
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
STC	Southeastern Technology Center
STM	Stirling thermal motors
syn-gas	Synthesis gas
TCLP	Toxicity Characteristic Leaching Procedure

(Continued)

ABBREVIATIONS (Cont.)

TDS	Total dissolved solids
TLEV	Transitional low-emission vehicle
TMI	TeraMeth Industries
TOC	Total organic carbon
ULEV	Ultra-low-emission vehicle
VOC	Volatile organic compound
YCCL	Yolo County Central Landfill

SYMBOLS

Btu	British thermal unit (1 Btu = 1.055 kilojoules)
°C	Degrees Celsius (°F = 9/5 °C+32)
CH_4	Methane
Cl^-	Chloride
CO	Carbon monoxide
CO_2	Carbon dioxide
°F	Degrees Fahrenheit [°C = 5/9 (°F-32)]
ft	Foot or feet (1 ft = 0.3048 meter)
gal	Gallon (1 gal = 3.785 liters)
GGE	Gallons of gasoline-equivalent
gpd	Gallons per day
H_2	Hydrogen
HC	Hydrocarbon
H_2O	Water
hp	Horsepower [1 hp = 1.0139 horsepower (metric)]
hr	Hour
H_2S	Hydrogen sulfide
kW	Kilowatt
kWh	Kilowatt-hour
L	Liter (1 L = 0.2642 gallon)
lb	Pound (1 lb = 0.4536 kilogram)
mg	Milligram (1 mg = 0.0154 grain)
MMBtu	Million Btu (1 MMBtu = 1.055x10^6 kilojoules)
MMscf	Million standard cubic foot or feet (1 MMscf = 0.0283x10^6 standard cubic meters)
MW	Megawatt
MWh	Megawatt-hour
NO_x	Nitrogen oxides
Nm^3	Normal (dry standard) cubic meter (1 Nm^3 = 35.31 normal cubic feet)
O_2	Oxygen
PM	Particulate matter
PM_{10}	Particulate matter less than 10 micrometers in diameter
ppb	Parts per billion
ppbv	Parts per billion by volume
ppm	Parts per million
ppmv	Parts per million by volume
psi	Pounds per square inch (1 psi = 0.06804 atmosphere)
scf	Standard cubic foot or feet (1 scf = 0.0283 standard cubic meter)
scfd	Standard cubic foot or feet per day
scfh	Standard cubic foot or feet per hour
scfm	Standard cubic foot or feet per minute
sg	Specific gravity
SO_2	Sulfur dioxide
tpd	Tons per day (1 tpd = 0.9072 megagram per day)

1.0 INTRODUCTION

In October 1993, President Clinton released the U.S. Climate Change Action Plan, a blueprint for reducing emissions of GHGs in the U.S. (Clinton and Gore, 1993). The plan is designed to reduce emissions of GHGs in the U.S. to 1990 levels by the year 2000 in a cost-effective manner. For landfills, the plan includes actions for increasing the stringency of landfill regulations to control emissions, the establishment of the Landfill Methane Outreach Program, and expansion of R&D for CH_4 recovery from landfills.

The EPA finalized regulations for new landfills, and guidelines for existing landfills, to reduce landfill emissions on March 12, 1996 (61 FR 49, 1996). However, the regulations do not require the utilization of LFG to produce energy or other products. Of the landfills expected to be constructed over the next 5 years, about 45 are estimated to require LFG collection and control systems. For existing landfills with capacities greater than 2.5 million megagrams, approximately 300 will be required to install collection and control systems (Roqueta, 1997). Projects using current technologies for LFG utilization that are operational or planned for use in the U.S. are summarized in Table 1-1.

Table 1-1. Operational or Planned LFG Utilization Projects

Technology	Operational Facilities	Construction/ Advanced Planning	Capacity Range of Installed Facilities (kW) or Equivalent
Reciprocating Engines	89	>30	80 - 12,300
Gas Turbines	22	4	740 - 16,500
Combined Cycle	2	1	13,600 - 20,500
Boiler/Steam Turbine	5	1	7,000 - 50,000
Medium Btu Fuel	27	11	300 - 17,000
High Btu/Vehicle Fuel	5	5	800 - 19,000

NOTE: kW = kilowatt, Btu = British thermal unit.
Adapted from Roqueta, 1997.

The EPA's APPCD is conducting ongoing research to provide information on options for managing and utilizing LFG as a means of assisting landfill owners/operators that may be affected by the regulations. The purpose of this report is to present information on emerging technologies for managing or utilizing CH_4 and CO_2 from municipal solid waste (MSW) landfills. Essentially, these are technologies other than those which have been in commercial use for at least several years. Examples of these well-established technologies are shown in Table 1-1 and include electricity generation with reciprocating internal combustion (RIC) engines and gas or steam turbines and production of medium British thermal unit (Btu) fuel for input to boilers (for process or space heating).

The technologies that are presented in this report are divided into three tiers: Tier 1 technologies are those that are considered to be commercially available in the U.S.; Tier 2 technologies are those that are currently undergoing additional R&D, have been tested at the bench- or field-scale, and may be ready for commercial application; and Tier 3 technologies are those that may have applicability to LFG utilization or management based on applications with similar fuel types (e.g., natural gas). The differentiation of technologies is based on technical demonstration of a project and is not meant to imply that a particular technology will be economically viable (i.e., profitable) at any given site. However, at a minimum, the technologies described in this report should help an MSW landfill owner or operator to offset the costs of controlling landfill emissions.

The report is not intended to represent an exhaustive review of emerging technologies for the management or utilization of LFG, but those processes that are being demonstrated, are planned for demonstration, or that are technically-feasible. The array of technologies presented, as well as the level of detail provided, are limited by the information made available by the technology developers. Discussion of the emerging technologies is based on information that was made available to EPA as of September 1997.

It is recognized that in addition to new technologies for LFG utilization and management, advancements are being made to existing technologies (such as those shown in Table 1-1). However, information on the improved performance and emission reduction capability is not readily available. In response to this, EPA is establishing the Center for Technology Verification for Greenhouse Gas Emissions (the Center). Landfill methane is to be one of the priorities of the Center. There is $2,000,000 in funding for 1997 and EPA will make data available from technology verification studies on the performance of either existing or emerging technologies. Additional information on the Center's program can be found at the web site: http://www.epa.gov/etv. Future updates to the information provided in this report will include data resulting from research carried out through the Center. Although the focus of the Center is on GHG emissions, information obtained on emission reductions of other pollutants and energy efficiency will also be provided, as it becomes available.

1.1 Overview of the Report

Section 2.0 of this report contains a discussion of Tier 1 technologies. These technologies have been demonstrated at a commercial level and show promise for economic viability at various scales of application:

- Use of phosphoric acid fuel cells (PAFCs) for generating electricity and waste heat;
- Conversion of CH_4 from LFG to compressed landfill gas (CLG) for vehicle fuel; and
- Utilization of CH_4 from LFG to evaporate landfill leachate and LFG condensate.

Tier 2 technologies are described in Section 3.0. These technologies are currently undergoing additional R&D and have been demonstrated either at the bench- or field-scale. Included in this group are:

- Operation of landfills as either anaerobic or aerobic bioreactors;
- Production of methanol from LFG;
- Production of commercial CO_2 from LFG; and
- Use of LFG for heating and CO_2 enhancement in greenhouses.

Tier 3 technologies are presented in Section 4.0. These technologies are considered to be potentially applicable for LFG management and utilization. These technologies include the Stirling and ORC engines.

For those technologies that are considered to be technically-feasible at a commercial scale (Tier 1), the report provides an introduction and general overview of the demonstration project, a project history (of known projects), a process description, information on performance, a discussion of air emissions and secondary environmental impacts, and available information on project economics. For Tier 2 technologies, an introduction and general overview of the technology is followed by a process description and information on air emissions and costs. For the Tier 3 technologies, the report provides information on the process, current usage, potential for use on LFG, and potential air emissions and costs.

All of the above-mentioned information for each technology is given to the extent that the developers were able to provide such information. The development of LFG management and utilization technologies is ongoing. Therefore, interested readers should contact the technology developers identified in each section of the report for the most current information.

1.2 Incentives for LFG Utilization Projects

1.2.1 Tax Incentives

There are currently two federal tax incentive programs that may apply to LFG, *Tax Credit for Producing Fuel from Nonconventional Sources*, Section 29 of the Internal Revenue Code, and *Renewable Energy Production Incentives* (REPI). Some states have their own tax incentive programs as well.

Section 29 - Tax Credit for Producing Fuel from Non-Conventional Sources—
Section 29 provides a tax credit for the production and sale of certain non-conventional fuels, including LFG. Section 29 was enacted by congress in 1980 and has been extended four times, the last extension being granted August 20, 1996, as part of the Small Business Job Protection Act of 1996, however a fifth extension appears to be unlikely (Hickman, 1997). To be eligible, a LFG facility must have had a written binding contract by December 31, 1996, and must be placed in service by June 30, 1998 (per key elements of the fourth extension). The value of the tax credit (established April 1997) is $1.0259 per million Btu (MMBtu), based on $5.95 per Equivalent Barrel of Energy [i.e., 42 gallons (gal) of oil equaling 5.8 MMBtu].

To qualify for the credit, the gas must be sold to an unrelated party. No tax credit is available for the production of electricity. Facilities placed into service after January 1, 1993 may receive the tax credits on fuel produced and sold through 2007. Facilities in service prior to 1993 may receive tax credits through 2002.

REPI—
REPI was authorized by section 1212 of the Energy Policy Act of 1992 to provide incentives to advance the commercialization and use of electricity generating systems using renewable energy. The program provides state-owned and non-profit electric cooperatives (who would not otherwise benefit from a tax-incentive program) financial incentives for the production and sale of electricity using certain renewable resources, subject to the availability of annual appropriations. Facilities must begin their initial operation between October 1, 1993 and September 30, 2003. Qualified facilities are eligible for production payments for the first ten fiscal years of their operation. Payments, subject to available appropriations, are based on 1.5 cents per net kilowatt-hour (kWh) produced (1993 dollars) and are adjusted for inflation. Payments are to be made only for "electric energy generated and sold."

Qualified renewable energy facilities include solar, wind conversion, biomass energy systems (including LFG), and geothermal systems. However, so-called "closed-loop" biomass systems, where energy is derived from dedicated plant crops are considered "Tier 1" facilities and are treated differently than "open-loop" systems, such as CH_4 gas collected from a landfill (classified as Tier 2 facilities). Payments are made to Tier 1 facilities (i.e., solar, wind, geothermal, closed loop, etc.) first. If funds are available after Tier 1 facilities are paid, Tier 2 qualifying facilities, such as open-loop biomass technologies (which include LFG) are paid with remaining funds. If there are insufficient funds to make full payments to all Tier 2 qualifying facilities, payments are made to those facilities on a pro rata basis. This funding priority reflects the tax treatment of new generation technologies as contained in sections 1914 and 1916 of the Energy Policy Act of 1992. REPI incentives are viewed by developers with caution because funds are subject to annual appropriation decisions by Congress.

1.2.2 Other Incentives

There are several other non-regulatory federal government incentives for LFG projects. EPA operates one of the most important programs, the Landfill Methane Outreach Program, which is part of the Climate Change Action Plan. This program assists MSW landfill owners/operators, States, Tribes, utilities, and other federal agencies in promoting the use of LFG as an energy resource. Some of the outreach services include providing information to increase awareness of project opportunities, and enhance the understanding of environmental, energy, and economic benefits of LFG projects. The outreach program works with Federal and state regulators to streamline the regulations and permitting procedure. The program works with utilities and energy purchasers to increase project recognition of the environmental value of energy recovery and its energy resource benefits (EPA, 1996).

The U.S. Department of Energy (DOE) has ongoing programs to encourage the development of LFG projects. The Climate Challenge Program is an initiative where utilities agree to achieve GHG reductions in ways that make sense for them. Voluntary Reporting is a program in which utilities are eligible to report methane reductions from landfill energy recovery projects.

1.2.3 State Incentives

In the past, several states have passed laws requiring utilities to pay certain qualifying facilities, such as alternative and renewable energy facilities (including LFG facilities), more than the utilities' avoided cost for electricity. In January 1995, the Federal Energy Regulatory Commission found that these laws violate the Public Utility Regulatory Policies Act of 1978, which holds that a utility should not be required to pay more than their avoided cost to any entity.

At present, many utilities’ avoided costs are too low to offer revenues adequate to support an LFG to electricity facility because the utilities do not plan to install additional generating capacity in the near term. In addition, the current restructuring on the electric industry may result in an industry where consumers purchase power from independent suppliers and utilities simply deliver the power. This could make the concept of “utility avoided cost” somewhat meaningless.

Restructuring of the electric industry offers new potential markets for electricity generated from LFG and other renewables by allowing the LFG facility to sell power directly to a consumer. Another alternative is the sale of LFG fueled power to a power marketer that aggregates power from a variety of sources, and resells it to the consumer. It is unclear whether LFG fueled power will be able to compete in these new markets as restructuring is expected to reduce electricity prices. Recent surveys indicate that some consumers are willing to pay a premium above standard electricity rates for “Green Power”, but the results of these surveys have not been tested in the marketplace. Even with limited consumer purchases of higher priced “Green Power”, state incentives will continue to be important for continued LFG utilization. Examples of state incentives are (1) exemptions from various state taxes for LFG facility operators, (2) a requirement that renewables comprise a minimum percentage of the power supply mix of each utility or power supplier, and (3) financing assistance including low interest or interest-free loans from the state to the LFG facility.

2.0 COMMERCIALLY AVAILABLE (TIER 1) TECHNOLOGIES

Information on technologies that are ready for commercial application in the U.S. is presented in this section. The projects described cover the following technologies:

- Use of PAFCs for generating electricity and waste heat;
- Conversion of CH_4 from LFG to CNG for vehicle fuel; and
- Utilization of CH_4 from LFG to evaporate leachate.

All of these projects require the processing of LFG to remove contaminants and use gas cleaning technologies that have already been developed and demonstrated. Therefore, this report does not provide a detailed discussion of the gas cleaning technologies, unless the developer of the emerging technology has modified an existing gas cleaning technology. Several technologies have been developed to process LFG to remove contaminants to meet specifications for pipeline quality gas (i.e., 91 percent CH_4) or for other purposes. An excellent summary of the various gas cleaning technologies that have already been developed is presented in an early study by EMCON Associates, CalRecovery Systems, Inc., and Gas Recovery Systems, Inc. (1981).

2.1 Phosphoric Acid Fuel Cells

2.1.1 Introduction and General Overview

Fuel cells may be compared to large electrical batteries (with ancillary equipment, such as catalysts) which provide a means to convert the chemical bonding energy of a chemical substance directly into electricity. The difference between a battery and a FC is that, in a battery, all reactants are present within the battery and are slowly being depleted during battery utilization (though they can be regenerated in rechargeable batteries). In a FC, fresh reactants (fuel) are continuously supplied to the cell. A simple schematic of a FC is shown in Figure 2-1. Oxygen ions (from air) pass from the cathode, through an electrolyte (which allows passage of oxygen ions but not electrons), and combine with hydrogen ions and carbon at the anode (derived from a hydrogen-rich fuel) to form water [as steam, (H_2O)] and CO_2. Fuel cells are differentiated, in part, by the type of electrodes and electrolytes used in their construction.

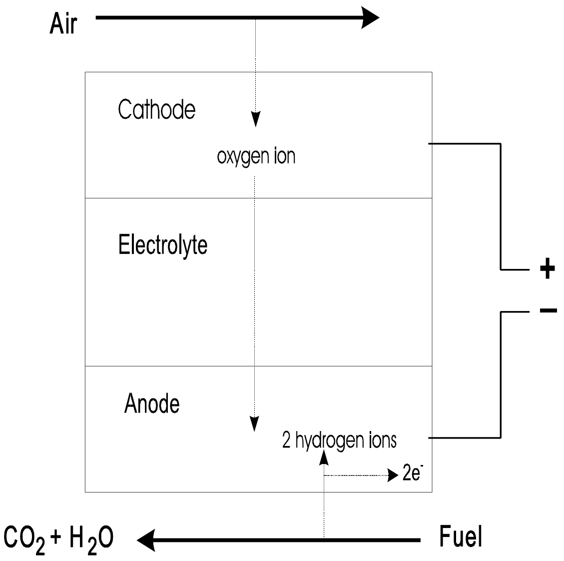


Figure 2-1. Simplified Schematic of a Hydrogen-Oxygen FC

There are four basic types of FCs, each of which has a different combination of performance characteristics. One type, the PAFC, is ahead of the others in its developmental stage and has been demonstrated commercially on landfill gas. PAFCs are suitable for utility distributed power use, commercial light industrial use, and heavy vehicular use (Arthur D. Little, Inc., 1993; Hirschenhofer et al., 1994). The other FC types (molten carbonate, solid oxide, and solid polymer) are in varying stages of development and demonstration and may be ready for the market in 10 to 20 years (Arthur D. Little, Inc., 1993). None of these have been demonstrated on LFG. Commercial PAFCs use hydrogen gas or reformed methanol as fuel sources to produce electricity. The hydrogen gas may be bought in purified form for small scale applications, or it may be obtained via conversion from a hydrogen containing fuel, such as natural gas, LFG, digester gas, or alcohols.

Compared to traditional power generation technologies, FC technology has two distinguishing performance characteristics:

- high electrical conversion efficiency levels (i.e., 40 to 50 percent) are maintained over a wide range of capacity levels: traditional technologies (e.g., fossil-fuel power plants) typically achieve efficiencies of 33 to 35 percent. Efficiencies are expected to increase to the 50 to 60 percent range in the near future, and if the waste heat from the FC is utilized (e.g., in a cogeneration system) overall efficiencies could exceed 85 percent (DOE, 1997a); and

- air emissions from FC systems are extremely low: due to their efficiency, CO_2 emissions are reduced for the same amount of power produced (as compared to traditional power sources). Also, FCs powered on natural gas have nitrogen oxide (NO_x) emissions of about 0.0004 pounds per megawatt-hour (lb/MWh) (DOE, 1997a). As a comparison, a coal-fired power plant using staged-combustion (achieving 25 percent NO_x control) and achieving a plant heat rate of 1,035 Btu per kWh would have NO_x emissions of about 6.5 lb/MWh (Roe et al., 1995). A highly controlled boiler (e.g., using selective catalytic reduction to achieve another 80 percent control) would still release about 1.3 lb/MWh.

In addition, FCs have other advantages such as low labor and maintenance requirements and minimal noise impact. Furthermore, FC plants are inherently modular, making the technology applicable to a wide range of landfill sizes. Power plants can be configured from 0.025 megawatts (MW) up to 50 MW. FCs also have the advantage of fuel flexibility. The primary source of fuel for the FC is hydrogen, which could be obtained from a number of potential backup hydrocarbon (HC) fuels (e.g., natural gas, methanol, other liquid fuels) as long as the gas processing system is properly designed (DOE, 1997a).

The major technical consideration associated with the application of FCs to LFG projects is the gas purification system. The major non-technical consideration associated with fuel cells in general has been the capital cost of the technology. To further evaluate the technical and non-technical feasibility for the application of FC technology to LFG utilization, EPA provided funding to IFC, a subsidiary of United Technologies Company, to demonstrate energy recovery from LFG using their commercial PAFC power plant. The following discussion summarizes the results of this successful project. It is also worth mentioning that plans are already underway for another PAFC project at a closed New England landfill. The preliminary plans for this project include selling the waste heat from the PAFC to an adjacent hotel (Trocciola, 1997).

2.1.2 EPA's LFG FC Project

IFC was awarded an EPA contract to demonstrate energy recovery from LFG using their PC25 commercial PAFC. The design of the LFG energy utilization system is based on providing a modular, packaged, energy conversion system which can operate on LFG over a wide range of compositions as typically found in the U.S.

The system is laid out to process approximately 18,000 standard cubic feet per hour (scfh) of LFG and incorporates the LFG collection system, landfill gas pretreatment unit (GPU), and a FC energy conversion system. In the fuel gas pretreatment section, the raw LFG is treated to remove contaminants to a level suitable for the FC energy conversion system. The FC energy conversion system converts the CH_4 in the treated LFG to hydrogen which serves as fuel for the FC. In the PAFC, hydrogen and oxygen from air are used to create electricity and steam. The system is capable of recovering waste heat for nearby use; otherwise, waste heat is discharged to the ambient air.

The PAFC research program was divided into three phases. Phase I, initiated in January 1991, was a conceptual design, cost, and evaluation study which addressed the problems associated with LFG as the feedstock for FC operation (Sandelli, 1992).

Phase II of the program included construction and testing of the GPU to be used in the demonstration. Its objective was to determine the effectiveness of the pretreatment system design to remove critical FC catalyst poisons such as sulfur and halides. The section below describes the pretreatment equipment. Phase II activities began in September 1991, and were completed in early 1994 (Trocciola and Preston, 1995).

Phase III of the program was a demonstration of the FC energy recovery concept using LFG. During this phase, IFC installed and operated a GPU and a 200 kilowatt (kW) PAFC. The location was Penrose Station, an existing landfill gas-to-energy facility owned by Pacific Energy in Sun Valley, California. Penrose Station is an 8.9 MW RIC engine facility supplied with LFG from four landfills. The electricity produced by the demonstration was sold to the electric utility grid. Phase III activities began in October 1994, and after successful completion of the demonstration, the FC was moved to Connecticut for additional testing. Results of the Phase III work are described below.

Additional field testing was conducted with the equipment at the Groton landfill in Connecticut beginning in July of 1996 by IFC in conjunction with EPA and Northeast Utilities. As of May 1997, the GPU had been run for a total of 3,166 hrs (over 29 test runs) and the FC had been run for a total of 2,350 hrs (over 15 test runs). Additional details on this test program and system performance are given below (IFC, 1997).

