FULL SCALE BIOREACTOR LANDFILL FOR CARBON SEQUESTRATION AND GREENHOUSE EMISSION CONTROL

Final Technical Progress Report

Reporting Period Start Date: September 4, 2001
Reporting Period End Date: March 31, 2005

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Date Report Issued
March 2006

D.O.E. Award Number
DE-FC26-01NT41152

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ABSTRACT

The Yolo County Department of Planning and Public Works constructed a full-scale bioreactor landfill as a part of the Environmental Protection Agency's (EPA) Project XL program to develop innovative approaches for carbon sequestration and greenhouse emission control. The overall objective was to manage landfill solid waste for rapid waste decomposition and maximum landfill gas generation and capture for carbon sequestration and greenhouse emission control. Waste decomposition is accelerated by improving conditions for either the aerobic or anaerobic biological processes and involves circulating controlled quantities of liquid (leachate, groundwater, gray water, etc.), and, in the aerobic process, large volumes of air.

The first phase of the project entailed the construction of a 12-acre module that contained a 6-acre anaerobic cell, a 3.5-acre anaerobic cell, and a 2.5-acre aerobic cell at the Yolo County Central Landfill near Davis, California. The cells were highly instrumented to monitor bioreactor performance. Liquid addition commenced in the 3.5-acre anaerobic cell and the 6-acre anaerobic cell. Construction of the 2.5-acre aerobic cell and biofilter has been completed. The current project status and preliminary monitoring results are summarized in this report.

EXECUTIVE SUMMARY

Introduction

Organic materials in municipal solid waste (MSW) landfills decompose via microbial action to a gaseous mixture of methane and carbon dioxide, termed "landfill gas" (LFG). LFG is already widely used for power generation, with about 1000 MWe installed capacity in the U.S. However, LFG remains an underutilized renewable energy resource, with only about half of the United States' generated LFG being captured and less than 25% actually used for power generation (with the balance of collected gas flared). The main factors limiting LFG utilization are the very long, slow rates of waste decomposition and LFG generation in landfills, combined with inefficient recovery of the gas that is generated. Contributing factors are unpredictability of gas recovery, contaminants in LFG, and the economic limitations associated with smaller scale power generation from typical low-rate recovery.

Landfilling of MSW is considered by many environmentally concerned citizens and regulatory agencies as a less desirable technology to be avoided and limited as much as possible. However, landfills can be used for a much greater degree for treatment, essentially, composting of the waste they contain. Evolving sanitary landfill engineering practices now avoid many of the problems with historical landfill practice, in particular leachate contamination of groundwater. Other problems have remained in association with recent conventional practice. Recent conventional practice has mandated exclusion of moisture from landfills, keeping waste relatively dry and thereby depressing the metabolism of the microorganisms that degrade the organic fraction of MSW. This results in so-called dry-tomb landfills that require long-term post-closure monitoring and management because leachate and gas production will resume once the containment barrier is breached. This can leave an undesirable legacy for future generations.

These problems with recent conventional landfill practice can be overcome. The biological degradation and stabilization of waste in landfills can be greatly accelerated and completed in a few years by increasing microbial activity through increases in *in situ* moisture levels. Landfills wherein biodegradation of waste is enhanced through liquid additions are generally called "bioreactor landfills". In the earliest years, the bioreactor landfill used only leachate recycling. However, this proved insufficient to achieve maximum acceleration and breakdown of biodegradable organic matter. Rapid, complete, and permanent landfill stabilization requires further liquid addition to allow the anaerobic microbial processes to go to completion, producing an inert, stabilized residue. We call this process herein, "accelerated anaerobic composting".

The advantage of accelerated anaerobic composting technology (also termed the "controlled landfill bioreactor", and "controlled landfill" for convenience below) is that it mitigates the expected long-term environmental problems with current sanitary landfilling practices. Importantly, it also allows essentially complete LFG production and collection over a relatively short period of time. This allows for more economical LFG power generation. It also eliminates the great bulk of fugitive LFG emission that is normally experienced because of inefficient LFG collection. This fugitive LFG can otherwise be an important source of greenhouse methane emissions and a major source of local air pollutants.

This report details the design, construction, and operations of a full-scale landfill at the Yolo County Central Landfill using the accelerated anaerobic composting technology previously demonstrated at this site during 1994 – 2002 (see below). The present project was supported by the National Energy Technology Laboratory (NETL) of the U.S. Department of Energy (USDOE), in addition to cost-sharing by Yolo County and other state and federal agencies.

Landfill Bioreactor Technology and the Yolo County Project

The development of the bioreactor landfill technology started with laboratory work in the 1970's demonstrating that static reactors filled with organic matter from MSW could exhibit high rates of biodegradation and methane production. In summary, projections and experience with vessel-based MSW to methane technology have been adverse. Despite being practiced at numerous sites in the European Union today, methane from vessel-based MSW-to-methane conversion has proven very expensive; energy cost equivalent to $200/barrel oil. At the same time, controlled landfill bioreactor technology has been proving in tests at Mountain View, CA and Yolo County, CA to be a promising alternative for MSW-to-methane conversions.