Northeast Utilities (current operator of the equipment) and the town of Groton, CT have plans to operate the FC for several years. Further, negotiations are currently ongoing to install a greenhouse on-site in order to utilize the waste CO_2 and heat from the FC (Borea, 1997).

GPU—

The fuel pretreatment system has provisions for handling a wide range of gas contaminants. Multiple pretreatment modules can be used to accommodate diverse landfill sizes. The collection system delivers raw LFG at approximately ambient pressure to the GPU. In the GPU, the gas is treated to remove halide and sulfur compounds [especially hydrogen sulfide (H_2S)], and non-methane organic compounds (NMOCs). The system was designed to achieve a maximum exit level of 3 parts per million by volume (ppmv) sulfur (as H_2S) and 3 ppmv total halide [as chloride (Cl^-)]. A block diagram of the GPU is shown in Figure 2-2 (Spiegel et al., 1997).

The GPU first removes H_2S by adsorption on a packed carbon bed (carbon impregnated with potassium hydroxide). This bed is not regenerable, so the spent carbon must be sent off-site for regeneration or disposed of in a landfill. Next, the system incorporates two stages of refrigerated condensation. The use of staged condensation provides tolerance to varying concentrations of LFG constituents (e.g., NMOCs). The first refrigeration stage [2 degrees Celsius (°C)] significantly reduces the H_2O content and removes the bulk of the heavier HCs from the LFG. This step provides flexibility to accommodate varying landfill characteristics by delivering a relatively narrow cut of HCs for the downstream beds in the GPU. Inbetween the first and second refrigeration stages, two regenerable dryer beds are used (one is in use, while the other is being regenerated). Each bed contains both activated alumina and Davidson 3 angstrom molecular sieve. The primary function of these regenerable beds is to remove additional H_2O to prevent freezing in the second condensation stage.

The second condensation stage occurs at -28 °C. This stage of refrigeration may condense out heavier HCs, if they are present at high enough concentrations. In addition, this step reduces the temperature of the next carbon bed downstream which increases its performance. The condensate from both refrigeration stages is discharged to a condensate treatment system (no condensate was collected in the second stage during the Penrose test program). The second refrigeration stage and the final activated carbon filter remove the remaining HCs, including halides and organic sulfur. Two regenerable beds are used in the final activated carbon adsorption step, as with the first, so that one can be regenerated while the other is operating. Finally, the gas passes through a filter to remove particulate matter (PM) and is warmed indirectly by an ambient-air finned tube heat exchanger before being fed into the unit (Spiegel et al., 1997).

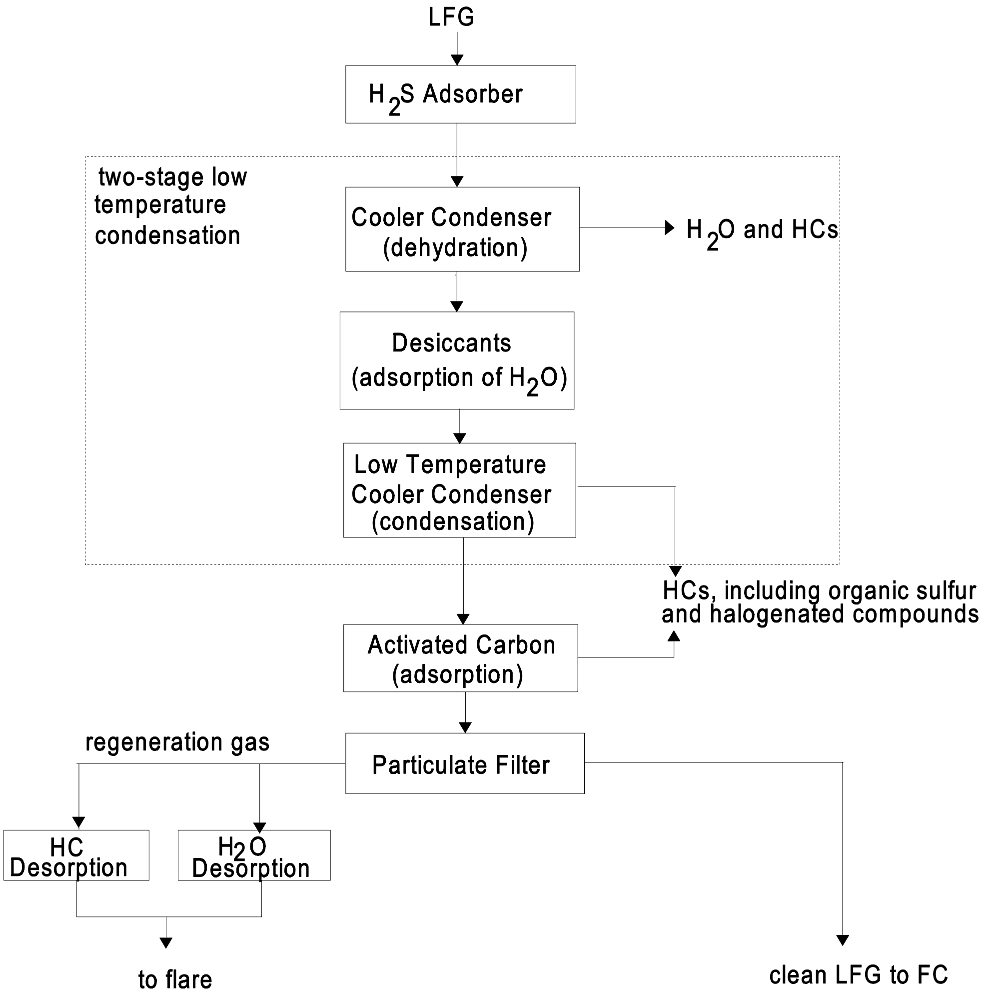


Figure 2-2. GPU for the PAFC

The dehydration and adsorbent beds are regenerated by using clean gas from the process stream. A portion of the treated LFG (approximately 30 percent) is heated to 288 °C with an electric heater and then passes through the beds in the sequence shown in Figure 2-2. After exiting the beds, the spent regeneration gas is fed into the low-NO_x incinerator where it is combusted with the vaporized contaminants from the dryer/adsorption beds.

FC power plant —
The LFG power plant consisted of a 200 kW PC25 natural gas FC manufactured by ONSI Corporation, a cooling module (for waste heat), and an interconnection to the power grid. Field tests were conducted in December 1994 at the Penrose site, and between July 1996 and May 1997 at the Groton site. Performance of the FC during the field tests at Penrose and Groton is described below.

The FC is designed to produce 200 kW of net power when operated on natural gas with a heating value of about 900 to 1,050 Btu/scf. Modifications made to the FC for the Penrose test program included a larger fuel control valve and fuel flow venturi, a new process fuel recycle orifice, a new cathode exit orifice, a new redundant start fuel shut-off valve, and modifications to the control software. The LFG used during the field test at the Penrose site had a heating value of about 440 Btu/scf. Consequently, with the available LFG flows, a net peak power production of approximately 137 kW was achieved and an endurance operating level of 120 kW was achieved during the bulk of the field test operations (Spiegel et al., 1997). At Groton, the heating value of the LFG was approximately 560 Btu/scf and an operating level of 130 kW was selected, although higher power levels were achieved (IFC, 1997). Additional details on performance during the two field tests are given below.

Performance—

During the field test at Penrose, the GPU operated for more than 2,000 hrs and purified the LFG to a level which is more than suitable for FC use. In particular, the GPU removed the sulfur and the halide compounds contained in the LFG to a level significantly below the specified value of 3 ppmv. The GPU removal efficiencies for both total halide and reduced sulfur compounds were estimated to be greater than 99 percent (Spiegel et al., 1997).

For the field program at the Penrose landfill, the GPU was operated for a total of 2,297 hrs. During this time, the FC was operated for a total of 709 hrs on LFG. As mentioned above, an endurance level of 120 kW was achieved (137 kW peak). The FC efficiency was calculated to be 37.1 percent during a six-day period of operation, and 36.5 percent during a second eight-day period which included a brief shut-down. During the six week test program, there were a total of eight shutdowns. Four of these were due to site-related causes (e.g., power losses, interruption of LFG flow to GPU). Three of the shutdowns were due to the GPU: two due to refrigeration over-temperature; and one due to a loose flame sensor on the flare. The final shutdown was due to a failure of an inverter cooling fan sensor module in the FC control system (Spiegel et al., 1997).

During the Groton test program, the longest test runs were 524 hrs and 448 hrs for the GPU and FC, respectively. As mentioned above, the FC was operating at 130 kW in May 1997. Two operational issues with the GPU identified during the Groton program were icing of the d-limonene coolant and problems with the LFG compressor valves. The compressor valves were replaced and a de-icing procedure was developed for the coolant. For the FC, the only problem encountered was the need to replace a feed H_2O pump (IFC, 1997). Since replacement of this pump, no FC operational issues had been encountered for over 2,350 hrs of operation.

Emissions—

Table 2-1 provides a summary of available emissions data measured for the GPU during the two test programs. At Penrose, the GPU flare had average NO_x emissions of 10.4 ppmv and 3.0 ppmv for carbon monoxide (CO). PM emissions for the flare averaged 0.03 milligrams per normal (dry standard) cubic meter (mg/Nm^3) (Spiegel et al., 1997).

Besides electrical energy, the electrochemical reactions inside the FC produce only H_2O and CO_2. For the most part, emissions, such as NO_x, PM, or CO, that are typically associated with combustion are not produced. Small quantities of these emissions from the fuel processing unit where CH_4 is converted to hydrogen are emitted from the reformer natural gas burners.

As with other LFG utilization projects, a net reduction in air pollutant emissions (especially criteria pollutants and GHGs) will occur from the avoided use of a fossil energy source that otherwise would have been needed to produce the electricity generated by the FC. In addition to the electrical energy, the FC can produce up to 760,000 Btu/hr of thermal energy. If this energy is utilized, additional net reductions via avoided fossil fuel usage can be realized.

Secondary Environmental Impacts—

The non-regenerable carbon beds in the GPU used to remove sulfur compounds have to be regenerated off- site or disposed of in a sanitary. During the tests in California, the spent carbon was tested and found to be non-hazardous which allowed for disposal in a municipal landfill. The alternative to disposal of the spent carbon is to regenerate it. Typically, regeneration of activated carbon is done via heating of the spent

TABLE 2-1. Summary of Emissions and Removal Efficiencies for the GPU

Pollutant	Inlet Concentration (ppmv)		Outlet Concentration (ppmv)		Removal Efficiency[a] (%)
	Groton	Penrose	Groton	Penrose	
Total Halogens (as Cl^-)	16-45	45-65	<0.001 - 0.014	<0.002 - 0.032	99.5
Total Sulfur (as H_2S)	n/a	113	<0.002 - 0.385	<0.010 - 0.047	99.96
Particulates	n/a	n/a	n/a	<0.5 (mg/Nm^3)	n/app
Silanes, Siloxanes	n/a	<0.076 (mg/Nm^3)	n/a	n/a	n/app
Phenol	n/a	<0.03 ppmv	n/a	n/a	n/app
NMOCs (as CH_4)	n/a	5,700 ppmv	n/a	13.8 ppmv	99.8

Note: n/a = not available, n/app = not applicable.
Based on information supplied by Spiegel et al., 1997 and IFC, 1997.
[a] Refers to results from the Penrose field test.

carbon in a high temperature kiln at temperatures capable of destroying the adsorbed organics. Although these processes are often highly controlled, criteria pollutants, hazardous air pollutants, and GHGs are all emitted at varying levels during the regeneration process.

In addition, the pretreatment process produces condensate containing H_2O, organic sulfur, HCs, and halogenated HCs. The GPU described above is expected to produce a condensate with a higher loading of organics than a typical LFG processing system (i.e., due to the two stages of condensation). At Penrose, the condensate was transferred to the existing Penrose condensate treatment system, which consisted of an enclosed flare. Depending on the process used to treat condensate, there could be a higher potential for emissions of organics from volatilization during treatment (since the concentrations within the condensate are likely to be higher).

Economics—
The major non-technical consideration associated with FCs has been the capital cost of the technology. IFC, the manufacturer of the PAFC, has guaranteed the capital cost for the new advanced power module to be $3,000 per kW for delivery in 1995, and plans to reduce the cost to $1,500 per kW by 1998. FC costs may be reduced with maturation of the technology and the scale advantage of increasing production. It is expected that the next generation of LFG FCs will be up to 30 percent smaller in size compared to the first FC that was tested.

These estimates do not include the cost of a GPU. According to IFC, the cost of pretreating LFG for use in FCs is around $250 per kW. IFC has started a program to test a new pretreatment concept to further reduce the pretreatment cost to approximately $100 per kW, however no comprehensive information on this program was available at the time this report was prepared. Based on the findings of the Phase II test report (Trocciola et al., 1995), it may be economically beneficial on future installations to eliminate the low temperature cooler and simplify the refrigeration system in exchange for slightly increasing the activated (regenerable) carbon bed volume.

As a comparison, the capital cost of RIC engine plants (including gas pretreatment equipment) may range from $950 to $1,250 per kW (Thorneloe, 1992). These costs are likely to be even lower as of the writing of this report due to increased competition and maturation of the RIC technology.

2.2 Production of CLG for Vehicle Fuel

2.2.1 Introduction and General Overview

Use of CNG has been recognized for its environmental benefits because it is a cleaner burning fuel relative to gasoline and diesel fuel (especially in regards to NO_x and PM emissions). The technology for using CNG as an alternative fuel for motor vehicles has been demonstrated for several years. In Europe and South America, hundreds of thousands of vehicles are operated on CNG. In the U.S., the use of CNG as an alternative to gasoline and diesel fuel has gained interest as a method for decreasing vehicle emissions particularly in areas designated as nonattainment with the National Ambient Air Quality Standards for ozone, CO, and PM with an aerodynamic diameter less than 10 micrometers (PM_{10}).

The DOE projected that the number of natural gas vehicles (NGVs) would grow about 30 percent from 1995 to 1996, and a number of CNG-powered vehicles and engines are now available from original equipment manufacturers (DOE, 1997b). These new vehicle/engine offerings include the CNG-dedicated 1998 Honda Civic GX sedan (available in the fourth quarter of 1997), General Motors Corporation (GMC) Sierra and Chevrolet C-Series light-duty pickup trucks, and Cummins 5.9 B series engines (for light-, medium-, and heavy-duty applications). In addition, Visions Helicopter Technologies, Inc. (Woodbridge, VA) recently developed two light-utility helicopters that run on CNG.

One of the major drawbacks to using CNG in motor vehicles is that the driving range of vehicles is limited because of fuel storage capacity constraints. Where needed, this problem has been minimized by installing bi-fueled systems (e.g., CNG, and gasoline or diesel) on the vehicle. Another limitation has been the availability of fuel dispensing facilities. However, the American Gas Association (AGA) reports that the number of refueling facilities in the U.S. tripled between 1994 and 1997 (to over 1,100 in 46 states in 1997) (AGA, 1997). Historically, because of these constraints, the use of CNG has often been limited to vehicle fleets that return to the same location each day. With expanding CNG demand and refueling infrastructure, this situation is expected to change during the next several years.

The use of CNG as a vehicle fuel usually involves the conversion of a gasoline engine to operate on both CNG and gasoline (i.e., a bi-fueled engine). The conversion process is relatively simple because no internal modifications of the engine are required. Conversion equipment generally includes a variable gas-air mixer as part of the fuel injection system, a series of regulators and valves which deliver the gas from the storage tanks, and an electronic module to interface with the onboard computer.

Use of LFG to produce CLG (the equivalent of CNG) has gained interest because it provides an alternative use for LFG projects that cannot utilize all of the CH_4 recovered. Using LFG to produce CLG involves extraction, purification, and compression. In 1994, there were two field demonstration projects in the U.S. for producing CLG from LFG. The remainder of this section of the report summarizes these projects, as well as a third project in Tours, France.

2.2.2 Puente Hills Landfill, Los Angeles, California

Background—
The Los Angeles County Sanitation Districts (LACSDs) have demonstrated the technical and economic feasibility of producing CLG, and its use as a fuel in light-duty gasoline and heavy-duty diesel fueled vehicles used at the Puente Hills Landfill (Wheless et al., 1996). The CNG demonstration facility has been fully-operational since October 1993. In 1994, LACSD identified and corrected operational problems and the facility is now in full service. The facility provides CLG on demand as supplies are depleted at the refueling station and has a design capacity of 1,000 gallons of gasoline-equivalent (GGE) CLG per day. As of 1996, the demand has been over 800 GGE per day (Wheless et al., 1996). LACSD is continuing to evaluate the performance of the CLG processing facility and a wide range of CLG vehicles which routinely operate at the landfill (e.g., heavy-duty equipment, garbage trucks, and light-duty utility vehicles).

The landfill has a nominal fill rate of 10,000 tons per day (tpd). LACSD installed a gas collection system which yields about 27,000 standard cubic feet per minute (scfm) of LFG. The LFG (about 22,000 scfm) is used as a fuel in boilers and turbines to generate 50 MW of power. Another 1,500 scfm is used to generate power in a 2.8 MW gas turbine. In addition, about 200 scfm is sent to a nearby college for use as boiler fuel. The motivation for undertaking the demonstration program was that the gas collection system had been producing excess gas which was not used to generate electricity. This was due to a combination of excess power generating facilities in the area and the low cost of natural gas which resulted in power rates lower than the production costs for new power generating facilities. LACSD was interested in finding alternative uses for the LFG. Use of LFG as a vehicle fuel potentially has both environmental and economic benefits. The environmental benefit would result from reductions in air emissions if LFG is used as a substitute for gasoline or diesel fuel rather than being burned in flares for pollution control.

The existing gas collection system is designed to capture the LFG by maintaining a negative pressure within the landfill and to prevent odors and meet the stringent air emission regulations of the South Coast Air Quality Management District (SCAQMD). However, this results in air being drawn into the landfill (air intrusion), and the concentrations of oxygen and nitrogen in the LFG must be reduced to meet the California Air Resources Board's (CARB's) fuel specifications for CNG (less than 5 percent inert compounds by volume). Therefore, cryogenic separation would be needed to remove air from the LFG. LACSD determined that it would be too difficult and expensive to remove the air from the LFG for CLG production.

To get around this problem, wells that extract gas from the deep core of the landfill were identified that had minimal air intrusion. Then, a new piping system was connected to the wells to draw a richer "core" gas with less than 1 percent oxygen. An oxygen sensor was installed at the inlet of the processing system to continuously monitor for air entering the processing system above specified levels. Adjacent wells were adjusted to insure that proper odor and air emission concentrations were maintained at the surface of the landfill. This approach limits the quantity of LFG available for vehicle fuel from a selected site. However, at the Puente Hills Landfill, it requires less than 5 percent of the available gas to meet the needs of the on-site equipment.

Process Description—
Figure 2-3 shows a diagram of the facility. The facility includes a compression and processing system, compressed gas storage tanks, and a fuel dispensing station. The equipment is mounted on three separate skids: the compression skid, the membrane skid, and the gas storage skid. A gas dispensing facility is located at a convenient place approximately 1,000 ft from the processing and storage skids. The facility is designed to remove H_2O vapor, CO_2, H_2S, and trace NMOCs which include some hazardous air pollutants. Table 2-2 shows CARB's specifications for CNG produced from natural gas to ensure consistent emission test results. The CLG produced from LFG must also meet the specifications. The table also shows the specifications of the CLG at the inlet and outlet of the processing facility.

TABLE 2-2. Alternative CNG Fuel Specifications Compared to CLG Produced by the LACSD Project

Constituent	CARB[a]	LACSD Project	
		Inlet Gas	Product Gas
CH_4	88% min	55% min	96%
Ethane	6% max	n/a	[b]
HCs (C_3 and higher)	3% max	n/a	n/a
HCs (C_6 and higher)	0.2% max	n/a	[b]
Hydrogen	0.1% max	n/a	n/a
Oxygen	1.0% max	0.2%	0.2 - 0.3%[c]
CO	0.1% max	n/a	n/a
Inert Gas (CO_2 and nitrogen)	1.5 - 4.5%	0.8%	4%
H_2O	0.9 lb/MMscf	Saturated	0.5 lb/MMscf

[a] CCR Title 13, Section 2292.5.
[b] These constituents were analyzed but not detected (detection limits not available).
[c] Wheless, 1997.

A 75 horsepower (hp) rotary vane blower is used to draw 250 scfm of LFG from the dedicated wells into the processing system. The LFG is saturated with moisture which is removed during the compression and cooling stages of the process. The condensed H_2O is collected in a H_2O knockout tank located on the compressor skid which is emptied into the LFG collection system for on-site treatment. The blower compresses the gas to 40 pounds per square inch (psi) followed by a series of heat exchangers and reciprocating compressor stages which compress the gas further to 525 psi, and a maximum temperature of 115 degrees Fahrenheit (°F). The compressed gas then passes through an activated carbon bed to remove trace NMOC. Two guard beds are provided in parallel to allow regeneration of the bed media without disruption in the operation of the system. A silica gel is installed in the top layer of each bed to remove H_2O vapor contained in the gas. If not removed, the H_2O vapor would be adsorbed on the activated carbon thus reducing the efficiency of the beds for adsorbing HCs. The gas then passes through the activated carbon which selectively adsorbs heavier HCs. The activated carbon used also has a high affinity for sulfur and halogenated Hcs.

The gas purification membranes (Separex™) consist of a series of spiral wound cellulose acetate membrane elements fitted into three separate tubular housings. The tubes are connected in series. Since the membranes used will dissolve in H_2O, the gas is heated in a glycol H_2O bath to increase the gas temperature above the dew point before being fed to the membrane purification elements. The temperature is set to ensure that any moisture present is in the vapor state. The higher temperature also allows for a more efficient operation of the membrane. The membrane elements are selectively permeable to CO_2 while rejecting CH_4. The process is enhanced, within operating limits, by a high-temperature and high-pressure differential across the membrane elements. The permeate, containing about 28 percent CH_4 and 72 percent CO_2, is diverted to the energy recovery facility where it is combusted in turbines or boilers. The CH_4 content of the residual product gas is about 96 percent. Of the 250 scfm feed gas, approximately 150 scfm is waste gas and 100 scfm is product gas.

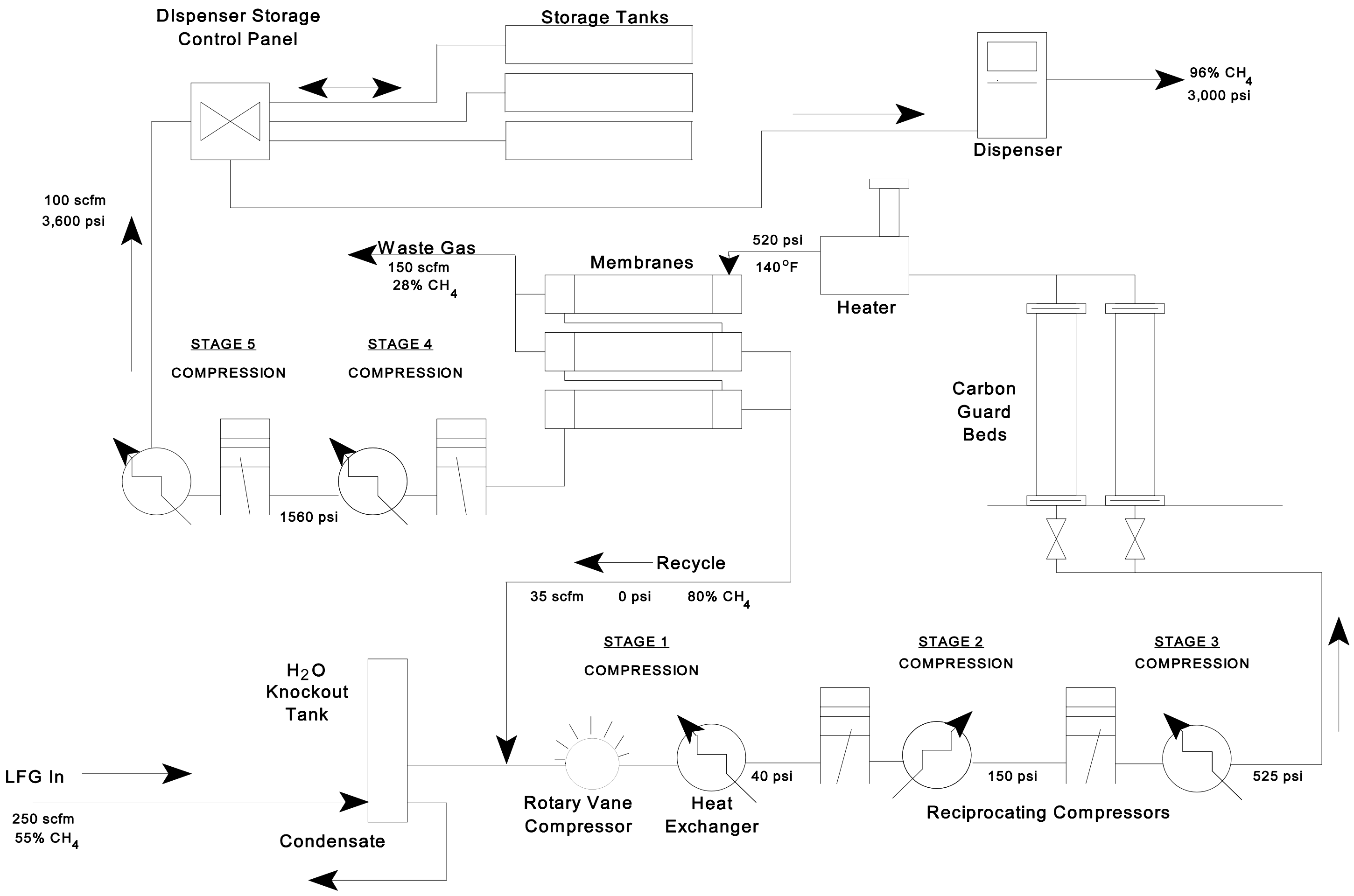


Figure 2-3. Flow Diagram of the LACSD CLG Production Facility (adapted from Wheless et al., 1996)

After passing through the membrane, an odorant is metered into the product gas to provide an early warning in the event of a leak. The odorant is metered in so as to be detectable at one-fifth of the lower explosive limit of the product gas. The gas is then compressed in a series of stages to a final pressure of 3,600 psi and is stored in six 10,000 scf pressure vessels. The entire system conforms to National Fire Protection Association Code 52 (NFPA 52) which governs CNG vehicular fuel systems. As shown in Table 2-2, the CLG produced conforms to CARB's fuel specifications for CNG. For this reason, the CLG can be used in any vehicle designed to operate on CNG with predictable air emissions.

The dual dispenser is similar to a conventional gasoline pump with two fill hoses, a fuel meter, and a card-operated automatic system to initiate operation and to record billing information. To accommodate the needs of the CNG fleet, one of the dispensing hoses is dispensing at 3,000 psi and the second hose is dispensing at 3,600 psi.

To provide a fast-fill operation, storage vessels are emptied sequentially. The six storage tanks are divided into low, medium, and high pressure banks. CLG is initially dispensed from the low pressure bank and then switches automatically to the medium and high pressure banks as the gas flow rate to the vehicle falls below a specified value. The time to transfer the equivalent of 50 gal of diesel is less than 10 minutes (Wheless et al., 1996).

Evaluation of Alternative Processing Technologies—
LACSD evaluated the Selexol® and pressure swing adsorption technologies, which are the leading technologies for producing pipeline quality gas (natural gas) from LFG. LACSD decided not to use these technologies because they are predominantly applied to large gas flow rates [more than 3 million scf per day (scfd)]; both are usually operated as steady-state, continuous-duty systems with regular operator attention; and both require some form of license. In addition, the need for the facility to operate intermittently to replenish the CLG storage tanks was important because fuel usage for the available fleet of CLG vehicles at the landfill was initially much lower than the facility was designed to produce at full capacity.

Performance—
During initial start-up and operation of the facility, only minor problems were experienced with the processing system. The problems encountered were associated with properly managing the extraction of the LFG from the wells and the design of the fuel dispensing facility. Improved instrumentation and training of technicians was needed to manage the flow of gas from the wells to the system. The instrumentation needed to monitor and tune the wells had to be more sensitive than what is typically used for LFG recovery projects. Only 1 percent air was allowed in the feed gas; consequently, the oxygen concentration needed to be measured in the field down to 0.2 percent.

Problems encountered with the facility's design were those that could also occur with normal pipeline gas CNG fueling stations. The problems encountered were associated with the fuel dispenser and associated card reader, the odorant addition system, and process instrumentation. The compressors experienced several failures, but only two of these were attributable to the LFG. There was some H_2O damage to one of the first stage compressors, which could be resolved by improving the drain system. Also, the valve springs in the second stage compressor fractured from corrosion causing damage to the pistons, crosshead rods, and crosshead bearings. These problems were resolved by using springs of a more suitable steel alloy.

In 1994, LACSD completed an evaluation of the system and have transferred operation and maintenance (O&M) of the facility from LACSD R&D engineering staff to technicians responsible for landfill operations. Vehicles at the landfill are currently consuming about 50 gallons per day (gpd) of diesel equivalent CLG. LACSD also began trucking CLG to another LFG to energy facility in March 1996 [100,000 cubic feet (ft^3) tube trailer]. With this trailer making one round trip daily, the demand has been increased to over 60 percent of design capacity (equivalent to about 600 GGE).

The CH_4 content of the CLG ranges from 96 to 99 percent and averages 97.5 percent. The oxygen content ranges from less than 0.3 percent to 0.6 percent. H_2S and other sulfur bearing compounds are removed by the activated carbon beds to more than the 40 parts per billion by volume (ppbv) detection limit.

LACSD plans to review the facility to identify how operation of the facility can be simplified and improved. Items under investigation include the use of heat from the compressors to replace the gas heater, elimination or simplification of the carbon guard bed, and restricting the purge gas usage. These modifications would significantly simplify the process and make the system comparable to standard pipeline CNG compression stations.

Economics—

LACSD prepared the design specifications for the facility and used a competitive, sealed bid process to procure turnkey services for construction of the facility. Table 2-3 shows a breakdown of capital costs for the facility. Costs are presented in 1992 dollars. The total installed capital cost, including design, construction, and initial start-up was $970,000. The cost of piping for the dedicated wells is not included in the capital costs. The applicable taxes, LACSD staff costs related to engineering, construction management, and inspection brings the total cost to approximately $1,100,000.

Operating costs for the facility are presented in Table 2-4 in terms of cents per gallon of gasoline for 25, 50, and 100 percent utilization. The operating costs include capital recovery costs which were calculated using a 15-year equipment life and 7 percent interest rate. O&M labor and materials were calculated as 3 percent of construction costs. Power usage was estimated at 5 cents per kWh. A gallon of gasoline was assumed to be equivalent to 125 scf of CLG. Because capital recovery represents a majority of the fuel production costs, fuel usage is key to low cost production of CLG.

CLG project economics will depend on the amount of gas being processed. According to LACSD, the processing capacity of LACSD's fueling facility represents the minimum economical size. Figure 2-4 shows the estimated economies of scale for production of CLG using the process developed by LACSD (Wheless et al., 1996). This figure shows that a facility with a capacity of about 2,000 GGE could be economically competitive when CNG is sold at $0.70/GGE. The data supporting this figure do not include Internal Revenue Service Section 29 Tax Credits, the benefits of a NGV fleet, or the costs of a dual LFG collection system. Further, it is assumed that there is demand for the entire plant capacity.

Many of the capital cost components such as those for the dispenser, storage, and continuous monitors are independent of processing capacity, while costs related to engineering design, compressors, and the membrane are expected to increase by only 50 percent if the capacity is doubled. If the fleet of vehicles is large enough to justify a larger facility, the price per gallon equivalent can be expected to drop to approximately half the existing cost of diesel or gasoline, and about two-thirds the cost of retail CNG (as shown in Figure 2-4). If diesel or gasoline prices continue to increase, even smaller facilities may be attractive.

CNG-powered refuse trucks are more expensive than comparable diesel trucks. Due to economy of scale, as more trucks are being built, the price per truck is expected to decrease. However, since natural gas is normally less expensive than diesel fuel, the capital cost of the vehicle will be recovered over time. The payback time depends on vehicle mileage, fuel economy, and the difference in fuel costs. Based on typical LACSD annual mileage of 75,000 miles, the estimated $5,000 difference in purchase cost can be paid back in 2.5 years. This analysis assumes that CLG is available at $0.50 per gallon and diesel at $0.80 per gallon. (Wheless et al., 1996).

TABLE 2-3. Capital Costs For The CLG Production Facility

Item	Cost ($1992)
Compressor Skid	175,000
Membrane Skid	140,000
Dispenser	50,000
Storage	45,000
Instrumentation/Controls	115,000
Electrical	100,000
Miscellaneous	95,000
Engineering, Overhead, & Profit	250,000
TOTAL CONSTRUCTION COST	970,000

TABLE 2-4. Estimate of Fuel Costs for CLG Production

Percent Utilization	$/GGE
100	0.48
50	0.74
25	1.26

Basis:
Capital recovery, 15 years @ 7 percent interest.
Power, 5¢/kWh.
O&M, 3 percent of construction cost.
Gallon of Gasoline = 125 scf of CNG.

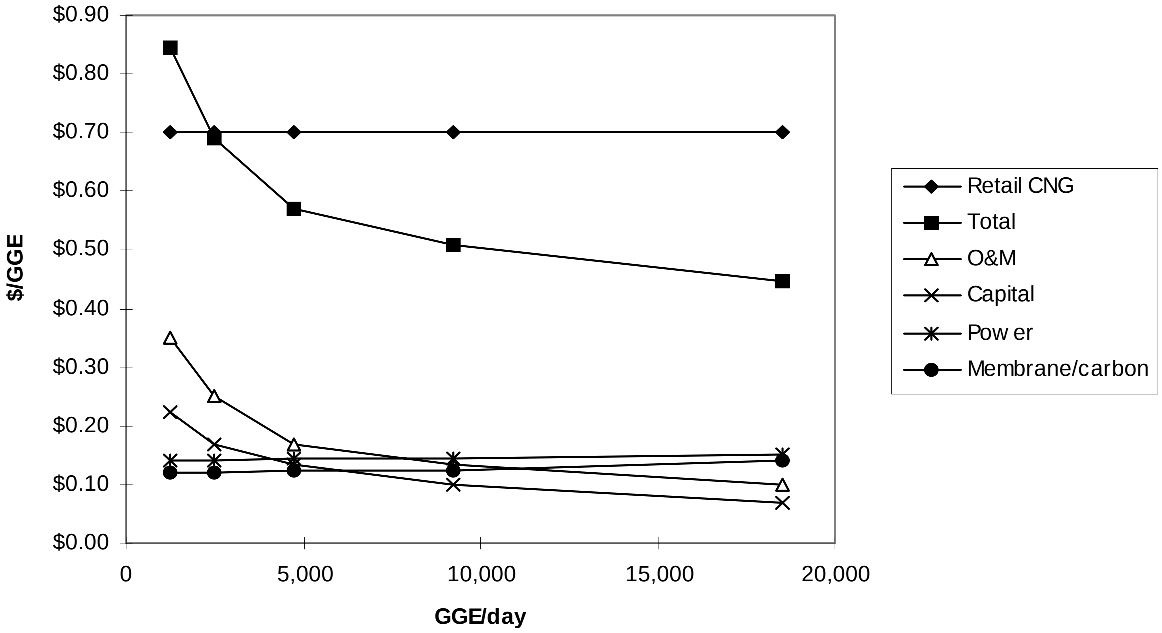


Figure 2-4. Estimated Economies of Scale for CLG Production Facilities

Vehicle Demonstration Program—
In late 1991, LACSD initiated a program to evaluate the use of CLG as a clean-burning, alternative fuel for its vehicles and heavy-duty equipment. LACSD also envisioned that fuel could be made available to users of the landfill to further reduce air emissions and dependence on petroleum products. According to LACSD, the program is primarily dependent on the engine manufacturer's ability to produce low-emission, dedicated CNG engines. Manufacture of low-emission, dedicated CNG engines is an emerging technology with a limited number of equipment suppliers.

Passenger vehicles—
In mid-1993, a 1988 Ford Taurus V-6 passenger car was converted to run on dual-fuel (CNG and gasoline) using CARB's approved gaseous fuel injection (GFI) system. The conversion included the addition of two 5.5 GGE CNG cylinders in the trunk with a manual switch to select the fuel desired. In the dual-fuel applications, the GFI system is designed to automatically return the engine to gasoline operation when the gas fuel storage pressure drops below a preset minimum.

The use of this vehicle was discontinued in October 1996 due to the age of the vehicle. The cooling system in the vehicle needed overhaul and it would have cost more than the vehicle was worth. The operation of the CNG system was considered successful and the driver was pleased with the performance.

Since the conversion, the vehicle has traveled predominantly on CLG for over 22,000 miles. The car has averaged 20 miles per GGE when using CLG for both city and highway driving, which is comparable to operating on gasoline. The performance of the vehicle was excellent according to LACSD. A temporary problem was encountered with the GFI system which caused the car to stall and surge; however, this problem was fixed.

Light-duty trucks—
Since mid-1992, LACSD have been operating a GMC 3/4-ton Sierra pick-up truck that uses only CLG. The vehicle is one of 1,000 light-duty vehicles produced by the GMC Truck Division with assistance from the Southern California Gas Company. The initial operating experience was poor with problems including engine stalling and surging, limited mileage per GGE, and lack of experience of the dealer service personnel. After replacing fuel injectors several times, repairing the throttle body meter, cleaning the fuel tank solenoid, replacing the fuel pressure regulator, and adjusting the timing, the performance improved, and the vehicle was operating like a conventional gasoline engine model. An additional ten GGE CNG cylinder was also installed to increase the driving range of the vehicle.

LACSD's first pick-up truck was eventually recalled due to CNG cylinder safety concerns. LACSD subsequently acquired a replacement 1994 GMC Sierra 2500 gasoline-fueled truck. This vehicle was converted by NGV Ecotrans to bi-fuel (use either gasoline or CLG) with the GFI system. The vehicle is used off-road at the landfill during the day, and is driven to and from the site at other times. Since August of 1994, the truck has accumulated over 16,000 miles fueled predominantly on CLG. The truck has achieved an average fuel economy of over 13 miles per GGE. Drivers report little to no noticeable power loss between the two fuels for this vehicle.

Medium-duty vehicles—
In 1995, LACSD purchased six Chrysler dedicated CNG minivans for the rideshare program. The vans are fueled with CLG. The vans are partially funded by the California Assembly Bill 2766 Discretionary Fund Program administered by the Mobile Source Air Pollution Reduction Committee, and the California Department of Transportation. Assembly Bill 2766 authorized an additional $4 fee per vehicle registration which is collected by the California Department of Motor Vehicles. The fee is provided to the SCAQMD annually to fund various research projects for reducing air emissions from motor vehicles.

The dedicated Chrysler CNG minivans are certified by CARB as ultra-low-emission vehicles (ULEVs). The vans are fitted with sequential multi-point fuel injection, heated oxygen sensors, exhaust gas recirculation, and a three-way oxidation catalytic converter.

The vans are originally equipped with three CNG cylinders mounted under the body chassis, each carrying eight GGE. To increase the driving range of the vehicles, each van was installed with an additional six GGE. The driving range (175 to 200 miles) of the vehicles is still limited, which causes a lot of complaints from the vanpool. No significant problems associated with the use of CLG has occurred. The average fuel economy of the vans is 20 miles per gallon equivalent.

Heavy-duty vehicles—
LACSD has been operating a new water truck on CLG for dust control at the landfill since October 1993. The truck is a GMC conventional cab-chassis with a Hercules 5.6 liter (L), 6-cylinder, dedicated natural gas engine. This medium-duty engine is being used in trucks and buses rated between 15,000 and 30,000 lb gross vehicle weight and is the first CARB-certified engine that meets emission standards without exhaust after-treatment. The engine is a lean-burn combustion system equipped with a turbo-charger and after-cooler which provides a maximum output of 190 hp. When operating properly, the vehicle provides adequate power on inclining grades.

Since 1993, the water truck has only been driven approximately 13,000 miles at the landfill using strictly CLG. This truck has had its share of problems, mostly related to the fuel (GFI) and electrical systems. In three years of its operation, six compuvalves were replaced. Most of the problems were related to the compuvalve draining of the battery, and when the battery voltage is below nine volts, it causes the GFI to fail and damages the low flow injectors (o-ring in the injectors gets hot and causes fuel leakage). When the vehicle is jump started, the voltage is too high and it fries the microcompressor. GFI improved the compuvalves with Generation II by having the low- and high- voltage protection. The compuvalve II was installed, and still had the same problem. Hercules and GFI have no clues to what is causing the problem. Due to continual problems and complaints from operators, this truck was re-powered with a CAT3126 dual-fuel engine in February 1997. Since then, the truck has only accumulated 1,500 miles. The truck has not been used very much because of non-engine related problems, such as transmission and hydraulic pump systems. On the dynamometer, power output is identical between diesel and dual-fuel firing (Wheless and Wong, 1996).

A 1986 Volvo White refuse packer truck was re-powered from a diesel engine to a Detroit Diesel Series 50 dedicated CNG spark-ignited engine. The truck was provided by Athens Disposal for the demonstration program with funding provided by the Assembly Bill 2766 Discretionary Funding Program. As of October 1994, the Athens Disposal vehicle had accumulated well over 10,000 miles running solely on CLG. The vehicle achieved approximately 2.3 miles per gallon of diesel equivalent, which is comparable to the fuel economy of the diesel engine prior to conversion.

Potential heavy-duty vehicles—

In 1994, LACSD received funding through the Assembly Bill 2766 Discretionary Funding Program to convert two water trucks and two refuse transfer tractors from diesel to CLG. The water trucks and one refuse transfer tractor will be using the low-emission technology identified by MARK I and MARK II systems developed by Clean Air Partners, Inc. The MARK II system uses pilot ignition which allows leaner gas/air fuel ratios with a minimum plasma ignition of 1 percent diesel and a very lean mixture of CNG, which is expected to result in very low emissions.

LACSD re-powered an existing class eight tractor with a rebuilt Cummins N14 dedicated CNG engine. The tractor is used to haul sludge and travels about 200 miles per day. A new class eight refuse transfer tractor was purchased with a dedicated CNG Detroit Diesel Series 60 engine. The tractor will be used to haul refuse from a transfer station to the landfill. The CNG Detroit Diesel Series 60 engine is a 6-cylinder version of the 4-cylinder Series 50 used in the Athens' refuse truck. The engine is capable of providing from 350 to 450 hp with a minimum of 1,200 foot-pounds of torque. The engine is expected to produce significantly lower emissions than a typical diesel engine used to haul refuse throughout its entire operating range.

Emissions—

Emission reduction benefits resulting from the production and use of CLG are primarily associated with the reduction in vehicle emissions. There are, however, some emission reductions associated with recovering the CH_4 from the LFG to produce CLG rather than burning the CH_4 in flares. In addition, there are emissions associated with the disposal of waste gas generated during the purification process. In the LACSD system, the waste gas is combusted in an on-site energy recovery facility. Emissions of CO, volatile organic compound (VOC), and PM from combustion of the waste gas are expected to be small. Emissions of NO_x from combustion of LFG in flares or turbines is on the order of 0.09 lb/MMBtu (Roe et al., 1995).