Planning for the first Yolo County Controlled Bioreactor Landfill pilot-scale study started in 1989. With support from the California Energy Commission and the Department of Energy, with cost sharing from Yolo County and assistance from Sacramento County, two 9,000 ton pilot-scale landfill bioreactor landfill cells were constructed, one operated without and one with addition of supplemental liquids and liquid recirculation. Actual operations and monitoring were initiated in 1994 with the following operations sequence:

- Fill waste as received.
- Cover cells with surface membrane for high-efficiency gas capture; and liquid addition to the first (enhanced) cell, but not the second (control) cell.
- Capture of an estimated 90% or more of generated LFG was made possible by early installation of the gas capture cover system before liquid addition was initiated.

Results obtained with the enhanced versus control cells indicated the following key benefits of this approach:

- Over five-fold acceleration of methane production and recovery for maximum yield.
- Reduction of fugitive greenhouse methane emissions to <5% of generated LFG.
- Rapid and extensive volume reduction in the enhanced compared to the control cell.
- Waste stabilization (indicated by methane recovery, volume loss and other indicators) compared to the dry-tomb control.

These pilot-scale results suggested that LFG extraction and utilization would be much more economical, greenhouse gas emissions would be greatly reduced, landfill capacity increased, and aftercare minimized through the addition of moisture to engineered bioreactor landfills. A key finding was the feasibility of straightforward means for distributing liquid relatively evenly throughout the enhanced cell, on desired schedules. Moisture addition combined with significantly above ambient temperature resulted in accelerated biodegradation and methane generation, as well has highly desirable volume reduction in the landfilled waste.

This earlier success of the 9,000 ton pilot program at Yolo has now led to scale-up of the controlled landfill bioreactor approach to larger cells, which is the topic of this report.

Bioreactor cells totaling over 250,000 tons of waste are now constructed and are operating. The present project was supported by NETL.

The Yolo County Accelerated Anaerobic Composting Demonstration Project

Permitting and Regulatory Issues

Federal and California State regulations have, until recently, barred the addition of supplemental liquid other than leachate to a lined landfill module. This addition was essential for implementation of the controlled bioreactor landfill. Yolo County applied for, and was granted, special regulatory flexibility through the United States Environmental Protection Agency (EPA) XL Program, which stands for "eXcellence and Leadership." The XL program allows government and business entities to develop, cooperatively with EPA, innovative strategies to test prospectively better or more cost-effective ways of achieving environmental and public health protection.

Bioreactor Cell Design and Construction

Two new 6 and 3.5-acre methane enhanced anaerobic bioreactor cells were designed and constructed for this project. Extensive instrumentation and provisions for measurements have allowed the detailed study of waste decomposition and methane enhancement. Multipoint measurements within cells have included temperature, moisture, static head over the base liner, and liquid pore pressure. High accuracy flow recorders also provided accurate measurement of landfill gas recovery and liquid inflows and outflows. Careful measurement of MSW placed into the cells and gas and liquid measurements allowed gas recovery, liquid flows, and material balances to be quantified with high accuracy.

The majority of sensors and instrumentation were standard and commercially available. Moisture sensors that were leachate resistant were custom made by the project staff with either larger gypsum elements or plastic bead matrices. Breakage of instrumentation lead wires (reported in other large-scale bioreactor landfill tests) was avoided by combining strong protective housing and line slack or "snaking" to accommodate expected lead elongation with settlement. Yolo County staff, cooperating closely with local contractor, A-TEEM Electrical Engineering, developed a highly automated Supervisory Control and Data Acquisition (SCADA) system radio-linked to a host computer. This system has been upgraded and expanded as the project progressed, and has maintained state of the art status as software and instrumentation features have improved.

In addition to these sensors, instrumentation, and monitoring capabilities, the main design modifications relative to conventional landfill practice in the U.S. include:

- Base and drainage layer construction,
- Liquid addition methods and control,
- Gas collection methods and control,
- Surface liner and containment,
- Slope stability.

The construction of the cells included the installation of sensors, wires, pipes, wells for liquid introduction, and gas collection system. Other construction aspects key to the controlled landfill included precautions taken in placing cell elements that would undergo strain during decomposition and settlement.

Aerobic Bioreactor Landfill Tests

An additional component of work at Yolo has been assessment of greenhouse methane suppression by another means: aeration of the landfill, i.e. the aerobic landfill. This is essentially aerobic composting of landfill contents by introducing atmospheric air through the landfilled waste. Testing of this approach was, in part, for the Greenhouse Gas Abatement program of NETL of the U.S. Department of Defense (DOE) and in part for the California Integrated Waste Management Board (CIWMB).

An advantage of this approach is that a higher fraction of organic waste (particularly the normally significant lignin and woody lignocellulose) can be oxidized compared to the fraction of organic wastes that can be decomposed by anaerobic digestion. Thus, higher fractions of the landfilled waste can be destroyed, in turn, giving greater landfill life extension.

Disadvantages of this approach, however, include the amount of energy use required to operate the system and loss of methane energy production.

Operational Results

Internal cell temperatures

From the start of full-scale operations, elevated temperatures (about 110-140°F or 45-60°C, roughly 5-15°C higher than conventional) have been measured throughout the bulk waste in both cells. Waste temperatures inside the cells have remained constant and essentially independent of ambient temperature. These elevated temperatures, achieved at no additional effort or cost as a consequence of biological heat generation, contributed to the acceleration of the microbial degradation of the waste and methane production.