Table 2-5 shows CARB standards for existing and low-emission vehicles (LEVs), and CARB's certified emission standards for the 1992 GMC 3/4 ton Sierra pick-up truck, 1994 Chrysler minivan, and 1993 Ram Van models. For the Sierra pick-up truck operated on CNG, CARB's certified non-methane hydrocarbon (NMHC) emissions are between the CARB standards for transitional low-emission vehicles (TLEVs) and LEVs. The pick-up truck's CO emissions are between CARB's standards for LEVs and ULEVs, and its NO_x emissions are significantly less than CARB's standards for ULEVs. The pick-up truck's certified NMHC and NO_x emissions for CNG are 50 percent less than the certified emissions for gasoline fuel; however, CO emissions are higher than for gasoline.

TABLE 2-5. Comparison of Emissions For Light-Duty Trucks and Medium-Duty Vehicles

Vehicle Type	Emissions (gram/mile)		
	NMHC	CO	NO_x
Light-Duty Trucks			
CARB Standards			
Existing	0.50	9.0	1.0
TLEV	0.16	4.4	0.7
LEV	0.10	4.4	0.4
ULEV	0.05	2.2	0.4
CARB Certified Emissions			
1992 GMC 3/4 ton Sierra, Gasoline	0.29	2.2	0.4
1992 GMC 3/4 ton Sierra, CNG	0.14	3.8	0.2
1994 Chrysler Minivan, CNG	0.021	0.35	0.04
Medium-Duty Vehicles			
CARB Standards			
Existing	0.60	9.0	1.5
LEV	0.20	5.0	1.1
ULEV	0.12	2.5	0.6
CARB Certified Emissions			
1993 Ram Van, Gasoline	0.19	3.4	0.5
1993 Ram Van, Dedicated CNG	0.03	2.3	0.05

The dedicated CNG Chrysler Minivans and Ram Vans are certified by CARB as ULEVs and LEVs, respectively. CARB's certified NMHC, CO, and NO_x emissions for both vehicle models are significantly less than CARB's standards for ULEVs. Certified NMHC, CO, and NO_x emissions for the 1993 Ram Van dedicated to CNG are significantly less than CARB's certified emission standards for gasoline.

Emission tests were performed on the Hercules 5.6 L diesel engine used to operate the water truck. Table 2-6 shows the emission test results for the medium-heavy-duty water truck operated on CNG relative to emissions for a typical diesel equivalent and CARB's standards for heavy-duty vehicles. Emissions of NMHC, CO, NO_x, and PM for the Hercules engine are significantly lower than CARB's emission standards. Emissions of NO_x and PM are lower than emissions for a typical diesel equivalent, but NMHC and CO emissions are higher than for a typical diesel equivalent engine.

TABLE 2-6. Comparison of Emissions for Medium-Heavy-Duty Trucks and Heavy-Duty Trucks

Vehicle Type	Emissions (gram/brake hp-hr)			
	NMHC	CO	NO_x	PM
Medium-Heavy Duty Trucks				
CARB's Existing Standard	1.3	15.5	5.0	0.10
Typical Diesel Equivalent	0.5	1.6	4.7	0.24
Hercules 5.6 L, CNG engine	0.9	2.8	2.0	0.10
Heavy Duty Trucks				
CARB's Existing Standard	1.3	15.5	5.0	0.10
Typical Diesel Equivalent	0.5	2.0	4.6	0.23
Detroit Series 50, CNG engine	< 0.5	< 2.0	< 2.0	< 0.05

Baseline emission testing on the refuse packer truck was conducted to determine the net air emission reductions for converting the refuse packer truck from diesel to CNG fuel. The Detroit Diesel Series 50 CNG engine was certified by CARB in mid-1994. Table 2-6 shows the expected emission values for the CNG engine relative to a typical diesel equivalent engine and CARB's standard. Emissions of NMHC, CO, NO_x, and PM for the CNG engine are significantly lower than CARB's existing standards, and slightly lower than emissions for the diesel equivalent engine.

Secondary Environmental Impacts—
The facility is designed to remove H_2O vapor, CO_2, H_2S, and trace NMOC which include some hazardous air pollutants from the LFG. The LFG is saturated with moisture which is removed during the compression and cooling stages of the process. The condensed H_2O is collected in a H_2O knockout tank located on the compressor skid which is emptied into the LFG collection system for on-site treatment. Information on the type and amount of pollutants collected in the H_2O knockout tank was not available. However, because the condensate is treated in the existing leachate treatment system, the incremental costs for treatment are negligible.

Baseline emission testing on the refuse packer truck was conducted to determine the net air emission reductions for converting the refuse packer truck from diesel to CNG fuel. The Detroit Diesel Series 50 CNG engine was certified by CARB in mid-1994. Table 2-6 shows the expected emission values for the CNG engine relative to a typical diesel equivalent engine and CARB's standard. Emissions of NMHC, CO, NO_x, and PM for the CNG engine are significantly lower than CARB's existing standards, and slightly lower than emissions for the diesel equivalent engine.

2.2.3 Tork Landfill, Wisconsin Rapids, WI

Gas Resources Corporation (GRC) of Colorado installed a CLG conversion process in 1994 at a LFG utilization facility in Wisconsin Rapids, WI. The LFG utilization facility was designed to produce LFG product gas equivalent to pipeline-quality natural gas. The product gas was used to heat three buildings and to fuel two RIC engines to produce electrical power for the site. Additional LFG product gas was sold to a nearby asphalt plant for use as process fuel. GRC designed and installed a small demonstration facility to produce CLG from excess LFG product gas. The system was successfully brought on-line with no major technical problems. However, because only two CNG-powered vehicles were available for consumption of the CLG produced, the facility was not economically viable (initial plans had called for additional use of CLG in garbage trucks). In 1995, the facility was shut down, and the equipment was sold to Westchester County, New York for use at the Croton landfill in New York metropolitan area (Bahl, 1997). A brief description of the projects at both the Tork and Croton Landfills follows.

At the Tork Landfill, the gas processing facility was a skid-mounted prototype that was operated 24 hrs per day and produced gas with as high as 96 percent CH_4. The facility was equipped to convert CH_4 to CLG which was used as fuel for two pickup trucks. The gas processing facility included two separate steps. The first step was the cleaning of the gas to remove moisture and NMOC. This gas cleaning step is a patented process where moisture and NMOC are condensed out of the gas using elevated pressures (200 psi) and reduced temperatures.

The second step involved separating CO_2 from the CH_4. This was done by mixing the gas with a liquid solvent called Selexol®, which is a poly-glycol compound sold by Union Carbide. The Selexol® solvent has long been used by gas processors and refiners; however, it has only been made available to the general public for the last few years. When the Selexol® solvent is mixed with the gas under high pressure, CO_2 goes into solution. The Selexol® is then depressurized, allowing the CO_2 to come out of solution where it is discharged to the ambient air. The Selexol® is then recirculated through the system for reuse.

During start-up at the Tork Landfill, some problems were encountered. For example, the Selexol® compound dissolved rubber seals in valves and pumps which required replacement with seals that would not be dissolved by the Selexol® compound. After shake-down of the system was completed, the process was operated for six months without interruption. The major operational problem noted was an undersized fuel delivery system (e.g., storage tank, compressor) which required extensive periods of time for refueling (Bahl, 1997).

The capital cost of the facility used at the Tork Landfill was $400,000 in 1992. GRC received a $75,000 grant from the State of Wisconsin to fund construction of the facility. The cost of converting each of the two pick-up trucks to operate on CNG was about $2,600 in 1992. The Wisconsin Rapids area is too small in population to qualify for the tax breaks under The Energy Policy Act of 1992, which includes provisions for vehicle fleets to deduct a significant potion of the cost of buying and outfitting a truck to burn alternative fuels.

At the Croton Landfill, the system has been running with no significant problems for about 15 months (Gavin, 1997). Savin Engineers (contractor to Westchester County) upgraded the fuel storage and compression equipment prior to start-up. Problems encountered have been related to typical O&M issues (e.g., replacement of seals on the Selexol® pump). The system produced CLG with 85 to 95 percent CH_4 for use in several county vehicles. Plans are to also use the fuel in two county tractor trailers that are being converted to use CNG. The CLG produced has met specifications set by CARB (see Table 2-2). The equipment is currently processing 20,000 scfd of raw LFG containing over 50 percent CH_4. The Croton Landfill is a 113 acre site currently producing a million scfd. Economic analyses will soon be performed to determine the economic viability of a commercially sized system. The biggest preliminary concern is the availability of a large enough customer base for the CLG produced, especially since there is already a local CNG supplier (Gavin, 1997).

2.2.4 Sonzay Landfill, Tours, France

Background—
The SITA Group (Paris, France) successfully demonstrated another CLG project at the Sonzay Landfill near Tours, France (about 135 miles southwest of Paris). This landfill supports a population of about 125,000, opened in 1985, and accepts approximately 100,000 tpd of municipal (80 percent) and non-hazardous industrial (20 percent) waste (Balbo, 1997). The landfill site covers 222 acres with 150 acres allocated to

landfill operations. Planning for the CLG facility began in 1993, and the facility has been fully functional since 1994.

Process Description—

The LFG undergoes primary compression to approximately 200 psi via two stage compression. After both low-end and high-end primary compression, the LFG is cooled with a heat exchanger. In the second step, the crude CLG is scrubbed with H_2O in a packed counter-current wet scrubber. The H_2O absorbs most of the CO_2 and H_2S out of the crude CLG. The H_2O containing the CO_2 and H_2S is then regenerated by introducing it back into the top of the column and stripping these compounds out using ambient air. The air exhaust stream from the scrubber is then cleaned in a biofilter. It is important to note here that this demonstration project has shown the technical feasibility of using a physical absorption system using H_2O instead of a chemical absorption system which may have associated secondary environmental impacts and costs.

The third step in the process is drying. The scrubbed CLG is passed through an adsorption column using an undisclosed adsorbent. The system uses dual columns, so that one column can be regenerated while the other is operating. The final step is secondary compression via another two-stage compressor. Following both the low pressure and high pressure compression stages the CLG is cooled by heat exchange with circulating H_2O.

Following secondary compression, the gas is analyzed for CH_4 content. The CLG is then either stored on-site or in a city of Tours mobile storage unit (about a 950 gal capacity). The on-site storage consists of 120-50 L bottles (approximately a total capacity of 1,600 gal of CLG or 400 gal of diesel fuel). Excess or poor quality CLG is flared.

Performance—

As mentioned above , the facility has been fully functional since 1994. The facility has produced both a high Btu CLG (86 to 95 percent CH_4) and a high Btu CLG (about 97 percent CH_4). Oxygen in the final products is less than 0.5 percent and H_2S is less than 5 ppmv. SITA estimates that for each ton of waste landfilled, they can produce just over a half gallon of CLG for up to 15 years (Balbo, 1997). No additional information was available as to system downtime, malfunctions, or other performance issues.

The city of Tours converted 30 small cars to run on either CLG or diesel fuel. SITA reports that it takes an average of 5 minutes for a typical filling operation. Each car has a CLG capacity of about 21 gal, yielding a 130 mile range. Combined with the existing diesel fuel tank, the cars have a total range of about 450 miles.

Genet (the subsidiary of SITA, which runs the landfill) also retrofitted mini-vans and a waste-haul truck to run on CLG. The 40-ton waste-haul truck transports compacted waste from a local transfer station four times daily and covers a total daily distance of 130 miles. The truck has an effective range of 98 miles and therefore must refuel twice daily (filling time is approximately 15 minutes). No additional information was available as to vehicle malfunctions or performance.

Economics—

Capital costs for the CLG plant are estimated at about $900,000 [1994 dollars (DuPuis, 1996)]. No information was available on operating costs. It should be noted that fuel costs are much higher in Europe than the U.S. Hence, a process such as the one described above may be economically feasible in Europe, but not in the U.S. or other parts of the world.

2.3 Leachate Evaporation

2.3.1 Introduction and General Overview

Leachate collection and treatment is one of a number of environmental concerns of MSW landfill operators. Landfill design, construction, and operating costs can be heavily influenced by needs for leachate collection, conveyance, storage, treatment, and disposal.

In some landfills in arid or semi-arid climates, precipitation, humidity, and soil conditions are such that little or no leachate is generated. Therefore, in these instances, no leachate collection is needed. In some areas, local jurisdictions allow leachate to be collected and recirculated (i.e., returned to the landfill using an appropriate delivery method). This is usually the most economical alternative when leachate is present.

Leachate also may be accepted at a municipal waste water treatment plant directly through a sanitary sewer line. As leachate is a very high strength waste, compared to industrial waste waters, an additional fee may be required. In cases where a sewer line is not available, it may be necessary to truck the leachate to a treatment plant. This may or may not be a permanent solution, as future acceptance of leachate is at the treatment plant's discretion.

If recirculation or off-site disposal are not options, on-site treatment is usually the next option. On-site treatment includes evaporation ponds, aerated stabilization basins, filtering systems, and biological and chemical treatment facilities. Treatment plants generally must include chemical processes to remove metals through pH adjustment, followed by biological treatment. Biological treatment may be combined with powdered activated carbon treatment to remove organic compounds and often includes anaerobic and aerobic treatment with or without nitrification.

The principle of leachate evaporation systems (LESs) is simple and direct: use LFG collected at the site as an energy source to evaporate H_2O and combust the organic compounds in the leachate. Depending on local requirements, the highly concentrated (hence very low volume) effluent is returned to the landfill or shipped off-site for disposal. LESs concentrate and precipitate metals, primarily as salts, while stripping organics to a thermal oxidizer (e.g., flare) or RIC engine for destruction.

There are several variations of leachate evaporator systems. They differ only in the methods used to transfer heat to leachate and how the exhaust vapor is treated. One commercial design theme simply destroys the leachate vapors and LFG not consumed in the evaporation process in a slightly modified enclosed flare [Organic Waste Technologies, Inc. (OWT)]. Another variation combusts the evaporated vapors and LFG in an RIC engine to produce electricity; the waste heat from the engines is used to aid in evaporating the leachate (Power Strategies L.L.C.).

2.3.2 LES and Technair System

Process Description—

OWT offers two LESs. The LES is marketed through its Omni-Gen Technologies, Inc. subsidiary. OWT is also a licensee of the Technair system (Italy). A schematic of the LES is presented in Figure 2-5. A process flow diagram for a 10,000 gpd LES with typical flow quantities is presented in Figure 2-6. Leachate is continuously fed to the evaporator vessel. A LFG-fired burner introduces hot gas into the leachate as fine bubbles below the surface (gas sparging) and direct heat transfer occurs between the liquid and hot gas. The leachate is maintained at 180 to 190 ^{o}F. Direct contact of hot gases with leachate acts to strip most of the organic compounds within the leachate to the vapor phase. Organics are transferred from the liquid leachate phase to the exhaust vapor phase by a process analogous to air stripping (i.e., contaminants partition between the vapor and liquid phases according to their respective vapor pressures and concentrations within the liquid). As the process occurs at elevated temperatures, the stripping action is

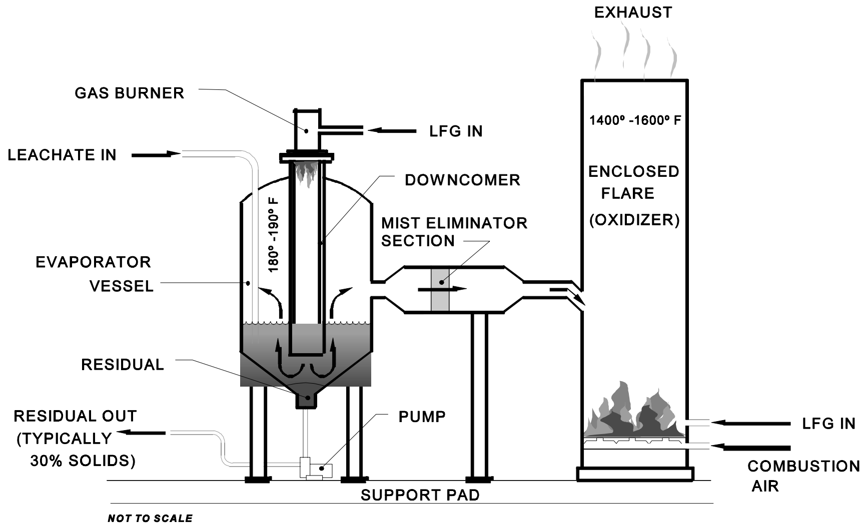


Figure 2-5. Schematic of OWT LES

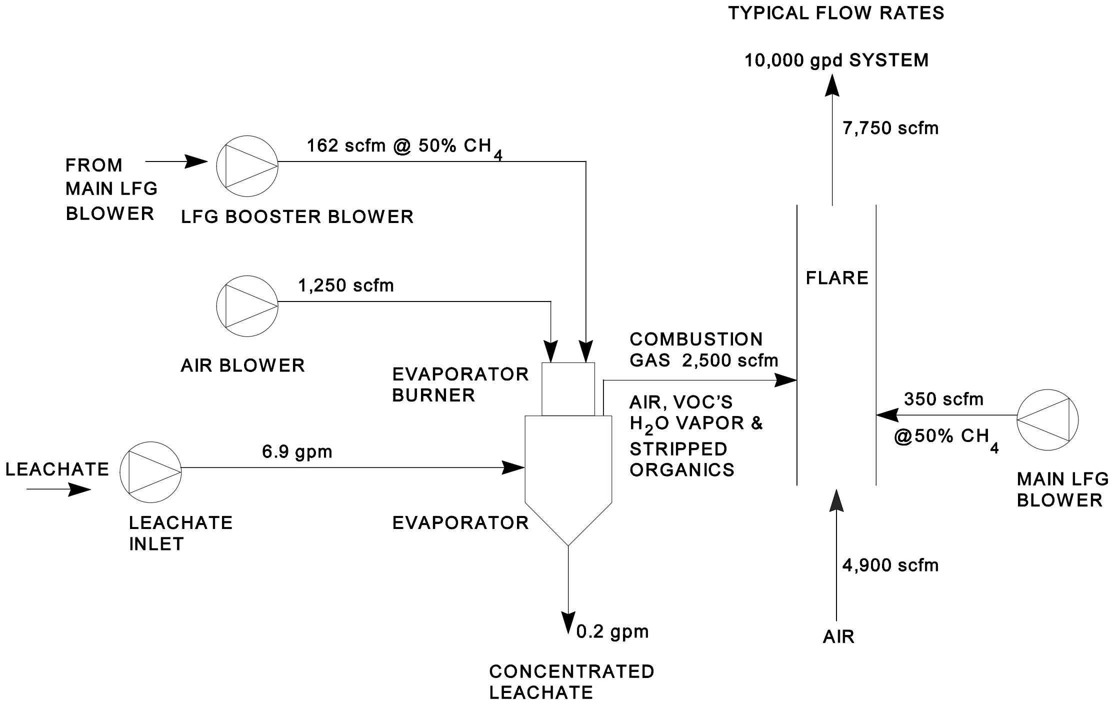


Figure 2-6. OWT/LES Sample Process Flow Diagram

generally more efficient than that obtained with most conventional air strippers operating at ambient temperatures.

The high vapor pressure and high concentration in the liquid phase promote efficient mass transfer to the gas phase in vapor stripping. Mass transfer of low vapor pressure organics at low concentrations is enhanced by the fact that the average residence time of liquid in the evaporation zone is long, typically measured in minutes or hours, and the total volume of vapor in contact with liquid is relatively large. The VOC-laden, saturated air is fed to the flare, where it is thermally oxidized.

A process flow diagram of the Technair system is presented in Figure 2-7. The Technair system uses indirect heat transfer from hot air that has been heated by a LFG burner. Leachate is circulated and concentrated in two tanks in series. Evaporation/stripping occurs in the densifier. VOC-laden air from the densifier is preheated and is introduced to the combustor, along with LFG. Thus, the burner provides thermal energy for both evaporation and thermal treatment of exhaust gases.

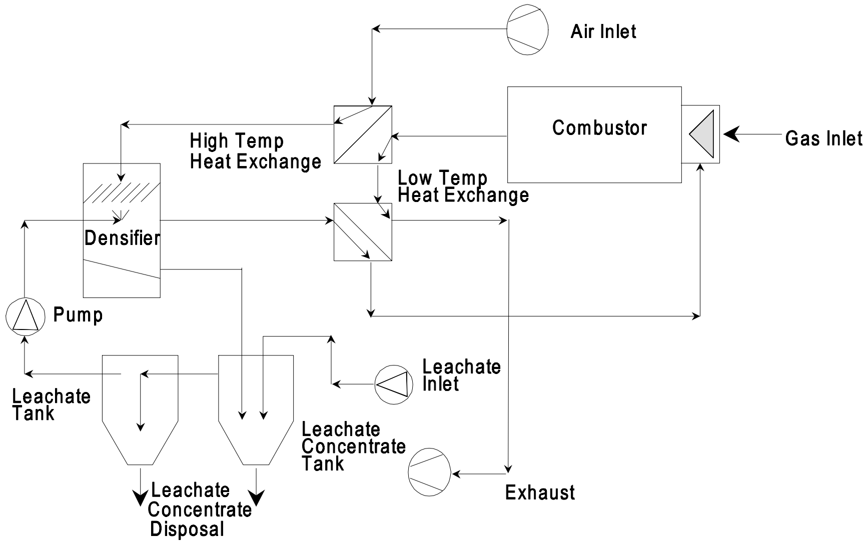


Figure 2-7. OWT/Technair LES

Performance—
Adequate energy from LFG must be available to treat the quantity of leachate generated. The amount of energy required to evaporate one pound of H_2O from leachate is approximately 1,150 Btu, based on the sensible heat (one Btu/lb-°F) and latent heat of vaporization of H_2O (approximately 1,000 Btu/lb; as the total concentration of organic compounds is relatively small, the energy requirement to heat and vaporize these contaminants may be neglected). Assuming heat losses within the evaporator are 15 percent, and that an additional amount of heat is necessary to evaporate the amount of leachate that is raised to the operating temperature of 180 °F, but is not evaporated (about 3 percent), the total heat required is about 1,350 Btu/lb leachate. Assuming LFG containing 500 Btu/scf, the required gas flow to treat one pound of leachate feed is approximately 2.7 scf/lb, or 22.5 scf/gal.