Moisture Flows and Waste Moisture Balances

Moisture additions (i.e. liquid infiltration) began in June 2002 and June 2003 in the 3.5 and 6-acre cells, respectively. Liquid infiltration has proceeded somewhat more slowly with these larger cells than with the earlier 9000-ton pilot-scale cells. The moisture sensors have indicated elevated moisture levels for the majority of the sensors. However, core samples suggested that moisture distribution was somewhat irregular. Liquid added to date has been 43 gal/ton in the 3.5-acre cell, and 21 gal/ton in the 6-acre cell, compared to 55 gal/ton in the 9,000-ton pilot-scale cell. Other findings included apparent permeability (deduced from moisture infiltration rates) of approximately 3×10^{-5} cm/sec. The issues encountered with liquid management included seeps and some variation in moisture content with the larger cells and were attributed to remnants of less-permeable cover soil. These issues should be resolvable in future designs and operations by following practices recommended in this report.

Leachate Head Over Base Liner

Liquid head over the base liner is a major regulatory concern, because of the potential for groundwater pollution and decreased slope stability. Observed head in the cells was 2 inches, under half of allowable limits under California regulations, and less than 20% of the maximum allowed under federal regulations.

Leachate Compositions

Composition of liquid leachate draining from the waste serves both to indicate the progress of waste decomposition and to show effectiveness of biological treatment in terms of reduction of normal leachate pollutants. Leachate pollutants have fallen, and key parameters, five-day biological oxygen demand, BOD_5 and pH, all indicate a stable ongoing methane production process. A number of leachate components including ammonia and dissolved salts have reached low and relatively stable levels.

Landfill Gas Composition and Recovery

A primary goal of this project was to generate LFG suitable for use in power generation. . Methane content from the recovered gas in both anaerobic cells quickly reached about 50% within 3 months after leachate additions started. This methane content is eminently suitable for fueling power generation. One very interesting phenomenon, not heretofore reported, was a sharp decline with time in the concentration of most of the volatile pollutants and other undesirable components in the collected landfill gas. Two components out of hundreds of trace components in LFG, mostly man-made, are decreasing benzene and hexane. Thus far, the observed decline in many such pollutants is up to ten-fold, and is attributed to a combination of biological decomposition and the compounds' evaporation and partitioning into the landfill gas.

Methane Generation and Analysis using Standard Model

Controlled generation of the maximum possible amount of landfill methane energy to supplement California, U.S. and world energy needs was a primary objective of this project. The two anaerobic full-scale cells have shown very encouraging methane enhancement, currently 4 to 7-fold, by comparison, to that expected from conventional landfill operation. Some variation in methane recovery was observed, not due to variation in LFG production, but due to extraction and vacuum variation, factors uniquely site specific to these pilot-scale cells (see report). From the northeast 3.5-acre and west 6-acre cells, methane recoveries of 78.3 and 77.5 million cubic feet would equate to 6,525 and 6,458 MWh, or a total close to 13 GWh electric at an estimated heat rate of 12,000 ft^3 of methane per MWh.

Figure ES-1 shows the normalized methane recovery per pound of MSW that would be expected, the initial 9000-ton enhanced cell, and the more recently started northeast and west-side cells described in the main text.

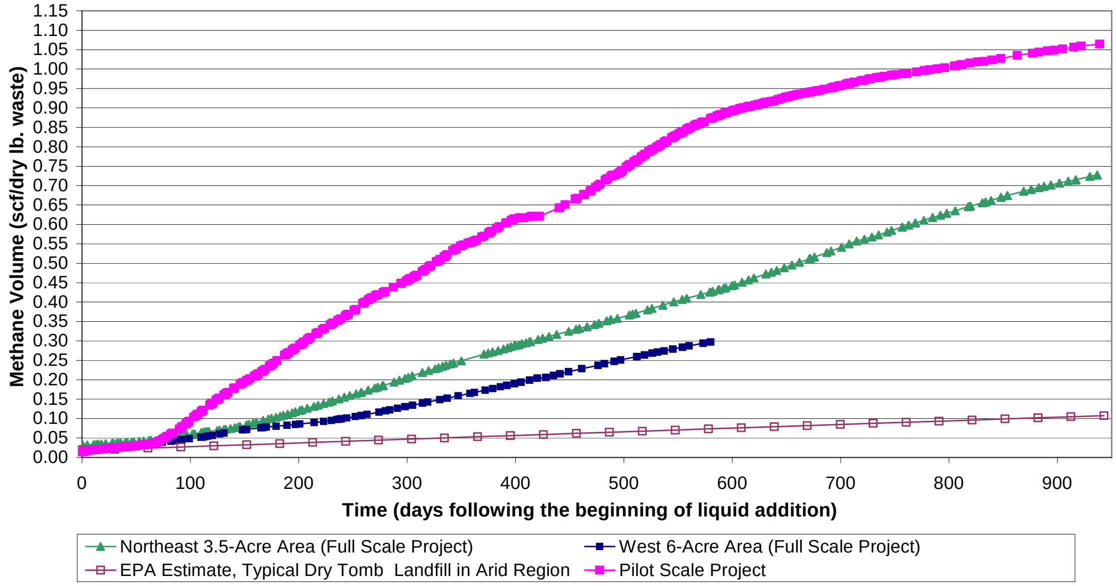


Figure ES-1. Comparisons among normalized methane production for conventional (brown), Yolo pilot-scale (magenta), northeast (green), and west (blue) accelerated anaerobic composting cells. Note enhancement of methane in pilot-scale, northeast, and west side versus conventional operation.

Methane Greenhouse Emission Abatement

Another major objective of this project was to demonstrate that this technology could reduce greenhouse gas emissions, principally methane gas, to a minimum. With very infrequent exceptions, surface combustible gas concentrations (the regulatory criterion for effectiveness) have been ten to 100-fold less than allowed by federal and state limits. This provides another major drive to the adoption of this improved energy technology.

Waste Core Sampling Results

Core samples of the landfilled waste have been tested for moisture, biochemical methane potential (BMP), and other characteristics. Up to this point in the addition process, moisture levels, though generally elevated, remained variable with location in the waste. Though enhancement results (see above) are encouraging, the core moisture results suggest need for longer-term leachate recirculation and moisture addition to better distribute moisture.

Settlement and Volume Loss

Waste volume loss and settlement are particularly important benefits to waste management jurisdictions because of prospects for increased landfill capacity and life extension. Full-scale cells, still in early stages of operation, show encouraging volume loss at much greater rates than that for a controlled dry-tomb cell. Through September 2004, settlement in the 3.5-acre cell has averaged 8.5%, and the 6-acre cell has averaged 4%.

Projected Energy Balance for Controlled Landfill

An estimated energy balance has been developed for this accelerated anaerobic composting (controlled bioreactor landfill) technology. The only significant incremental energy inputs over conventional landfill operation are those for liquids and landfill gas pumping, which are under 1% of the total landfill gas energy output, a negligible amount. Nearly all landfill methane energy will be recovered. For comparison, it can be noted that the much more costly mixed vessel anaerobic digestion MSW-to-methane technology, used in Europe now, requiring careful waste separation, grinding, mixing, etc., and has very high parasitic energy inputs, from 35% up to over 100% of the methane produced. Hence, information to-date suggests bioreactor landfills will yield greater net energy than vessel processes (and at about tenfold less cost -- see Project Economics.

Maintenance

Maintenance needs were tracked. These included either routine needs or maintenance due to equipment breakdown, repairs of gas and liquid leaks, and membrane cover and gas flowmeters, among others. Some maintenance needs specific to bioreactor operations have included instrumentation maintenance and dealing with fouling of base liquid pressure sensors due to scale buildup by periodic withdrawal and cleaning. The liquid injection lines also clogged temporarily due to leachate pH increase, which resulted in precipitation of calcium carbonate and buildup of scale. Some simple chemical tests established that this scale was largely calcium carbonate and removal by citric acid gave excellent results.

Project Economics

In estimating energy or electricity costs from LFG, it must be recognized that landfills and LFG recovery are already required for most MSW disposal facilities. Thus, the cost factors in such an analysis are only the incremental costs that come with bioreactor operation as opposed to conventional operation. There are major waste management benefits other than energy that can easily justify all incremental costs. The cost analysis was based on the following:

- Bioreactor operations are justified by other benefits even without energy recovery.
- LFG capture using best available control technology is required, regardless of use.
- The recovered LFG is available for power production at low or no marginal cost.
- Thus, LFG has near-zero incremental cost since methane must be destroyed by some method, which an internal combustion or turbine engine does.

Power generation costs are mainly for the genset procurement and operation. The present report does not detail the capital and operating costs of engine-generator sets. Based on experiences of Waste Management, Inc. (WM), the following parameters are assumed for a "base case" landfill gas-to-energy project: 1,600 cubic feet per minute (CFM) of LFG, or 400,000 million Btu per year, generating 32 million kWh per year. For such a size plant, capital costs are $3.2 to $5 million ($800 to $1250/kWe), including site work, buildings, gas conditioning, power generation equipment, interconnections and other miscellaneous capital costs. For such a size plant, capital costs are $3.2 to $5 million ($800 to $1250/kWe), including site work, buildings, gas conditioning, power generation equipment, interconnections and other miscellaneous capital costs. At the best (largest) sites, the total cost to generate power was estimated by Waste Management to be in the range of 2.5 to 3.5 cents/kWh, assuming no value for the LFG. For smaller scales at smaller sites, an estimated range for generated power cost would be between 3 and 4.5 cents/kWh. This power generation cost range is similar to those of most other analyses for LFG power generation, including prior work for the Yolo County project, and depends on factors such as cost of capital, scale, gas clean-up requirements, location and many other factors.

The costs of power production from controlled bioreactor landfills, as described herein, would be significantly lower than the cost of LFG-to-electricity production for a similar size conventional landfill. This is due to the fact that more LFG is generated and over a shorter period of time, allowing for larger generating equipment. There can be more reliable estimation and control of gas production (avoiding flaring excess LFG or installing superfluous generating capacity). Because of such factors, it is likely that substantially more renewable power, as much as 50% to 100% more, would be produced from the same waste than with conventional practice. A more precise estimate would require fixing many assumptions, such as location, scale, type of waste, etc. The prospect for and value of greenhouse gas abatement credits are currently small compared to the value of electricity generation. However, greenhouse credits and benefits may become more important drivers in the future.

As power generation from landfill bioreactors increases, continuing attention must be given to factors aside from economics. These include the regulatory treatment and allowances, incentives for renewable energy, the case for bioreactor energy that can be made on the basis of environmental benefits that are described in detail, and making sure that regulatory agencies recognize the overall benefits in a "balance sheet" approach.