Fuel requirements for the thermal oxidation portion of the process varies according to the quality and quantity of vapor generated in the evaporation process. Based on OWT's operating experience the LES requires approximately 50 scf of LFG in the thermal oxidation section for each gallon of leachate feed treated. Therefore, it is estimated that the amount of LFG required to evaporate one gallon of leachate and treat the resultant exhaust vapor in the LES process is 22.5 + 50 = 73 scf/gal.

Less energy may be required for thermal oxidation if waste heat is recovered. The Technair system can be configured to include waste heat recovery. According to OWT, experience with this system in Italy using heat recovery has shown that overall LFG use can be reduced to 45 scf/gal at 50 percent CH_4 in the LFG feed.

OWT claims experience showing that 25 to 35 percent total solids in leachate effluent can be achieved by the LES and Technair evaporators, resulting in a significant volume reduction. Thus, for a hypothetical example of leachate feed concentration at 5,000 parts per million (ppm) solids and 25 percent total solids in effluent, the cycles of concentration (C_c) is:

$$C_c = C_2/C_1$$

substituting,

$$C_c = (25/100)/(5{,}000/10^6) = 50$$

Assuming leachate feed specific gravity (sg_1) is equal to H_2O: 1.0, and effluent specific gravity (sg_2) is 1.2 (representative of 25 percent aqueous salt solution), the percent volume reduction can be calculated by:

$$100 - [(1/C_c) \times (sg_1/sg_2) \times (100)] = \%\ \text{volume reduction}$$

substituting,

$$100 - [1/50 \times (1.0/1.2) \times 100] = 98.3\%\ \text{volume reduction}$$

Emissions—
No emissions test data are available for LESs using an enclosed flare to destroy LFG and organic vapors from leachate evaporation. Enclosed flares are considered to be best available control technology for LFG control. The amount of organic loading from evaporation is small; for example, adding only approximately 10 lb/day for a 10,000 gpd unit handling leachate at 100 ppm or less of organic compounds (typical). Emissions should be comparable to a well-designed enclosed flare operating on LFG.

Secondary Environmental Impacts—
As metals will remain in the concentrated leachate residue, testing was performed to confirm that no secondary problems exist. To date, all leachate processed in commercial and pilot scale LES and Technair evaporators has produced effluent that passes EPA's Toxicity Characteristic Leaching Procedure (TCLP) test as non-hazardous. In most cases, the concentration of all metals have been undetectable; the highest observed concentrations have been approximately 20% of the allowable level of any hazardous constituent. Thus, the effluent may be returned to the landfill.

Economics—
See costs reported for Orchard Hill Landfill and Sogliano al Rubicone Landfill below.

Demonstration Projects—
A 1,000 gpd LES is in demonstration service at the Brookhaven Municipal Landfill on Long Island, New York. This pilot scale evaporator was built through a partnership comprised of the New York State Energy Research and Development Authority, the Town of Brookhaven, EMCON, and Wehran Energy Corporation. The evaporator system is available for treatability tests on leachate and other dilute aqueous waste streams. The Brookhaven LES is sized to run one tankwagon (6,000 gal) of typical leachate for each pilot test.

The first full-scale LES was built and demonstrated at the Orchard Hill Landfill in Watervliet, Michigan in September of 1992. EMCON and Balkema Brothers, Inc. were partners in this venture. Prior to installation of the LES, leachate from the Orchard Hill Landfill was pre-treated and hauled approximately 40 miles to the Kalamazoo, Michigan wastewater treatment plant at a cost in excess of $0.11 per gallon. LFG was treated within an enclosed flare. Pretreatment consisted of pH adjustment and precipitation of heavy metals. Currently, Orchard Hill Landfill evaporates an average of more than 6,000 gpd of untreated leachate feed. Effluent at up to 30 percent total solids is returned to the landfill. Approximately one hour of labor per day is required to operate the evaporator. Annual maintenance costs are reported by the operator to be less than $25,000 per year. The estimated capital cost for this LES is $550,000 (1996 dollars).

The only problem encountered with the Orchard Hill LES related to the design of the gas sparging system. As a first full-scale demonstration project, the gas sparging system was originally constructed of carbon steel. Due to corrosion, the carbon steel parts were replaced in-kind with stainless steel after approximately 3 years of operation. As a result of this experience, LES evaporators are now built with higher alloy components.

The Orchard Hill LES is designed to fire approximately 125 scfm of LFG in the evaporator burner, and approximately 280 additional scfm within an attached enclosed flare. As with all LES units, the gas volume required in the flare section is a minimum value. Additional quantities up to the full capacity of the flare may be burned without affecting performance of the evaporator.

Technair (Concordia, Italy) constructed and placed their first commercial-scale unit into operation at the Sogliano al Rubicone Landfill near Bologna during 1992. The University of Modena provided technical support to Technair during the start-up phase of the project. Heat exchange devices were added to the design because the available volume of LFG at the site could not support a system without the assistance of waste-heat recovery. As a result of the addition of heat exchangers, only approximately 45 scf of LFG is required per gallon of leachate treated. The design rate for leachate evaporation for this Technair system is approximately 6,500 gpd.

The only operational problems with the Sogliano al Rubicone evaporator were with the quality of LFG and inconsistency in the electrical power supply. While the system did function with LFG at only 30 percent CH_4 during the start-up phase of the gas collection system, the maximum evaporation rate was reduced. Improvements in the gas collection system subsequently raised CH_4 levels to 40 percent and solved this problem.

An automated re-start system was added to accommodate frequent power outages. An on-site electrical plant fueled by LFG was added. Reported on-line time for the Technair unit is 95 percent of available hours. The plant has logged more than 25,000 operating hours without equipment failure. Reported installed cost is $750,000. Annual operating and maintenance costs are running at $5,000. Although the labor history for this system is not available, like the LES, the Technair system is designed to run unattended for periods of days.

Discussion—

As of late 1997, there were three commercial operating LES units in the US, plus the demonstration project in Brookhaven. An additional five units are scheduled to come on line in the spring of 1998.

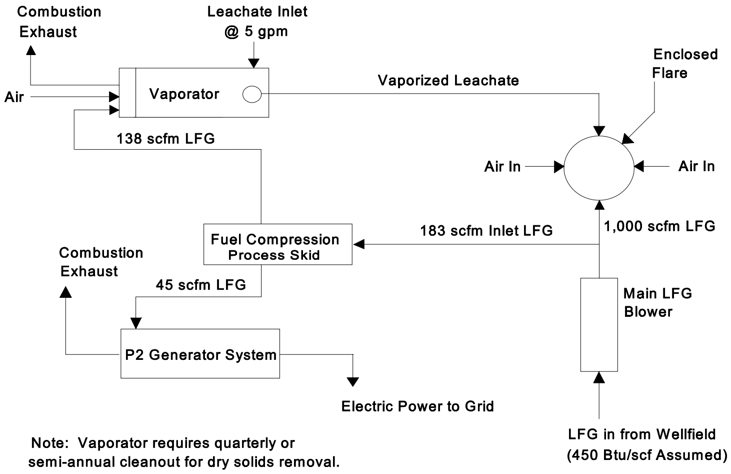
Future projects planned for LESs include: developing evaporation systems that run on waste heat from LFG engines; integrating control of NO_x and SO_x emissions from LFG flares and LFG driven engines with leachate evaporation; and controlling H_2S emissions from landfills within the evaporators. Benefits that can be realized by success in these areas include: broadening the applicability of leachate evaporation to sites where significant LFG is committed to power generation; providing an additional revenue stream for LFG to energy plants; and reducing the potential for sites to exceed "major source" trigger levels under the Clean Air Act. If LFG combustion has occurred historically at the site, potential reductions in NO_x and SO_x might be marketable as emission credits in certain non-attainment areas.

2.3.3 Vaporator System

Process Description—
Power Strategies L.L.C. markets a leachate destruction system, named the Vaporator™ (patent pending). The Vaporator also uses energy from LFG to evaporate leachate to a solid substance which can be returned to the landfill, and generates electricity to run all the electrical needs of the system. Additional electricity may be sold to a utility.

The primary equipment components include a fuel/compression/process skid, Vaporator, Engine Generator System, and a proprietary enclosed flare system. Fuel supply for the gas compression/processing skid is taken from the main LFG blower (compressor) discharge prior to delivery to the flare for incineration. Fuel gas is supplied to the internal combustion engine, which drives the Power Strategies P ^{2}™ tuned-reflux generator.

A process flow diagram for a typical system capable of destroying 5 gpm of leachate and generating 95 kW of electrical power is presented in Figure 2-8. The Vaporator requires 5 MMBtu/hr of energy from LFG to vaporize and destroy up to 5 gpm of leachate. The vapor or steam is controlled by a pressure-regulated valve and is released to the flare through an insulated flow line. The proprietary LFG flare provides for final destruction of the leachate steam. The vaporization process is a closed loop system, which the manufacturer claims provides for no odor or spillage.



Note: Vaporator requires quarterly or semi-annual cleanout for dry solids removal.

Figure 2-8. Power Strategies™ Leachate Destruction System

Enclosed LFG flare capacities vary from 1,000 to 5,000 scfm of LFG. Generator systems are available from 95 to 1,000 kW self-contained units, which can be configured in parallel, depending on specific needs.

Performance—
As of mid-1997, Power Strategies L.L.C. has four Vaporator units installed and operating, with four more projects in the design, engineering, and permitting stages, all in the U.S. The first prototype was designed to handle up to 5 gpm of leachate. It was installed in Quail Hollow, TN in mid-1995 and is still in commercial

operation. It is presently processing 3 gpm of leachate, as that is all that is generated at the site. All subsequent Vaporators are also 5-gpm modules. The second and third installations were in early 1997 (Virginia) and mid 1997 (Oregon). The fourth installation (also located in Virginia) is in startup mode as of September, 1997.

According to the manufacturer, the systems have been operating as expected, with only minor problems, such as supply pump leakage requiring a change in pump seals, and several leaky valves requiring repacking. The overall percentage of time the Vaporator systems have been online, or available for use while waiting for other systems to come back online, is in excess of 90% (Echols, 1997).

Emissions—
Emissions from the Vaporator system are generated from the following:

- Vaporator burner;
- RIC engine driving the generator; and
- flare used to destroy the LFG and leachate steam

Emission tests were conducted by Power Strategies to compare emission rates for flare-only operation and full system operation (i.e., Vaporator, engine and flare). LFG flow was approximately 1,100 scfm during the tests, leachate flow was 5 gpm, and electricity generation was 95 kW. The manufacturer reports that for flare-only operation, emission rates of NO_x and CO were 2.84 and 4.32 lb/hr, respectively. With full system operation, emission rates of NO_x and CO were 3.49 and 0.58 lb/hr, respectively. Thus, with full system operation, NO_x emissions increased by 23 percent and CO emissions decreased by 87 percent compared to flare-only operation.

Secondary Environmental Impacts—
No secondary environmental impacts are known. The Vaporator requires periodic cleaning (once every 3 to 6 months) to remove dry leachate solids, which resemble beach sand. The manufacturer claims that leachate solids have passed comprehensive TCLP testing with "non-detect" results on all tests to date. The dry solids are returned directly to the landfill.

Economics —
The installed cost of a Vaporator system capable of destroying 5 gpm of leachate and generating 95 kW is estimated to be about $750,000. At least one 95 kW generator system is recommended by the manufacturer to offset project electrical costs for operating LFG blowers and other electrical equipment. The landfill operator must determine whether it is advantageous to purchase more generating capacity by analyzing the local market and considering the cost of electricity, the wholesale price of electricity, the impacts of deregulation, etc. No data were available on operating and maintenance costs.

3.0 TECHNOLOGIES UNDER R&D (TIER 2)

Tier 2 technologies are those that are currently undergoing additional R&D, have been tested at the bench- or field-scale, and may be ready for commercial application. These technologies include both methods where the CH_4 in LFG is used as an energy source as a method for managing landfills to prevent or minimize the formation and release of CH_4 and other organic compounds (aerobic bioreactors).

The first two technologies, operating landfills as either anaerobic or aerobic bioreactors, are common in that the objectives are to increase the rate of waste biodegradation by enhancing the environmental conditions conducive to microbial activity (e.g., moisture, pH). The primary difference of the two technologies is that, in aerobic bioreactors, the objective is to enhance the generation of CH_4; whereas, in aerobic reactors, the objective is to minimize CH_4 generation. Both methods utilize leachate recirculation as a means to control and enhance moisture levels within the landfill. Leachate recirculation has been performed for a number of years primarily as a means to economically manage the leachate.

Data are presented in Table 3-1 on leachate disposal costs developed from a case study of a landfill in Georgia (Darragh, 1997). Initially, the leachate was hauled to an off-site treatment facility; however, the facility began experiencing treatment problems that were attributed to the leachate. The leachate was then hauled to a larger treatment facility for a period of time before odor problems forced consideration of other alternatives. The data in Table 3-1 are based on average annual costs projected over a 20 year time frame. Costs for equipment, labor, transportation, and maintenance are included (Darragh, 1997).

Table 3-1. Leachate Disposal Costs for a Case Study in Georgia

Method	Cost ($/gal)
Total Recirculation	0.011
Off-Site Treatment	0.090
On-Site Treatment with Rochem®	0.042
On-Site Treatment with Vacom®	0.037

Reference: Darragh, 1997.

Another leachate recirculation demonstration project was recently completed at the Roosevelt Regional Landfill in the State of Washington. The objectives of this project were to add 35,000 to 50,000 gallons of leachate and/or water per 1,000 tons of solid waste, maintain less than 12 inches of leachate head over the bottom liner, observe whether the recirculation of large amounts of leachate causes large increases in leachate generation, and, to a lesser extent, determine whether other operational or environmental problems would be encountered [Regional Disposal Company (RDC), 1997].

The demonstration area covered two acres of in-place solid waste of approximate 60 foot depth. Between October 1996 and March 1997, RDC added over 7,000,000 gallons of leachate to the demonstration area which was equivalent to about 50,000 gallons per 1,000 tons of waste. RDC installed a pipe below the demonstration area to observe leachate head on the bottom liner. Through September of 1997, no leachate head build-up has been observed (RDC, 1997). Further, RDC estimated that the total amount of moisture needed to reach field capacity for the Roosevelt demonstration project is 87,000 gallons per 1,000 tons of waste. No significant operational or environmental problems were encountered. The production or quality of LFG generated during the demonstration was not monitored. In addition, data on leachate quality specific to the test area were not gathered (RDC, 1997).

3.1 Operation of Landfills as Anaerobic Bioreactors

3.1.1 Introduction and General Overview

As mentioned above, the objective of operation of landfills as anaerobic bioreactors is to accelerate waste decomposition and gas generation by control of moisture, pH, temperature, and nutrients. Methods to enhance the collection efficiency of LFG may also be incorporated into an anaerobic bioreactor design. Of the control parameters, moisture is considered the most critical (Yolo County, 1997). Gas generation during conventional landfilling techniques occurs over long periods of time (more than 30 years). Over the lifetime of the landfill, CH_4 generated during the early stages (i.e., before extraction wells are in place) and late stages (i.e., when economic recovery is no longer possible) is typically not recovered. Further, final clay covers can be quite porous which limits the amount of CH_4 that can be collected.

Leachate recirculation is an important aspect of anaerobic bioreactors for moisture management and, as described above, can provide significant economic benefits. Additional benefits of anaerobic bioreactors include improved leachate quality, reduced costs for post-closure gas and leachate management, and problems related to long-term settling (subsidence). In addition, bioreactors can potentially provide additional revenue to the extent that enhanced subsidence during the active phase of the landfill offers additional volume for waste emplacement.

Another important aspect that can be incorporated into the design of an anaerobic bioreactor is a gas-impermeable (synthetic) membrane. These membranes, when installed over gas conducting layers (e.g., shredded tires), can achieve essentially 100 percent LFG collection efficiency. However, use of synthetic membranes alone (i.e., without moisture management) will likely result in degradation and gas generation rates much slower even than conventional landfills (Yolo County, 1997).

Early work on anaerobic bioreactors began in the mid-1980's during tests on six cells at a landfill in Mountain View, California. These tests showed gas generation rates three to five times that of conventional landfills in the area. Other tests have occurred since; however, data on gas generation are lacking. One of the test programs did show improvements to leachate quality. The following sections describe a pilot project conducted at the Yolo County Central Landfill (YCCL) which was designed to fill the knowledge gaps remaining from previous work on anaerobic bioreactors.

A description of a demonstration project being conducted in Yolo County, California is given in the following section. Although this project involves aspects of landfill construction that may be limited to consideration for new landfill cells, the EPA is aware of a project just underway where similar operating practices are being used on an existing landfill in Washington State. Unfortunately, details of this project were not available as of the preparation of this report.

3.1.2 Yolo County Central Landfill, California

The pilot project at YCCL consists of two test cells of approximately 9,000 tons of waste each (solid waste and green waste). An “enhanced” test cell is being operated as an anaerobic bioreactor, while the other test cell is serving as the “control” cell. Both cells are constructed to be gas-tight and are fitted with sensors to monitor moisture and temperature at multiple points within the waste. Characteristics of the enhanced and control cells are as follows (Augenstein et al., 1997):

	Control Cell	Enhanced Cell
Area (acres)	0.27	0.27
Average Depth (ft)	40	40
Solid Waste (tons)	7,283	7,133
Alternative Daily Cover - Green Waste (tons)	1,454	1,336
Average Compaction (lb/cubic yard)	1,014	1,027
Shredded Tires Used (tons)	200	295

A diagram of the YCCL Anaerobic Bioreactor Demonstration Project is shown in Figure 3-1. This figure shows the leachate recirculation system of the enhanced cell, including the leachate reinjection (distribution) manifold injection pits. Objectives of the project include:

- substantially accelerate LFG generation and maximize gas capture;
- monitor biological conditions within the test cells;
- provide technology transfer;
- gain a better understanding of moisture movement within the landfill; and
- assess the performance of shredded tires within the landfill as a medium for gas transfer.

Construction, filling, and covering of the test cells was completed in December 1995. Addition of liquid to the enhanced test cell was begun in October 1996. Table 3-2 contains data on the liquid balance of the enhanced cell. As shown in the table, the apparent minimum field capacity of moisture per weight of dry waste was estimated to be 113 gal/dry ton or 46 percent (Augenstein et al., 1997).

Table 3-2. Enhanced Cell Moisture Balance

Parameter	Volume (gal/dry ton waste)
Incoming Waste (20 percent moisture assumed)	60
Supplemental Liquid Added	55
Recycled Leachate	64
Total Liquid Input	**179**
Generated Leachate	64
LFG Condensate	0.2
Emitted Within LFG	2
Total Liquid Output	**66.2**
Apparent Field Capacity (179 to 66.2)	**113 (90 gal/as-placed ton)**

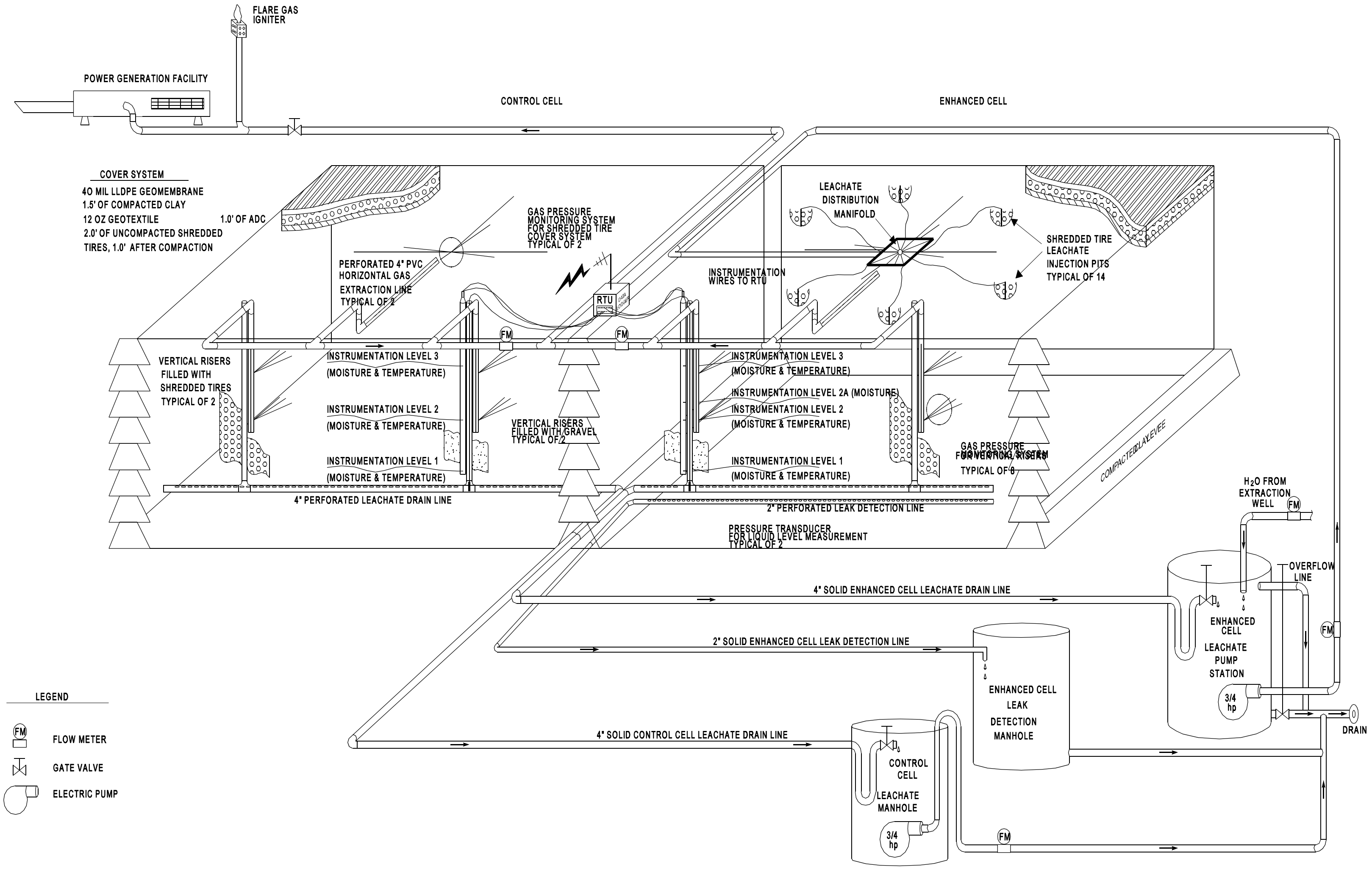


Figure 3-1. Anaerobic Bioreactor Demonstration Project at YCCL (adapted from Augenstein et al., 1997)

Data on leachate quality are presented in Table 3-3. These data represent changes in leachate chemistry following approximately eight months of leachate recirculation. Due to the limited amount of leachate collected from the control cell and the manner in which it is collected (leachate was in contact with the ambient air for long periods of time prior to sampling), the leachate chemistry from the control cell can not be compared to the data in Table 3-3 (Augenstein et al., 1997).