Conclusions

This project's work consisted of construction and operation of controlled landfill bioreactor (accelerated anaerobic composting) cells by over ten-fold from the original pilot study. Implementation of the large-scale northeast 3.5-acre and west 6-acre cells was accompanied by collection of technical data that would provide the justification to satisfy the regulatory community and lead to the commercialization of this technology. This was accomplished through activities including:

- Construction of the bioreactor landfill through waste placement, and in-waste placement of piping and instrumentation followed by horizontal tires gas collection system, cover soil, geotextile, and synthetic cover liner for the bioreactor cells.
- Liquid addition with careful measurements of liquid flows and indicators of moisture.
- Operation with monitoring of all relevant parameters to the reporting date.
- Assessing methane energy recovery and volume reduction.
- Monitoring methane emissions and assessing greenhouse methane emission abatement.
- Development of model and kinetic parameters for the landfill bioreactor cells' methane production.
- Economic analysis.

A photograph of the completed northeast cell with newly installed cover is shown in Figure ES-2.

Figure ES-2. Northeast cell, shortly after geomembrane coverage, is in the foreground. The northeast cell footprint is approximately 300 ft by 500 ft, and it contains 78,000 tons of methane-enhanced waste. The scale is also indicated by a person walking up the cell cover near the lower left corner of the cell.

The current Yolo County Demonstration project will need to be monitored until the end of the decade, and beyond, to obtain the full benefit from this project. However, the results of this project can be applied well before then, as they fit within the data sets from other prior projects, in particular the earlier Yolo County Pilot Project. As expected, the moisture distribution was not as rapid and uniform as in the pilot cells, and thus, LFG generation and waste stabilization was somewhat slower than in the Pilot Project. It is expected that such factors would increase the period of full stabilization and completed LFG generation from about 10 years at the pilot-scale to 15 years for full-scale cells. This will not significantly affect the economics of such a process, including settling freeing up air space for additional waste deposition. This period of time is well within the planning horizon of most active landfills. In conclusion, the present project is providing quantitative, proof of benefits of controlled bioreactor landfills, over conventional landfill technology. The objectives have been met with some of the most important results being:

- Findings continue to evidence that bioreactors can provide greater energy benefits than conventional landfilling. Other benefits occur in terms of accelerated methane generation and highly efficient methane capture. Methane enhancement continues to be shown manageable and controllable.

- The program illustrates environmental (greenhouse) benefits in terms of reducing methane emissions to minuscule levels (generally under 1/100 of existing regulatory standards).

- The larger scale cells are demonstrating waste management benefits, in terms of accelerated volume loss and more rapid stabilization as evidenced by the conversion rates of waste organic to methane and subsidence.
- The full-scale cells are generally confirming the benefits seen in the pilot-scale on an over ten-fold larger scale.

Further benefits will be evident in the main body of the report.

As an energy technology, when applied to the huge amount of post-recycling mixed municipal waste that are landfilled in the U.S., analyses elsewhere show the controlled landfill bioreactor with major advantages over other related MSW-to-energy and MSW-to-fuels processes.

1 INTRODUCTION

Sanitary landfilling is the dominant method of solid waste disposal in the United States, accounting for about 217 million tons of waste annually (U.S. EPA 1997). The annual production of municipal solid waste in the United States has more than doubled since 1960. In spite of increasing rates of reuse and recycling, population and economic growth will continue to render landfilling as an important and necessary component of solid waste management.

In a bioreactor landfill, controlled quantities of liquid (leachate, groundwater, gray-water, etc.) are added to increase the moisture content of the waste. Leachate is then recirculated, as necessary, to maintain the moisture content of the waste at or near its moisture holding capacity. This process significantly increases the biodegradation rate of waste, and thus decreases the waste stabilization and composting time (5 to 10 years) relative to what would occur within a conventional landfill (30 to 50 years or more). If the waste decomposes (i.e. is composted) in the absence of oxygen (anaerobically), it produces landfill gas (biogas). Biogas is primarily a mixture of methane, a potent greenhouse gas, carbon dioxide, and small amounts of volatile organic compounds (VOC). This by-product of anaerobic landfill waste composting can be a substantial renewable energy resource that can be recovered for electricity or other uses. Other benefits of a bioreactor landfill composting operation include increased landfill waste settlement and a resulting increase in landfill capacity and life, improved opportunities for treatment of leachate liquid that may drain from fractions of the waste, possible reduction of landfill post-closure management time and activities, landfill mining, and abatement of greenhouse gases through highly efficient methane capture over a much shorter period of time than is typical of waste management through conventional landfilling.

1.1 Background and Site Overview

The Yolo County Central Landfill (YCCL) is an existing Class III non-hazardous municipal solid waste landfill. The site encompasses a total of 722 acres and is comprised of 17 distinct Class III solid waste management units and two Class II leachate surface impoundments. The YCCL is located at the intersection of Road 104 and Road 28H, 2 miles northeast of the City of Davis. The YCCL was opened in 1975 for the disposal of non-hazardous solid waste, construction debris, and non-hazardous liquid waste. Existing on-site operations include a landfill methane gas recovery and energy generation facility, a drop-off area for recyclables, a metal recovery facility, a wood and yard waste recovery and processing area, and a concrete recycling area.

There are approximately 28 residences scattered within a 2-mile radius of the landfill. The closest residence is located several hundred feet south of the landfill, on the south side of Road 29, south of the Willow Slough By-pass.