Table 3-3. Changes in Leachate Quality for the Enhanced Cell

Parameter	During Initial Recirculation	After 4 Months Recirculation
pH @ 25 °C	5.8	7.0
BOD (mg O_2/L)	5,020	820
COD (mg O_2/L)	20,300	2,860
TDSs @ 180 °C (mg/L)	19,800	7,600
TOC (mg/L)	9,830	611
Iron (micrograms/L)	152,000	933
Manganese (micrograms/L)	41,900	4,000
Calcium (mg/L)	1,400	480
Toluene (micrograms/L)	160	75

Note: BOD = Biological Oxygen Demand, COD = Chemical Oxygen Demand, O_2= Oxygen, TDS = Total Dissolved Solids, and TOC = Total Organic Carbon.

Data on LFG recovered from the enhanced and control cells are presented in Table 3-4. From January 1997 to July 1997, average LFG flows in the enhanced cell were over 30 percent higher than the control cell with slightly higher CH_4 content. In addition, settling in the control cell was only 30 percent of the enhanced cell (Augenstein et al., 1997). Figure 3-2 is a graph comparing cumulative LFG and CH_4 production in the enhanced and control cells.

Table 3-4. LFG Summary Data for the YCCL Demonstration Project

Parameter	Control Cell	Enhanced Cell
Cumulative LFG Volume, 7/96 - 7/97 (10^6 scf)	9.0	12.2
Average LFG Flow Rate (scfm)	27	39
Average CH_4 Content (%)	50	53
Average Landfill Settlement, 5/96 - 5/97 (inches)	4.3	14

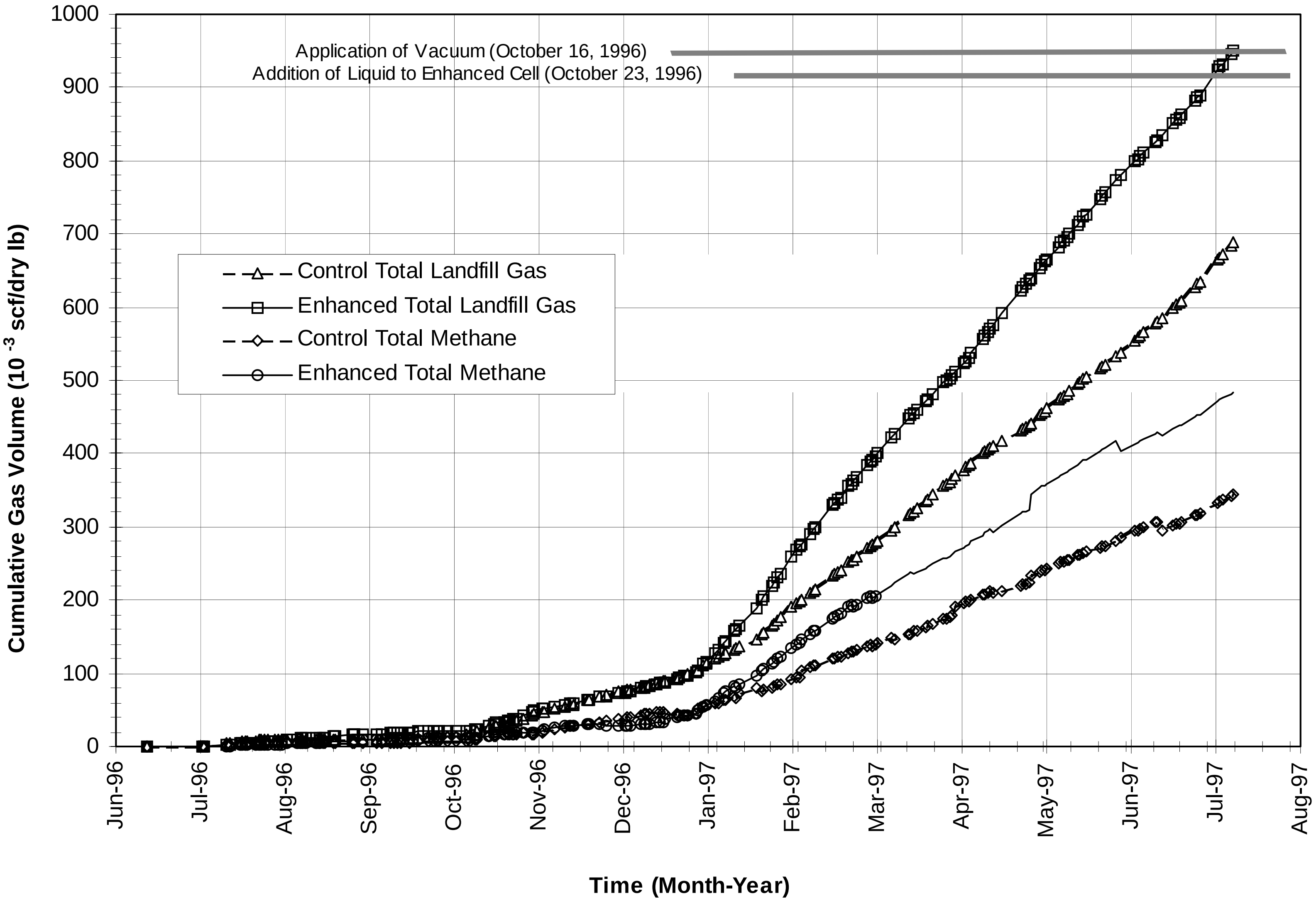


Figure 3-2. Cumulative LFG and CH_4 Production for the Control and Anaerobic Bioreactor Cells (adapted from Augenstein et al., 1997)

In addition to LFG generation, temperature trends in the enhanced and control cell are of interest. Soon after waste emplacement was completed, temperatures deep within both cells increased by approximately 6 to 10 °C. This initial trend is attributed to the methods of waste emplacement. Heat from initial aerobic activity is thought to have been captured by quick vertical filling of the cells and insulation from the ambient air (Yazdani, 1997). Over approximately the next 16 months, the refuse temperatures slowly decreased to about 40 °C. In the upper layers of both cells. Finally, as of February 1997 (approximately four months after liquid addition began in the enhanced cell), refuse temperatures within the enhanced cell have begun to climb while temperatures in the control cell have remained essentially constant (Yazdani, 1997).

3.1.3 Emissions and Costs

Costs for the YCCL pilot project are shown in Table 3-5. Costs include construction of both the enhanced and control test cells. Projections were made for the application of the technology on a new 22-acre waste management unit. The landfill unit would have a 58 ft depth and would receive between 450 and 500 tons of waste per day. Large differences were seen in capital costs depending on whether or not a double-lined containment system would be required. Some states are expected to require dual-liners, since liquid (recirculated leachate or H_2O) will be added to the landfill. Construction costs for double-lined containment systems were estimated to be \$50,000 to \$100,000 per acre higher than single-lined systems (Yolo County, 1997).

Table 3-5. Costs for the YCCL Anaerobic Bioreactor Pilot Project

Item	Cost ($)
Base Liner	114,000
Clay Levees	120,000
Waste Monitoring System	40,000
LFG Collection System	34,500
Leachate Recirculation System	47,500
Cover System	52,000
Initial Operation and Testing	7,000
Project Design	73,000
Reporting	25,000
Contingencies	50,000
Total Costs	**563,000**

Financial support for construction of the YCCL Bioreactor Project was received from the California Energy Commission, Yolo County, Sacramento County, and the California Integrated Waste Management Board. Cost components for the project are broken out in Table 3-5. The monitoring phase of the project (1996 to 1998) is being financially supported by the U.S. DOE's Western Regional Biomass Energy Program and Urban Consortium Energy Task Force, as well as Yolo County (Augenstein et al., 1997). The total costs associated with the two year monitoring phase are \$275,000 (these costs include O&M costs and technology transfer activities).

No data were available for estimating the costs of utilizing the anaerobic bioreactor process on existing landfills. For existing landfills, the technology could be considered at sites with a minimum single-liner containment system (e.g., in areas with deep groundwater). In areas where the depth to groundwater is low, the process should probably be limited to existing landfills with dual-liner systems. State or local regulatory agencies should be consulted regarding the suitability of this technology in any area.

Over the life of the landfill, application of the anaerobic bioreactor process will result in lower emissions of CH_4, NMOC, and other LFG constituents. As described above, this is due to more efficient LFG collection over a shorter time-frame and the fact that the waste is stabilized much sooner than with conventional landfill methods. Although the impacts are thought to be significant, data are not currently available to accurately quantify these benefits.

3.2 Operation of Landfills as Aerobic Bioreactors

3.2.1 Introduction and General Overview

As with anaerobic bioreactors, the operation of landfills as aerobic bioreactors involves maintaining sufficient moisture within the waste mass to promote biologic activity. However, in aerobic bioreactors, oxygen (from air) is continually added to the system to maintain an environment conducive to aerobic degradation of wastes. Some of the advantages of operating a landfill as an aerobic bioreactor include (Gordon et al., 1997):

- biodegradation rates up to 40 times faster than occur in anaerobic environments (i.e., accelerated waste stabilization);
- decreased solubility of metals leading to lower migration via leachate (also seen in anaerobic bioreactor processes, as shown in section 3.1.2);
- significant reduction in CH_4 production;
- reductions in odor (i.e., due to reduction in emissions of reduced sulfur compounds); and
- reduced leachate volume and strength [e.g., chemical oxygen demand (COD), biological oxygen demand (BOD)].

By increasing the rate of biodegradation, waste volume is reclaimed over a shorter period of time (estimates are less than 5 years). For a given volume of landfill space, this offers the potential for the addition of more waste to the space during the active life of the landfill. The economic value of this additional landfill space, the low cost of the technology, and the avoided costs of at least some leachate treatment or disposal are the key benefits for this technology.

Aerobic bioreactor technology has been in use in Japan, where land value is extremely high, for many years (Hanashima et al., 1989). More rapid landfill reclamation and improvements in leachate quality have been noted as the most important achievements. The technology is expected to become a prime candidate technology for landfills in the U.S. and elsewhere that can not generate LFG in sufficient quality or quantity to economically recover the associated energy. As seen in Japan, it may gain additional importance in areas where landfill space carries a premium value. In addition, this technology could also be considered as a follow-on technology for energy recovery projects at landfills that are no longer producing CH_4 at economically valuable levels.

3.2.2 Baker Place Road Landfill, Columbia County, Georgia

American Technologies Inc. (ATI) was contracted by the Southeastern Technology Center (STC) to pilot test an aerobic bioreactor at the Baker Place Road Landfill in Columbia County, Georgia. STC funded the pilot test through a cooperative agreement with the DOE. Testing began in January 1997 on 8 acres of the active 16 acre landfill cell. Early results after five months of operation have shown an increase in aerobic activity (e.g., increase in landfill temperature, decrease in CH_4 content of LFG), and the pilot test has been extended into 1998 to collect additional data on landfill settlement (Hudgins, 1997). A simplified schematic of an aerobic bioreactor system is shown in Figure 3-3.

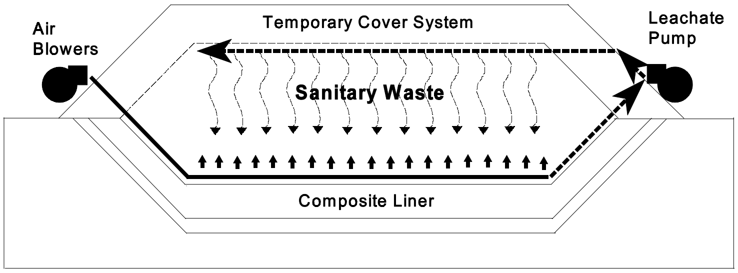


Figure 3-3. Aerobic Bioreactor System Schematic

As shown in Figure 3-3, an aerobic bioreactor system can utilize the existing leachate collection system supplemented by air injection wells to facilitate the proper balance of air flow, moisture, and temperature control (Hudgins, 1997). The entire system consists of the leachate collection/air injection piping, air blower(s), leachate holding tank (not shown), leachate injection pump/piping, and monitoring equipment (e.g., for waste mass temperature and moisture). Leachate is injected into the landfill through an intermediate clay cap to the top of the waste. Delivery of air and water are balanced to obtain optimal conditions for degradation. Improper balancing of air and water can lead to elevated waste mass temperatures and landfill fire potential. After completing aerobic decomposition on a lift of waste, the leachate injection system can be removed and placed on top of a new lift of waste, minimizing material costs.

As mentioned above, early results of the project showed an increase in temperature and a decrease in CH_4 production. Figure 3-4 shows the evolution of LFG composition during the first 50 days of operation while the landfill environment was being transformed from an anaerobic environment to a predominantly aerobic environment. The data for Figure 3-4 were taken at a single monitoring point typical of the overall landfill (Hudgins, 1997).

Early results also included reductions in leachate BOD (more than 65 percent), metals (more than 75 percent), and organics (more than 75 percent). At the onset of the project, approximately 120,000 gallons per month of leachate was being collected from the landfill. For the first six months of the project, all of the leachate was returned to the landfill. By the seventh month, some excess H_2O was being held in a holding tank. ATI anticipates that, at some point in the future, the net amount of leachate will exceed that which is returned to the landfill requiring some off-site treatment (Hudgins, 1997).

3.2.3 Emissions and Costs

Net emissions of CH_4 and VOC will be reduced, potentially at the levels described above or shown in Figure 3-4, assuming that gas generation rates have remained relatively constant (i.e., these data are concentration data and no flow rate data were available to generate mass emission rate estimates). CO_2 emissions will increase as CH_4 and NMOC decrease. However, since CH_4 is a much more potent GHG than CO_2, net GHG impacts will decrease. Depending on the characteristics of the leachate and how it is stored, the holding tank could become a source of NMOC emissions.

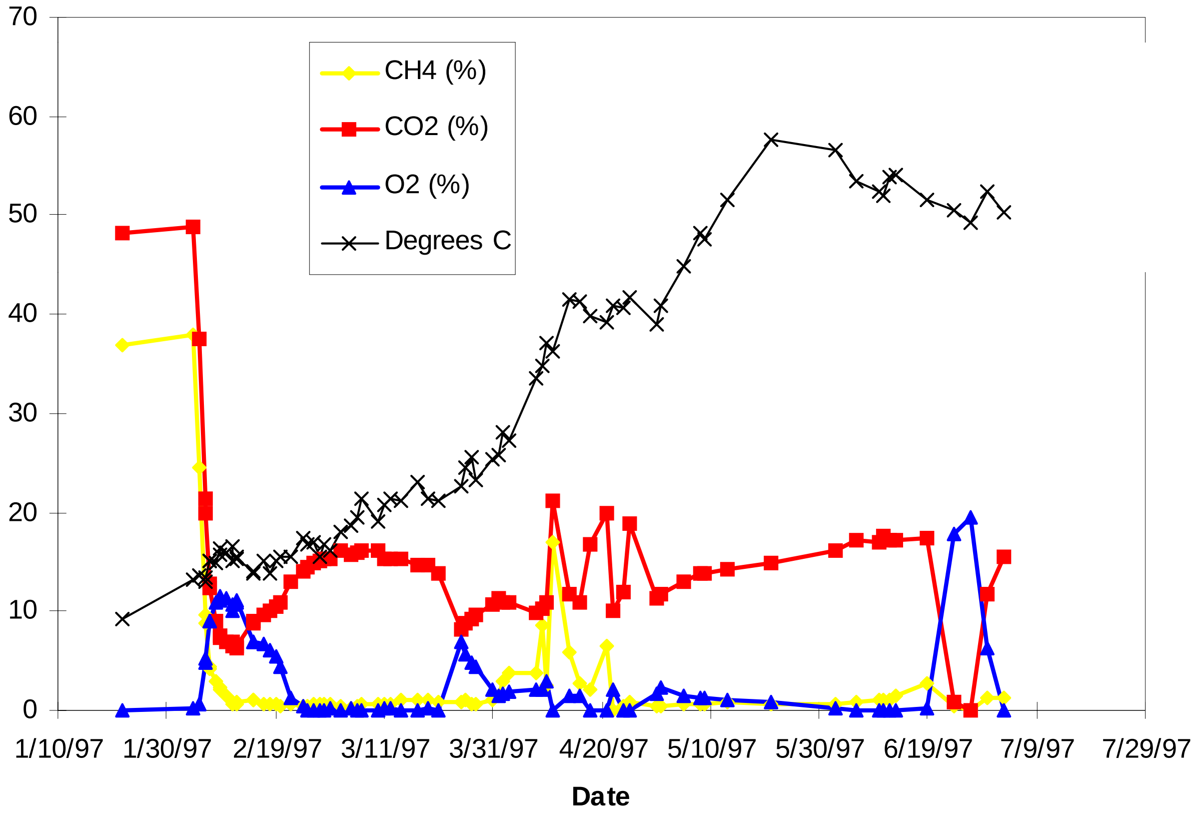


Figure 3-4. LFG and Waste Temperature Measurements Obtained During the First Six Months of an Aerobic Bioreactor Operation

Capital costs for an aerobic bioreactor system are estimated to be about $25,000 to $30,000 per acre (average 10 foot depth) based on the Baker Road Landfill Project (Hudgins, 1997). It is assumed that a leachate collection system is already in place and that this system is capable of delivering air to all portions of the landfill. Costs would be higher where no leachate collection system is in place or where additional air injection wells are needed to introduce air throughout the landfill. Capital costs include the costs of air blower(s), leachate holding tank, leachate injection pump and piping, and monitoring equipment. No information was available on O&M costs, however these will be similar to those for operating and maintaining a gas collection system plus some additional costs for landfill monitoring.

A physical survey was planned for Fall 1997 to determine the extent of landfill settling during the first ten months of the project. Estimates have been made that an additional $5,000,000 in revenue (from additional disposal fees) could be generated if 25 percent reduction in waste mass for the entire 16 acre cell could be achieved with an aerobic bioreactor (Darragh, 1997). Additional savings relative to the avoided costs of leachate treatment over an assumed ten year landfill life (as an aerobic bioreactor) could reach over $350,000, assuming that the average leachate production is 200 gallons per acre per day and that on-site treatment has a net cost of $0.03 per gallon ($0.04 for on-site treatment to $0.01 for recirculation).

Closure costs are likely to remain the same using either conventional waste management techniques or operation as an aerobic bioreactor, since, for new landfills, liners will still be required to meet Resource Conservation and Recovery Act Subtitle D requirements. Assuming that emission levels following the aerobic bioreactor process are below permit levels, a gas collection system will not be needed; however, gas vents or other gas control features will still be needed to allow venting through the cover system. Additional savings are expected relative to reduced post-closure groundwater/leachate sampling and post-closure leachate treatment (Darragh, 1997).

3.3 Production of Methanol from LFG

3.3.1 Introduction and General Overview

Conversion of LFG to methanol for use as a vehicle fuel or as a chemical feedstock has been investigated in the U.S. since the early 1980s. These early investigations concluded that methanol production from LFG was technically feasible; however, only marginal economic returns were expected with the pricing of methanol during that time [International Harvester Company (IHC), 1982; Science Applications, Inc., 1983]. However, during the early 1990's, the price of methanol increased substantially (2 to 3 times) due to the reformulated gasoline (RFG) requirements of the Clean Air Act Amendments of 1990 (Taylor, 1994). Methanol or its derivative, methyl tertiary butyl ether (MTBE), are prime candidates for use as oxygenates in RFG. Methyl tertiary butyl ether is currently being used in many RFG formulations in U.S. ozone nonattainment areas.