Groundwater levels at the facility fluctuate between 8 and 10 ft during the year, rising from lowest in the fall to highest in the spring. Water level data indicate that the water table level is typically 4 to 10 ft below ground surface during winter and spring months. During summer and fall months, the water table is typically 5 to 15 ft below ground surface. In January 1989, Yolo County constructed a soil/bentonite slurry cutoff wall to retard groundwater flow to the landfill site from the north. The cutoff wall was constructed along portions of the northern and western boundaries of the site to a maximum depth of 44 ft. The cutoff wall has a total length of 3,680 ft, 2,880 ft along the north side and 800 ft along the west. In the fall of 1990, irrigation practices to the north of the landfill site were altered to minimize the infiltration of water.

Additionally, sixteen groundwater extraction wells were installed south of the cutoff wall in order to lower the water table south and east of the wall, and to provide vertical separation between the base of the landfill and groundwater.

Prior to placement of the slurry wall and dewatering system, the groundwater flow direction was generally to the southeast. Under current dewatering conditions, the apparent groundwater flow paths are towards the extraction wells located along the western portion of the northern site boundary. In essence, a capture zone is created by the cone of depression created by the ground water extraction system, minimizing the possibility of off-site migration of contamination.

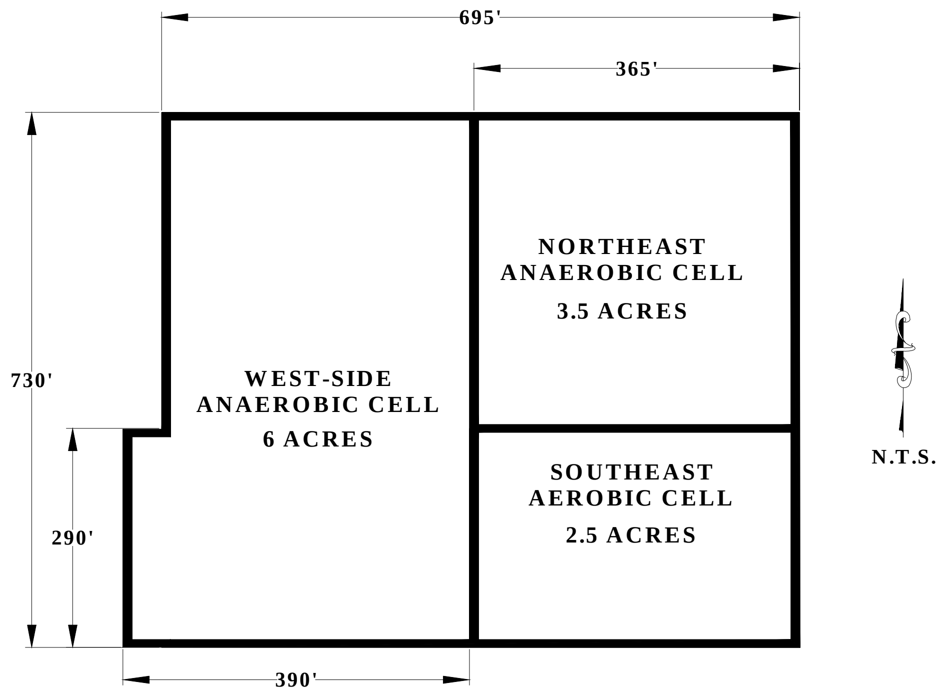
1.2 Project Description

The County of Yolo Planning and Public Works Department (Yolo County) has now scaled up its landfill bioreactor operations. The scale-up goal was to provide added technical and economic data, and provide solutions to the identified permitting conditions and other factors posing constraints to large-scale application and commercialization. This was to be accomplished by demonstrating the environmental and economic benefits of this technology and resolving technical issues. Another goal was to provide confidence regarding regulatory issues and constraints. In the first phase of this project, a 12-acre module was constructed containing a 6-acre cell and a 3.5-acre cell, which was operated anaerobically, and a 2.5-acre cell that was operated aerobically (Detail 1).

Co-sponsors of the project with Yolo County are the Public Interest Energy Research (PIER) program of the California Energy Commission (CEC), California Integrated Waste Management Board, Department of Energy, National Energy Technology Laboratory (NETL), the Solid Waste Association of North America (SWANA) and Institute for Environmental Management (IEM). As part of the Environmental Protection Agency (EPA) Project XL, which stands for "eXcellence and Leadership," Yolo County requested that U.S. EPA grant site-specific regulatory flexibility from the prohibition in 40 CFR 258.28 Liquid Restrictions, which may preclude addition of useful bulk or non-containerized liquid amendments. The County intended to use leachate and groundwater as their first option. In cases where sufficient groundwater, irrigation water, etc. might be lacking, then use of other supplemental liquids could be possible. For example gray-water from a wastewater treatment plant, septic waste, and food-processing wastes would be used. Liquid wastes such as these, that normally have no beneficial use, may instead have high value through their nutrient and organic content, beneficially enhancing the biodegradation of solid waste. However, for this Yolo County project, because sufficient groundwater and leachate was available, no other supplemental liquids were utilized.

Yolo County also requested similar flexibility on liquid amendments from California and local regulatory entities. Several sections of the California Code of Regulations (CCR), Title 27, Environmental Protection, address the recirculation of liquids in lined municipal solid waste landfills. While the regulations do not specifically endorse bioreactors, regulatory flexibility was provided by the State of California Title 27, Chapter 3, Subchapter 2, Article 2, Section 20200, Part (d)(3), Management of liquids at Landfills and Waste Piles. For additional information on this regulatory flexibility, see Section IV A of the Final Project Agreement (FPA) (Appendix F). In part as the result of Yolo County's program and project team communications with the U.S. EPA, greater Federal flexibility in liquids addition is being granted nationwide.

The State of California is in the process of increasing its own flexibility in line with federal guides.



Detail 1. Overview of Module 6D bioreactor cells

The project work plan consisted of construction, operation and collection of technical data that would satisfy the regulatory community and lead to the commercialization of this technology. This was to be accomplished through the following activities:

- Construction of the base liner system, leachate collection and removal system, tire operations layer, and installation of base layer instrumentation.
- Construction of the bioreactor landfill through waste placement and in-waste placement of piping and instrumentation (waste placement in the cells began in November 2000).
- Collection and analysis of waste samples for cellulose, hemicellulose, lignin and biochemical methane potential (BMP) to determine maximum remaining biodegradable material over time.
- Construction of all instrumentation and connection to the Supervisory Collection and Data Acquisition (SCADA) system.
- Connection of the liquid pumping system to the liquid injection piping and start of liquid addition to the waste.
- Placement of horizontal tire gas collection system, cover soil, geotextile, and synthetic cover liner for the bioreactor cells.

- Monitoring for methane emissions.
- Construction of the landfill gas collection system and connection of the system to power generation facility.
- Sampling and laboratory testing of leachate and landfill gas.
- Modeling of landfill bioreactor methane production.
- Data management, interpretation and reporting.
- Preparation of quarterly and annual reports and hold stakeholders meetings.

1.3 Project Goals and Objectives

The goal of this project was to provide technical data and solutions to the identified permitting constraints posed on this technology so that it could advance into the commercialization phase. Yolo County believes that with the demonstration of this project and acceptance of the bioreactor landfilling concept by U.S. EPA and the State of California, many other public and private landfill owners and operators will be able to implement this technology at other sites. The technology is expected to improve the economics of landfill gas-to-electricity by yielding more renewable landfill gas while providing many environmental benefits, not only for all regions of the U.S, but worldwide. Results from Yolo County's small-scale pilot-scale project have already been shared among many other jurisdictions as well as the private sector throughout the U.S. and internationally.

Project XL allows state and local governments, businesses and federal facilities to develop with U.S. EPA, innovative strategies to test better or more cost-effective ways of achieving environmental and public health protection. Through this program, EPA, in cooperation with state agencies and other stakeholders, allows regulatory flexibility to conduct experiments to demonstrate these prospective benefits. A Project XL Agreement and goals were developed as part of a joint statement of the plans, intentions and commitments of the EPA, the state of California, and Yolo County, to carry out this project

Through the EPA Project XL, Yolo County ultimately obtained regulatory flexibility from the federal and state regulatory agencies. This approval was based on accepted project performance goals, available controls, and environmental safeguards, which had already been demonstrated to a large degree in Yolo County's smaller-scale pilot project at the Yolo County Central Landfill.

CEC has also played an extremely helpful role in supporting the Yolo program since its inception (first planning in 1989). In fact, the initial pilot program startup support was through a contract with CEC's Energy Technologies Advancement Program (ETAP). Later, the combination of obvious severe shortfalls in California electricity generation, EPA's facilitation, and the California Integrated Waste Management Board support of the program, in conjunction with early pilot program successes, all combined to enable further support through the CEC. That supported work by CEC via the PIER program contract administered by the Sacramento Municipal Utility District (SMUD) is the subject of this report. This project's main objectives included the following:

- Acceleration of waste decomposition and leachate treatment, via liquid amendments and recirculation of leachate via a pipe network serving the waste mass. This was to be done while showing that recirculation could be accomplished without excessive leachate head build-up over the base liner. The ultimate objective is to accomplish rapid completion of composting, stabilization and generation of methane to the maximum practical yield.

- Efficient capture of nearly all generated methane, by withdrawing at slight vacuum from a freely gas-permeable shredded tire collection layer beneath low-permeability cover. The withdrawal is to be accomplished with negligible impact to the local air quality. Near-complete extraction with this approach has already been demonstrated in the 9,000-ton small-scale demonstration cell with the Yolo County demonstration project.

- Documentation of the capital and operations costs of a full-scale bioreactor and determination of the economic viability of its commercialization.

- Establish these environmental and renewable energy benefits to facilitate regulatory acceptance.

1.4 Historical Background

Earlier laboratory and field work
One process with long-recognized potential for adding a modest but significant increment of energy and natural gas for U.S. needs was the management of municipal solid waste (MSW) decomposition to provide a mix of methane and carbon dioxide, or "biogas". Although other approaches have been and are even being tried now, it has become clear based on a growing body of information that a promising MSW-to-methane approach for the U.S. is to manage the decomposition of waste in sanitary landfills to generate biogas termed "landfill gas". Some important elements of development along the path to the present Yolo program and controlled landfill technology are discussed below.

The earliest projections of controlled bioreactor landfills along the lines of the present Yolo program occurred in the early 1970's. The work leading to the Yolo program began with an investigation of methane generation from MSW by Dynatech R/D Company. The work was sponsored by the Consolidated Natural Gas Company of Ohio. It involved parallel components of (a) a major laboratory investigation of MSW-to-methane bioconversion in adaptations of conventional sewage digesters. Methane was to be generated in a process, which included grinding, stirring, a several week digestion period, and processing of all unconverted liquid and solid residues, and (b) a National Science Foundation (NSF) Grant of $500,000 to Dynatech R/D Company to conduct an engineering and economic analysis of such conversion.