Methane conversion to methanol is conducted in a gas reformer at an elevated pressure and temperature in the presence of steam and a catalyst (e.g., nickel). When CH_4 and steam come into contact with the catalyst, two reactions occur (IHC, 1982):

$$CH_4 + H_2O \rightleftharpoons 3H_2 + CO \qquad (reaction\ 1)$$
$$H_2O + CO \rightleftharpoons H_2 + CO_2 \qquad (reaction\ 2)$$

Varying amounts of the reactants and products exist from the two equations depending on reaction conditions. The resulting gas, which is a mixture of all of these species, is referred to as synthesis gas (syn-gas). The syn-gas is then fed into a methanol catalyst and reactor system to form methanol by the following two reactions (IHC, 1982):

$$CO + 2H_2 \rightleftarrows CH_3OH \qquad (reaction\ 3)$$
$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O \qquad (reaction\ 4)$$

An LFG to methanol conversion plant was proposed for start-up in the Spring of 1996 by TeraMeth Industries (TMI). This facility was to have been located in West Covina, California; however, the project was never constructed. Details on why the project was abandoned are not clear, but are apparently related to local permitting issues (Wuebben, 1997). TMI has completed permitting for a facility in the State of Washington and plans on construction to begin by the end of 1997.

Figure 3-5 shows a simplified process flow diagram for a methanol production facility. The process can be divided into four separate components:

1. Pretreatment. As with most other LFG utilization technologies, it is necessary to remove contaminants such as reduced sulfur compounds and halides. The pretreatment section of the process includes equipment for desulfurization, condensation, desiccation, halide removal, and CO_2 extraction. Significant pretreatment of halides and sulfur compounds (i.e., low ppbv levels) is necessary to reduce the potential for catalyst poisoning in the reformer.

2. Reforming. Following gas cleanup, the LFG is sent to a catalytic reformer where reactions 1 and 2, on the previous page, take place (to produce syn-gas). The syn-gas is then separated from condensate, and the H_2O is recycled back to the reformer.

3. Conversion. The syn-gas is compressed prior to entering the methanol convertor where reactions 3 and 4, on the previous page, take place.

4. Purification. The liquid from the methanol convertor is then distilled. Methanol from the top of the distillation unit is sent on to storage tanks, while the H_2O and byproducts are recycled back to the reformer.

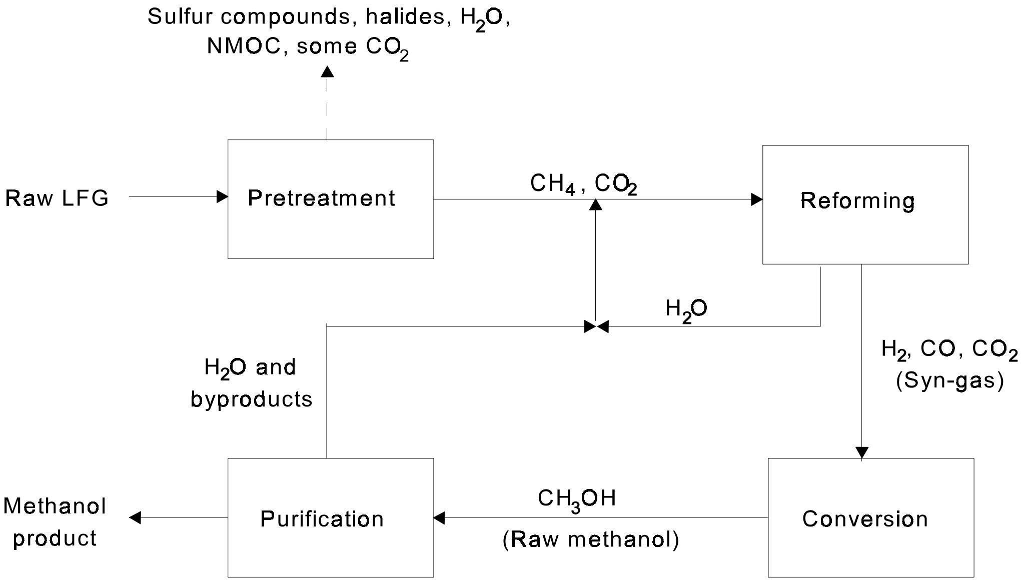


Figure 3-5. Simplified Process Flow Diagram of a LFG to Methanol Plant

LFG has been proposed for producing U.S. Grade A methanol that could be used as a chemical feedstock or as a vehicle fuel or fuel additive. Methanol is used in the production of many intermediate chemicals including formaldehyde, acetic acid, and methyl amines. End products which are manufactured from methanol-derived intermediates include plastics, disinfectants, adhesives, insecticides, and solvents.

3.3.2 Emissions and Costs

Estimates of emission reductions based on mass balance procedures for the proposed southern California project are given in Table 3-6. These data are taken from an air quality impacts assessment performed by SCAQMD (SCAQMD, 1994). The data summarized in this table compare the emission reductions associated with the proposed LFG to methanol conversion process to the emissions created by the same amount of flared LFG (3.6 million scfd).

Table 3-6. Air Emission Impacts for a Proposed LFG to Methanol Plant

Net Emission Reductions	Pollutant						
	CO	VOC	NO_x	SO_x	PM_{10}	CO_2	CH_4
lb/day	272	12.1	68	17.0	74.0	373,964	1,479
tons/year	49.6	2.2	12.4	3.1	13.5	68,248	270

Adapted from SCAQMD, 1994.

Emissions from the proposed process included NMOC emissions following gas clean up and destruction in the catalytic reformer (see Figure 3-5) with an estimated destruction efficiency of 99.5 percent. The difference in CO_2 emissions is due to consumption of CO_2 during pretreatment of the LFG and during formation of methanol from the syn-gas (see reactions 1 through 4 in section 3.3.1). Emissions of sulfur dioxide (SO_2) are reduced due to removal of sulfur-containing compounds during pretreatment. The reductions in NMOC and NO_x are determined based on vendor-guaranteed values for destruction efficiency and NO_x formation for the reformer.

Additional air quality benefits would be expected if some or all of the methanol produced by the facility is used as vehicle fuel. The SCAQMD estimated that, compared to gasoline engines, methanol powered vehicles would emit 30 to 50 percent less ozone-forming emissions (i.e., NMOC and NO_x) and reduce toxic emissions by 50 percent (Wuebben, 1991).

To the extent that dioxins and furans and combustion products are emitted via flaring, the LFG to methanol conversion process has the potential to reduce these emissions. Since only a small amount of the LFG used by such a methanol facility would be combusted (to heat the catalytic reformer), most of the LFG would no longer be flared (and the accompanying combustion products would not be emitted).

Few data are available for actual capital and operating costs for LFG to methanol plants. In a 1982 feasibility study for the State of New York, IHC estimated the capital costs for installing and start-up of a 6.7 million gallons per year Grade C methanol facility to be $14.9 million (over $17 million in 1997) for a modular-constructed (versus field-constructed) plant (IHC, 1982). Conversely, data provided by TMI for their West Covina facility provided capital costs of $9.4 million (Bonny, 1994). This facility's capacity was to be approximately 6.1 million gallons per year of Grade A methanol (highest purity), and the plant was also to be constructed in a modular fashion. The reason for the large discrepancy between these estimates was not apparent from available data sources.

Operating costs quoted for a plant in the IHC study were \$1.9 million (about \$2.2 million 1997 dollars). The operating costs, in terms of methanol produced, were estimated at \$95/ton (about \$110 in 1997 dollars; IHC, 1982). No comparable data were available for the proposed southern California facility.

3.4 Production of Commercial CO_2 from LFG

3.4.1 Introduction and General Overview

Most LFG utilization technologies do not attempt to capture the CO_2 component of LFG (LFG CO_2) for commercial use. Hence, the commercial value and environmental benefits associated with LFG CO_2 recovery are not realized from these projects. The value of recovering the energy associated with CH_4 from landfills has been discussed in previous sections. However, since CO_2 typically makes up 30 to 50 percent of LFG, there may also be merits associated with its recovery as a commercial product.

A study on the feasibility of LFG CO_2 recovery prepared by Acrion Technologies, Inc. (Acrion) for DOE indicated an increasing demand for high purity (food grade) liquid CO_2 (Acrion, 1992). In 1992, domestic sales were estimated to be 11,000 tpd and the historical growth rate was cited as 8 percent. Retail prices for high purity liquid CO_2 were stated to be between \$50 and \$200 per ton depending on volume and delivery point (transportation is the key driver of cost for CO_2). Domestic landfills were estimated to be able to supply twice the current CO_2 demand.

Current utilization technologies do not attempt to recover LFG CO_2 because: (1) recovery would require recompression of the CO_2 which is expensive; (2) trace contaminant removal to the purity requirements for food grade CO_2 cannot be performed by any single commercial process (Acrion, 1992); and (3) nontechnical hurdles, such as the public's perception of a food product developed from LFG.

The objectives of Acrion's process are to simultaneously recover fuel grade CH_4 (LLG) and food grade CO_2 from raw LFG. A simplified flow diagram of the Acrion process is shown as Figure 3-6. The process consists of the following four steps (Acrion, 1992):

1. Compression, inter-cooling, and H_2O removal is performed as with the other utilization options during LFG preparation.

2. CO_2 is condensed from the dried, chilled LFG at elevated pressures in a refluxed absorber column. In this step, the trace contaminants are absorbed by the liquid CO_2.

3. The overhead vapor from CO_2 condensation contains more than 80 percent CH_4, along with nitrogen, and CO_2. The residual CO_2 is removed with a conventional solvent. The vapor is condensed by refrigeration to produce the LLG product.

4. Purified (food grade) CO_2 is produced by triple-point crystallization (TPC). TPC is the formation of solid CO_2 in the presence of both liquid and vapor phases at temperature and pressure conditions near the triple point of CO_2 ($^{-}67\ ^{o}F$, 75.1 psi). Lowering the pressure slightly below the triple point pressure causes the liquid CO_2 to boil: that in turn cools the TPC chamber. This internal cooling causes solid crystals of CO_2 to grow that exclude contaminants. Trace contaminants that were not removed earlier in the process are left in the liquid phase in the upper portion of the chamber (mother liquor), and are separated from the pure solid CO_2 that moves downward, melts at the bottom of the chamber, and is removed as clean liquid product.

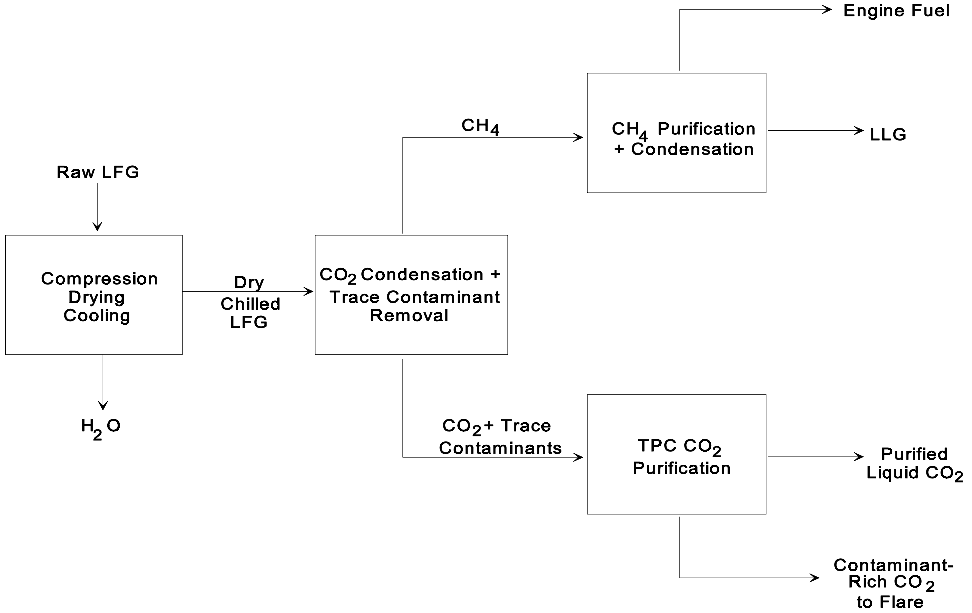


Figure 3-6. Flow Diagram for Converting LFG to LLG and Purified CO_2

Acrion estimated that over 98 percent of the CH_4 in the LFG is recovered by the process. Approximately 15 percent of the recovered CH_4 is consumed by engines to generate on-site power. About 70 percent of the LFG CO_2 is recovered as product. Most of the balance is lost in the fuel to the engines and as contaminated liquid absorbent that is incinerated in the onsite flare. The CO_2 product is estimated to contain approximately 1.5 ppm of total impurities that are present due to adherence of some of the mother liquor in Step 4 (Acrion, 1992).

Acrion is also investigating a similar process that does not utilize the TPC purification portion of the process to purify CO_2 (Brown, 1997). This process uses cold liquid CO_2 from the LFG to purify both the CH_4 and CO_2 product streams. Contaminants are concentrated in a separate stream of CO_2 that is fed to an on-site flare. According to Acrion, negotiations are nearing completion for a demonstration project at a site in the State of New York.

3.4.2 Emissions and Costs

An adequate characterization of potential plant emissions has not been made. The two primary sources of emissions at a facility such as the Acrion facility described above would be the power generation engines and the facility flare. Information on costs was not available.

3.5 Use of LFG as a Supply of Heat and CO_2 for Greenhouses

3.5.1 General Overview

One application of LFG currently in operation at Topgro Greenhouses Ltd., Langley, BC is the use of LFG as a fuel supply for heating a greenhouse (Hanson, 1997). In addition, the exhaust gas from one of two boilers is diluted and injected directly into the greenhouse to enrich the CO_2 concentration for the purpose of promoting plant growth. This type of application using natural gas or propane is typical for greenhouses.

Although the use of LFG to provide heat for greenhouses is not new, this project, where LFG is used to provide both heat and CO_2 enrichment, is the first known of its kind.

The Topgro system using LFG for CO_2 enhancement in greenhouses is the first known of its kind. Additional details of this project are given below. It is also worth noting that plans are underway to utilize waste heat and CO_2 generated by the PAFC project described in Section 2.1 in a greenhouse to be located at the landfill (Borea, 1997).

In February 1994, Topgro began utilizing LFG generated by the nearby Jackman Landfill as heating fuel. The landfill is located approximately one mile from the greenhouse. Some minor modifications to the boiler were necessary to burn "wet" LFG, such as a larger size burner head and stainless steel components. The project was designed and constructed by E.H. Hanson Engineering Group Ltd., Delta, BC. Use of exhaust gas as a CO_2 supplement occurred approximately four months later, after source tests and a detailed analysis confirmed that it posed no risk to the plants (Hanson, 1995, 1997).

LFG supplied to the Topgro greenhouse is composed of 35 to 55 percent CH_4 and 65 to 45 percent CO_2. Nitrogen is also present at between 2 and 22 percent. Additional CO_2 is produced by the combustion of CH_4. A feasibility study was initiated to determine if the boiler exhaust gas could be safely utilized in the greenhouse environment. It was determined that the exhaust gas contained approximately 9.9 percent, or 99,000 ppm CO_2 (the 45 to 65 percent CO_2 in the LFG is diluted by the large amount of combustion air required). As only 1,000 ppm CO_2 is required in the greenhouse, significant dilution of exhaust gas is necessary (Hanson, 1995).

3.5.2 Emissions and Costs

As the key part of the CO_2 enrichment feasibility study, there was concern that certain combustion products could be harmful to plant life (e.g., SO_2). However, initial test data confirmed that sulfur gases would not be a problem, because sulfur, mainly as methyl mercaptan, was found to be present at low levels (i.e., 50 ppm range). Resulting SO_2 concentrations were calculated by Hanson and determined to be well below levels harmful to plants (Hanson 1995).

In addition, a botanical consultant advised that the concentration of ethylene must be maintained below 100 parts per billion (ppb) in the greenhouse environment to avoid accelerated plant aging. Ethylene is present in the unburned LFG at approximately 2.3 ppm. Based on source test data, the highest stack gas concentration was found to be 0.4 ppm, indicating at least 83 percent destruction of ethylene in the combustion process. Dilution of the stack gas brings the ethylene concentration well below the 100 ppb level, as discussed below.

Source test data were collected for five boiler firing rates, from 10 to 90 percent. The stack gas data are presented in Table 3-7. Prior to introduction into the greenhouse, stack exhaust gas is diluted with ambient air (assumed 300 ppm CO_2) to meet the required 1,000 ppm CO_2 concentration. The concentrations of the diluted mixture are presented in Table 3-8. Thus, as long as proper combustion is ensured, the ethylene concentration of the diluted exhaust air will be well below the 100 ppb limit. All of the other contaminants analyzed are also well within acceptable levels for plants and personnel.

Economic benefits for a landfill owner or operator are dependent on the price of LFG delivered to the greenhouse. Pricing is often negotiated as a percentage of the local cost of natural gas or propane (on a Btu basis). Hanson estimates that a project should be economically favorable if the landfill is within two to three miles of the greenhouse (Hanson, 1997).

Table 3-7. Concentrations of Exhaust Constituents During LFG Combustion for CO_2 Enhancement

Boiler Firing Rate (%)	CO_2 (%)	CO_2 (ppm)	O_2 (%)	O_2 (ppm)	CO (ppm)	NO_x (ppm)	Ethylene (ppm)
10	8.7	87,000	10.5	105,000	93.0	4.6	0.3
16	8.1	81,000	10.9	109,000	108.7	5.0	n/a
39	8.6	86,000	10.6	106,000	90.2	8.0	0.4
70	9.6	96,000	9.1	91,000	50.1	11.8	0.3
90	9.9	99,000	8.6	86,000	20.9	15.9	0.3

Table 3-8. Concentrations of Exhaust Constituents in Diluted Make-Up Air to Greenhouse

Boiler Firing Rate (%)	Dilution Rate	CO_2 (ppm)	O_2 (%)	CO (ppm)	NO_x (ppm)	Ethylene (ppb)
10	124	1,000	20 (approx.)	0.75	0.04	2.41
16	116	1,000	"	0.94	0.04	n/a
39	123	1,000	"	0.73	0.07	3.26
70	137	1,000	"	0.37	0.09	2.19
90	141	1,000	"	0.15	0.11	2.12

4.0 POTENTIALLY APPLICABLE TECHNOLOGIES (TIER 3)

While some landfills can generate large quantities of gaseous pollutants, most generate only small amounts sufficient to support comparatively small power generation projects (300 to 1,000 kW). Traditional energy utilization technologies may not be cost-effective alternatives for conversion of LFG into useable energy at these small landfills, or may be difficult to permit due to their significant NO_x, CO, and VOC emissions (e.g., RIC engines). For landfills already using (permitted) flares for controlling LFG emissions, it may not be desirable to eliminate this type of control, but rather retrofit utilization equipment in order to take advantage of waste heat. In both of these situations, the Stirling engine and/or ORC may have potential applicability.

A study sponsored by the Coalition of Northeast Governors (CONEG) (SCS Engineers, 1997) examined the use of several emerging technologies for energy conversion using LFG, including the Stirling engine and ORC. Operating data and costs were estimated based on conceptual design information or, in the case of ORC, use in geothermal applications, as no operating experience is available at landfills.

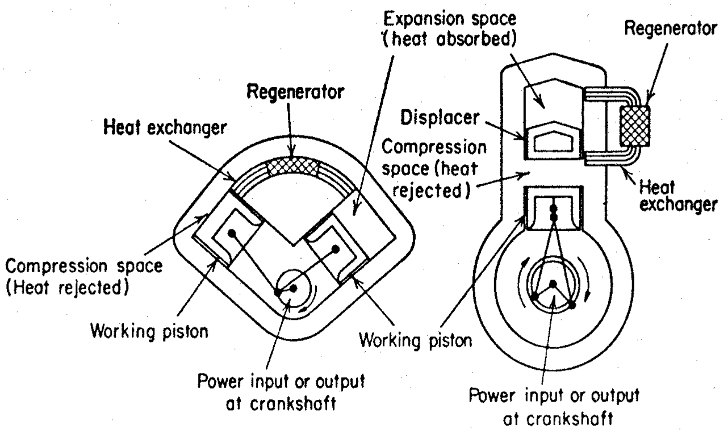
This section describes the applicability of using these emerging technologies for energy conversion from LFG. The research documented here is primarily based on general historic information and cycle descriptions, discussions with experts, extrapolation of operating and cost data from other applications, and engineering judgement.

4.1 Stirling Cycle

4.1.1 History and Cycle Description

The Stirling engine was invented in 1816 by Robert Stirling. Stirling's design was the first closed-cycle "hot air" engine. The cycle deals mainly with the regenerator principle, which is a means to reuse heat that would otherwise be wasted (Ross, 1981). An early Stirling-design engine was used to pump H_2O from a quarry in Scotland in 1818. In 1843, a steam engine was converted using the Stirling principle. Unfortunately, early use of the Stirling engine was hampered by two main factors: (1) the need for high operating temperatures (approximately 1,292 °F) caused material degradation problems, because heat resistant materials (e.g., stainless steel) were not yet available, and (2) competition from higher-power, more versatile spark-ignition and diesel engines (MTI, 1986).

In the Stirling engine, power generation is accomplished by compressing cool gas (working fluid) and expanding it when hot, a process common to most heat engines. The Stirling engine can be visualized as a cylinder with a piston at each end; between the pistons is a regenerator. Two main types of Stirling engines are shown in Figure 4-1, each has two variable-volume working spaces filled with the working fluid-- one for expansion and one for compression of the gas (Avallone and Baumeister, 1989). In the Stirling engine, gas is contained in a continuous, closed volume that is divided into hot and cold regions. The size of the volume is periodically varied to compress and expand the gas. Heating and cooling are accomplished by periodically transferring working gas between the hot and cold regions (MTI, 1986). Since the engine derives its heat from an external source, almost any type of fuel or combustible material can be used.



Double cylinders, two piston engine

Single cylinder, piston plus displacer

Figure 4-1. Stirling Engines
(© Copyright 1989. The McGraw-Hill Companies. Reproduced with Permission.)

4.1.2 Current Usage

Extensive research has been devoted to the development of Stirling engines for space power systems (using solar energy) and for use in automobiles. Today, there are no commercially available Stirling engines, although several manufacturers are hopeful to develop commercially viable units for industrial and automobile use (up to 100 kW) to small units (2.5 kW) to very small household units (0.5 kW) for areas of the world with very high energy costs.

Major research and resources have been directed at development of an automotive Stirling engine (ASE). The ASE program was underway at Mechanical Technology Incorporated (MTI) in Latham, New York, from 1978 until 1990, when funding ceased (Hicks, 1997). This program, sponsored by the DOE, and administered by the National Aeronautics and Space Administration's Lewis Research Center, was intended to "successfully integrate the Stirling engine into an automobile with acceptable drivability" (MTI, 1986). Adaptations of the ASE application include use in generator sets, irrigation pumps, solar electric units, heat pumps, industrial prime movers, submarines, and farm equipment. The ASE program concluded in 1990, and the automotive version of the Stirling engine has yet to be used by the American automobile industry. However, another company, Stirling Thermal Motors (STM), in Ann Arbor, Michigan, is presently actively developing a Stirling engine for commercial use in automobiles, as another low-pollution alternative to electric vehicles.

4.1.3 Potential for Use with LFG

In theory, the Stirling engine is adaptable for use with LFG. Its advantages are high efficiency and low emissions, compared to RIC engines (other advantages normally associated with Stirling engines, such as quiet operation, are not as important in an LFG application). CH_4 recovered from LFG can be used as an external combustion fuel to heat the working fluid (e.g., hydrogen is used in the ASE). Unfortunately, all recent research related to Stirling engines has been focused on small-sized engines, from less than 2.5 kW (Sunpower, Inc.) to about 100 kW (MTI's ASE engine, STM). Currently, no research is underway to develop a larger Stirling engine that could be used in an LFG application (greater than 300 kW).

4.1.4 Emissions and Costs

Emissions from a Stirling engine in an LFG application would be associated with the external combustion source (i.e., NO_x, VOC, CO, and CO_2). Virtually no emissions would be generated by the engine itself because it is a closed cycle.

Since no Stirling engine greater than 100 kW has been manufactured for commercial use, costs associated with the installation of a larger Stirling engine needed for a LFG application could not be ascertained from available literature. Significant costs to consider include the purchase, operation, and maintenance of not only the engine itself, but also the high-temperature (external) heat system. One expert doubts that a larger Stirling engine (or group of engines) could be cost-effective compared to gas turbines or RIC engines, in a LFG application (Beale, 1997).

4.2 Organic Rankine Cycle Engine

4.2.1 History and Cycle Description

An "ideal" (i.e., neglecting any energy losses) Rankine cycle is typically used to compare the performance of actual steam engines and steam turbines. The ORC is a process that uses an organic fluid (rather than steam) in a closed cycle to convert thermal energy into mechanical energy. The advantages of an ORC over a steam Rankine cycle are as follows: (1) Depending on the type and boiling point of the organic fluid chosen, the organic fluid will completely vaporize at a much lower temperature and pressure than steam, thus eliminating steam system problems (like turbine blade erosion caused by entrainment) and the need for an economizer, superheater, or boiler drum; (2) organic working fluid is noncorrosive; and (3) the ORC is a closed system which eliminates the need to continuously add fluid or pre-treat the fluid.

Perennial Energy, Inc. (PEI) of West Plains, Missouri, has developed a commercially available ORC that uses waste heat from a flare, thermal oxidizer, or other combustor as a heat source (PEI, 1993). The process flow for PEI's ORC is shown in Figure 4-2. In this system, the HC working fluid is held in a liquid state in the storage tank. The fluid is moved from the tank, at an elevated pressure, to the PEI (proprietary) recuperator for preheating. Next, the vaporizer, using the waste heat for an external source, heats and pressurizes the fluid. The vaporized fluid is then routed through an expander (turbine) where the expansion of the fluid, from high pressure to lower pressure, converts thermal energy into mechanical energy. The expanded fluid passes through the PEI recuperator where it is used to preheat the cooler fluid coming from the storage tank. After exiting the recuperator, the now saturated fluid passes through the condenser where it is converted back to a liquid state, and then on to the storage tank to perpetuate the process. The working fluid currently used by the PEI ORC is isobutane, but other organic fluids, such as propane, butanes, pentane, and toluene, may be used.

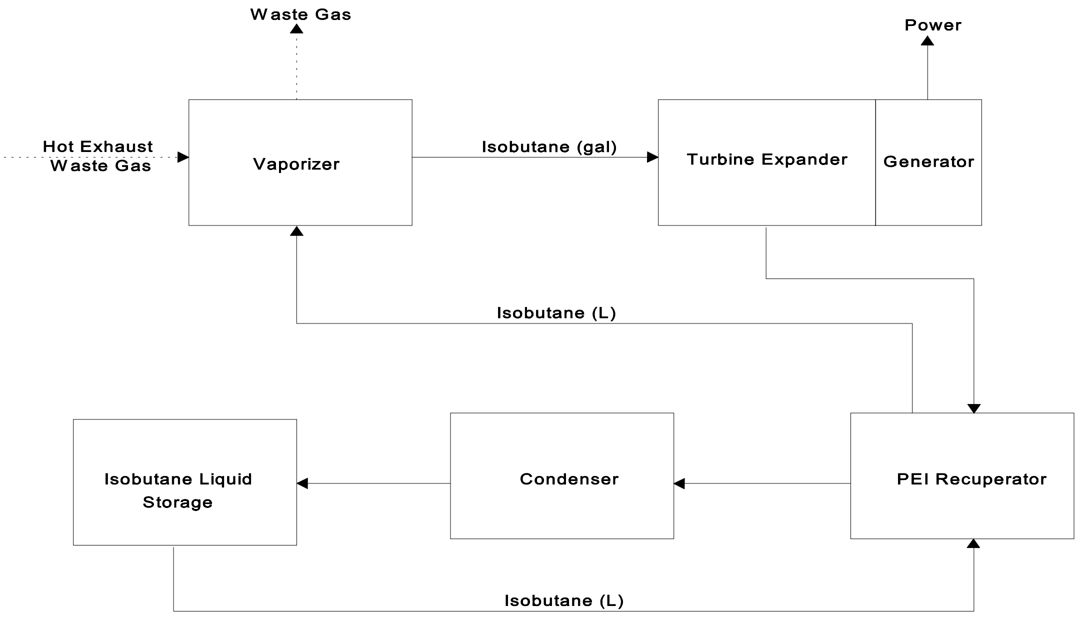


Figure 4-2. Process Flow Diagram for PEI'S Organic Rankine Cycle System

4.2.2 Current Usage

The ORC is currently being used to generate electricity using geothermal power at a plant site operated by Pacific Energy in Mammoth, California. This power plant comprises eight 10,000 hp turbines that each drives 5 MW generators. Hot (320 to 330 °F) geothermal H_2O is used by a tube-and-shell heat exchanger to vaporize the isobutane working fluid. According to PEI, the system performs well (Walker, 1997).

No current usage of an ORC in a LFG application was found in the literature or identified through contacts with experts.

4.2.3 Potential for Use with LFG

The ORC may represent a technically feasible alternative for electrical generation using LFG; however, no LFG pilot plant studies have been conducted or are planned for this technology. This may be due to resistance to "new" technology (even though the technology has been operating successfully in other applications) and current economic factors of electrical generation.

4.2.4 Emissions and Costs

As with the Stirling engine, emissions from an ORC in an LFG application would be associated with the (external) combustion source (e.g., a flare), mainly NO_x, VOC, CO, and CO_2. Virtually no emissions would be generated by the ORC itself, as it is a sealed system.

Since no ORC is currently utilized in a LFG application, costs associated with its use are considered to be rough estimates only. A typical system would be expected to be a modular-type, with several skid-mounted units. Electrical distribution, controls, and other operational equipment would be pre-installed and pre-wired.

The capital cost for such an ORC unit in the 5 to 25 MW range including installation and start-up is estimated by experienced sources to be in the range of $1,200 to $1,500 per kW (Conner, 1997; SCS Engineers, 1997).

Organic Rankine Cycle units are reputed to require limited maintenance, based on geothermal operating experience. Assuming that maintenance requirements for LFG would be comparable to geothermal operation, and based on comparison experience with RIC engines, a cost range is estimated by experienced sources at 0.5 to 0.8 cents per kWh (Conner, 1997; SCS Engineers, 1997).

4.3 Molten Carbonate Fuel Cells

Molten carbonate fuel cells (MCFCs) use an electrolyte of lithium and potassium carbonate (see Figure 2-1) and operate at temperatures of approximately 650 ^{o}C (1200 ^{o}F) compared to PAFCs (described in Section 2.1) which operate at about 200 °C (390 °F) (DOE, 1997a). The higher operating temperature of MCFCs creates a potential for higher system efficiencies (around 70%), if this heat can be utilized (e.g., in a cogeneration system). MCFC are considered "second generation" fuel cells, and application of this technology is in the very early stages.

DOE and EPRI are sponsoring a project to demonstrate use of an MCFC on LFG. An LFG cleanup system was successfully demonstrated at the Anoka Landfill in Minnesota (Shepherd, 1997). A laboratory demonstration (using synthetic LFG) was recently completed; however, data are not yet available. Project proponents state that MCFCs look particularly promising for LFG application due to their good tolerance of CO_2.

5.0 REFERENCES

13 CCR 2292.5, 1992. *California Code of Regulations*, Title 13, Section 2292.5, December 9, 1992.

61 FR 49, 1996. *Federal Register*, U.S. Environmental Protection Agency, “Standards of Performance for New Stationary Sources and Guidelines for Controls of Existing Sources, Municipal Solid Waste Landfills”, Final Rule and Guidelines, pp. 9905-9944, March 12, 1996.

Acrion, 1992. Acrion Technologies, Inc., LFG Recovery for Compressed Natural Gas Vehicles and Food Grade Carbon Dioxide, SBIR Phase I Final Report, prepared for U.S. Department of Energy, Morgantown Energy Technical Center, Contract No. DE-FG02-91ER81223, May 20, 1992.

AGA, 1997. Information downloaded from the GASWEB Home Page (http://www.gasweb.org/gasweb/ngvfuel.htm), May 27, 1997.

Arthur D. Little, Inc., 1993. Arthur D. Little, Inc., *The Role of Fuel Cell Technology in the International Power Equipment Market -Policy/Strategy Issues*, Arthur D. Little, Inc., prepared for The World Fuel Cell Council, Frankfurt, Germany, Ref. 44335, 1993.

Augenstein et al., 1997. Augenstein, D., Yazdani, R., Moore, R., and Dahl, K., “Yolo County Controlled Landfill Demonstration Project”, proceedings from the Solid Waste Association of North America 2nd Annual Landfill Symposium, Sacramento, CA, August 4-6, 1997.

Avallone and Baumeister, 1989. Avallone, A. and Baumeister, T., Standard Handbook for Mechanical Engineers, Ninth Edition, McGraw-Hill, New York, NY, 1989.

Bahl, 1997. Bahl, R., Superior Cranberry Creek Landfill, Wisconsin Rapids, WI, personal communication with S. Roe, E.H. Pechan & Associates, Inc., August 1997.

Balbo, 1997. Balbo, M.E., “Appointment in Sonzay: Landfill Gas Fueled Vehicles”, *Waste Age*, pp. 248-255, May 1977.

Beale, 1997. Beale, W., Sunpower, Inc., personal communication with J. Reisman, E.H. Pechan & Associates, Inc., June 1997.

Bonny, 1994. Bonny, A., TeraMeth Industries, personal communication with S. Roe, E.H. Pechan & Associates, Inc., May 1994.

Borea, 1997. Borea, C., Northeast Utilities, personal communication with S. Roe, E.H. Pechan & Associates, Inc., August 1997.

Brown, 1997. Brown, W., Acrion Technologies, Inc., personal communication with S. Roe, E.H. Pechan & Associates, Inc., September 1997.

Clinton and Gore, 1993. Clinton, W.J., and Gore, A. Jr., The Climate Change Action Plan, U.S. Government Printing Office, October 1993.

Conner, 1997. Conner, L., Perennial Energy, Inc., personal communication with J. Reisman, E.H. Pechan & Associates, Inc., June 1997.

Darragh, 1997. Darragh, T.M., “Comparison of Leachate Recirculation and Bioreactor Technology”, proceedings from the Solid Waste Association of North America 2nd Annual Landfill Symposium, Sacramento, CA, August 4-6, 1997.

DOE, 1997a. U.S. Department of Energy, Information on fuel cell technology down-loaded from the Federal Energy Technology Center (FETC) Web Site (www.metc.doe.gov/research.power/fc.html), May 5, 1997.

DOE, 1997b. U.S. Department of Energy, *News of the Alternative Fuels Data Center*, Volume 6, Issue 1, Spring 1997.

DuPuis, 1996. DuPuis, G.V., personal communication with M. Doorn, E.H. Pechan & Associates, Inc., July 1996.

Echols, 1997. Echols, R. L., Power Strategies, L.L.C., personal communication with J. Reisman, E.H. Pechan & Associates, Inc., September 16, 1997.

EMCON Associates, CalRecovery Systems, Inc., and Gas Recovery Systems, Inc., 1981. *Feasibility Study: Utilization of Landfill Gas for a Vehicle Fuel System, Rossman's Landfill, Clackamas County, Oregon*, prepared for U.S. Department of Energy, Office of Procurement Operations, Washington, D.C., DOE Grant No. DE-FG01-80RA50366, Report No. DE 83010622, January 1981.

EPA, 1996. U.S. Environmental Protection Agency, Turning a Liability Into an Asset: A Landfill Gas-to-Energy Project Development Handbook, EPA-430-B-96-0004, Office of Air and Radiation, Washington, D.C., September 1996.

Gavin, 1997. Gavin, J., Savin Engineers, personal communication with S. Roe, E.H. Pechan & Associates, Inc., August 1997.

Gordon et al., 1997. Gordon, M.E., Hudgins, M., Hazen, T., and Bartles, D., "Operational Characteristics of an Aerobic Landfill Bioreactor", proceedings from the Solid Waste Association of North America 2nd Annual Landfill Symposium, Sacramento, CA, August 4-6, 1997.

Hanashima et al., 1989. Hanashima, M., Matsufuji, Y., Nagano, S., and Tachifuji, A., "The Technical Progress of Landfill Disposal of Solid Waste in Japan", proceedings of the 2nd International Landfill Symposium, Sardinia, Italy, 1989.

Hanson, 1997. E.H. Hanson Engineering Group, Ltd., *Methods for Increasing the Utilization of Landfill Gas in Canada*, prepared for Environment Canada, July 1997.

Hanson, 1995. E.H. Hanson Engineering Group, Ltd., *Report #2 on Stack Gas Emission Generated by the Combustion of Landfill Gas for the Purpose of Carbon Dioxide Generation*, May 1995.

Hickman, 1997. Hickman, J., Solid Waste Association of North America, personal communication with J. Reisman, E.H. Pechan & Associates, Inc., June 1997.

Hicks, 1997. Hicks, D., Mechanical Technology, Inc., personal communication with J. Reisman, E.H. Pechan & Associates, Inc., June 1997.

Hirschenhofer et al., 1994. Hirschenhofer, J.H., Stauffer, D.B., and Engleman, R.R., Fuel Cells. A Handbook (Revision 3), prepared for U.S. Department of Energy, Office of Fossil Energy, Morgantown Energy Technology Center, Morgantown, West Virginia. DOE/METC-94/1006 (DE94004072), 1994.

Hudgins, 1997. Hudgins, M., American Technologies, Inc., personal communication with S. Roe, E.H. Pechan & Associates, Inc., August 1997.

IFC, 1997. International Fuel Cells Corporation, communication with S. Thorneloe, U.S. Environmental Protection Agency, May 23, 1997.

IHC, 1982. International Harvester Co., Methanol from LFG Technology and Economics, prepared for the New York State Energy Research and Development Authority, Albany, NY, PB83-169144, December 1982.

MTI, 1986. Mechanical Technology, Inc., The Stirling Engine, MOD II Design Report, NASA-Lewis Research Center, Cleveland, OH, 1986.

NFPA 52, 1995. National Fire Protection Association (NFPA), *Code 52 - Compressed Natural Gas (CNG) Vehicular Fuel Systems*, 1995.

PEI, 1993. Perennial Energy, Inc., Organic Rankine Cycle System, West Plains, MO, 1993.

RDC, 1997. Regional Disposal Company, *Roosevelt Regional Landfill Moisture Enhancement Demonstration, Final Report*, September 15, 1997.

Roe et al., 1995. Roe, S.M., Fields, P.G., and Coad, R.E., Methodologies for Quantifying the Pollution Prevention Benefits from Landfill Gas Control and Utilization, prepared for U.S. Environmental Protection Agency, Office of Research and Development, EPA-600/R-95-089 (NTIS PB95-243176), July 1985.

Roqueta, 1997. Roqueta, A., “Landfill Gas Utilization - Survey of United States Projects”, presented at the Solid Waste Association of North America’s Twentieth Annual International LFG Symposium, March 25-27, 1997.

Ross, 1981. Ross, A., Sterling Cycle Engines, Second Edition, published by Solar Engines, Phoenix, AZ, 1981.

Sandelli, 1992. Sandelli, G.J., Demonstration of Fuel Cells to Recover Energy from Landfill Gas. Phase 1 Final Report: Conceptual Study, prepared for U.S. Environmental Protection Agency, Office of Research and Development, EPA-600/R-92-007 (NTIS PB92-137520), January 1992.

SCAQMD, 1994. Letter and attached air quality impact assessment from J. Broadbent, South Coast Air Quality Management District, to J. Collier, City of West Covina, CA, October 4, 1994.

Science Applications, Inc., 1983. Science Applications, Inc., Methanol Production from Indigenous Resources in New York State. Volume 1 Executive Summary, prepared for the New York State Energy Research and Development Authority, Albany, NY, PB87-110540, May 1983.

SCS Engineers, 1997. SCS Engineers, “Comparative Analysis of Landfill Gas Utilization Technologies”, prepared for Northeast Regional Biomass Program, CONEG Policy Research Center, Inc., Washington, DC, March 1997.

Shepherd, 1997. Shepherd, P., U.S. Department of Energy, National Renewable Energy Laboratory, personal communication with S. Roe, E.H. Pechan & Associates, Inc., October 1997.

Spiegel et al., 1997. Spiegel, R.J., Trocciola, J.C., and Preston, J.L., “Test Results for Fuel-Cell Operation on Landfill Gas”, *Energy*, Vol. 22, no. 8, pp. 777-786, 1997.

Taylor, 1994. Taylor, T., Sacramento Metropolitan Air Quality Management District, personal communication with S. Roe, E.H. Pechan & Associates, Inc., September 1994.

Thorneloe, 1992. Thorneloe, S.A., “Landfill Gas Recovery/Utilization—Options and Economics”, presented at the Sixteenth Annual Conference by the Institute of Gas Technology on Energy from Biomass and Wastes, Orlando, FL, March 5, 1992.

Trocciola, 1997. Trocciola, J., International Fuel Cells Corporation, personal communication with S. Roe, E.H. Pechan & Associates, Inc., August 20, 1997.

Trocciola and Preston, 1995. Trocciola, J.C. and Preston, J.L., Demonstration of Fuel Cells to Recover Energy from Landfill Gas, Phase II: Pretreatment System Performance Measurement, EPA-600/R-95-155 (NTIS PB96-103601), prepared for U.S. Environmental Protection Agency, Office of Research and Development, Air and Energy Engineering Research Laboratory, October 1995.

Trocciola et al., 1995. Trocciola, J.C., Preston, J.L., and Spiegel, R.J., "Using Landfill Gas in Fuel Cells — A Step Closer to Commercial Reality", *Solid Waste Technologies*, 9:6, pp.28,31-34, November/December 1995.

Walker, 1997. Walker, M., Pacific Energy, personal communication with J. Reisman, E.H. Pechan & Associates, Inc., June 1997.

Wheless, 1997. Wheless, E., Los Angeles County Sanitation Districts, personal communication with S. Roe, E.H. Pechan & Associates, Inc., September 1997.

Wheless and Wong, 1996. Wheless, E. and Wong, M., "Production and Utilization of Landfill Gas Derived CNG in Heavy-Duty Class 8 Trucks", presented to Heavy-Duty Natural Gas Vehicles, Engines, and Fuel Supply TOPTEC, November 1996.

Wheless et al., 1996. Wheless, E., Cosulich, J., and Wang, A., 1996, "Converting LFG to Vehicle Fuel: The Results of Over 30 Months of Operation", presented at the Solid Waste Association of North America's 19th Annual LFG Symposium, March 1996.

Wuebben, 1991. Wuebben, P., South Coast Air Quality Management District, *Southern California at the Crossroads: The Anticipated Market for Fuel Methanol*, presented at the 1991 World Methanol Conference, Vancouver, BC, December 4, 1991.

Wuebben, 1997. Wuebben, P., South Coast Air Quality Management District, personal communication with S. Roe, E.H. Pechan & Associates, Inc., September 1997.

Yazdani, 1997. Yazdani, R., Yolo County Division of Public Works and Transportation, Division of Integrated Waste Management, personal communication with S. Roe, E.H. Pechan & Associates, Inc., September 1997.

Yolo County, 1997. Yolo County Department of Public Works and Transportation, Methane Enhancement by Accelerated Anaerobic Composting at the Yolo County Central Landfill, Final Report, Division of Integrated Waste Management, prepared for the California Energy Commission, April 1997.