The in-vessel MSW-to-methane conversions had been widely advocated, yet had never been closely examined for engineering and economic practicality. When the Dynatech R/D MSW-to-methane laboratory results were examined using the economic model developed under the auspices of the NSF, the envisioned (stirred tank) conversion was found to be both highly uneconomical and even energetically inefficient (i.e. the process consumed about as much energy as it produced). It was recognized on the basis of several lines of evidence that a more economic and energetically efficient MSW to methane process should be digesting waste in situ, in landfills themselves. The landfills would be suitably modified to optimize conditions for biological conversion. Tests in unstirred, high-solids laboratory reactors generally confirmed this with even better gas yields than in stirred reactors. Projections showed both an order-of magnitude lower cost and lower parasitic energy requirements. A very early, fairly detailed publication out of Dynatech R/D Company was that of Augenstein et al. (1976) projecting MSW-to-methane digestion within the landfill or controlled landfilling.

The Dynatech publication projected a particular energy-focused bioreactor approach, which included methane enhancement details, yields and costs, high-efficiency gas capture, and a fairly detailed projection for its large-scale application (Augenstein et al. 1976). These early Dynatech R/D Company projections have, in general, been confirmed as technology has progressed. Early literature also included papers by John Pacey and co-workers, and collaboratively with Robert Ham of the University of Wisconsin on in-landfill bioreactors. Larger-scale tests were performed with the main objectives of decomposing waste and obtaining relevant measurements, although not on methane gas (EMCON Associates 1975). At the same time, work was performed on the "leachate recycle" approach by Dr. Fred Pohland and co-workers (Pohland 1975, 1980).

Earliest operations elsewhere that might be included in the category of bioreactors, often envisioned limited objectives. In most cases, a primary objective (i.e. Pohland et al. viewpoints) was to dispose of landfill leachate (liquid draining through waste) via the capacity of as received waste at moisture content around 20-25% to imbibe water up to moisture contents up to 35-45%. More rapid stabilization of waste and some remediation of leachate pollutants were also foreseen. This allowed beneficial use of leachate liquids, whose disposal would otherwise pose a problem. As time went on, the expanded objectives of various projects included (a) accelerated decomposition of waste, (b) volume reduction of waste thereby extending landfill life, (c) earlier stabilization of landfilled waste to avoid later care, and (d) maximization of energy and electricity recovery and minimization of methane (greenhouse gas) and pollutant emissions from landfilled waste.

The potential for augmenting biological decomposition of landfills was also recognized early on by EMCON Associates (San Jose, CA), under the direction of its president John Pacey. Concurrently with the work from Dynatech R/D Company, EMCON Associates had conducted a series of larger-scale test cell operations in Sonoma County, California.

As the potential for practical in-landfill MSW-to-methane digestion became evident with continuing tests, Dynatech R/D Company, in the late 1970's, prepared a proposal for large-scale testing of the controlled landfill bioreactor. Testing of concepts in this proposal was ultimately funded in Mountain View, CA by a consortium lead by Pacific Gas and Electric Company of California with fieldwork undertaken by EMCON Associates (San Jose, CA).

The Mountain View demonstration involved methane enhancement in 6 test cells and over 30,000 tons of waste over 4 years. Although some of its findings were preliminary, and some performance unexplained, the Mountain View project had one extremely important outcome. From optimizing conditions for decomposition, it was possible to obtain a several-fold (3 to 10-fold) increase in methane capture compared to expectations from similar masses of waste in conventional landfills. This project, therefore helped greatly to set the stage for further evaluations of controlled landfilling (as it was termed) for maximizing energy recovery from landfilled waste and was an important development on the way to the present program.

The evident benefits of optimizing landfill decomposition conditions set the stage for the Yolo County demonstration project.

1.5 Yolo Pilot-Scale Project – 1993 to Present

In 1989, Yolo County became interested in applying the controlled landfill bioreactor technology at their Central landfill. At the same time, Don Augenstein (while at EMCON) and John Pacey were interested in further advancing bioreactor technology. Proposals to operate a bioreactor were prepared at EMCON Associates (San Jose, CA) with encouragements from John Pacey, EMCON President. A final version of an extensive proposal was approved by the California Energy Commission in December 1991. Additional cost sharing support was also provided by Sacramento County, California. Work began approximately a year later after necessary permits and approvals were obtained.

The main objective of the initial Yolo County Pilot-Scale Demonstration Project was, as with Mountain View tests discussed elsewhere, to optimize a landfill bioreactor to enhance methane generation to the maximum possible yield. Another objective was to mitigate landfill methane emissions, whose adverse climate effects were increasingly well understood as a major factor in the climate picture (Augenstein 1992). Gas capture would be maximized through operational sequence and a surface gas capture design. Another general goal was to overcome some of the difficulties and problems that were encountered in the earlier tests at Mountain View. Important specific goals included:

- Careful and complete material balances on all components (waste, liquids, and gas) entering and leaving test cells.
- Extensive instrumentation and measurements of temperature, moisture, and pressure. This included provision for moisture and temperature throughout the waste mass, base liner integrity, and leachate composition.
- Use of a top surface over the waste of a shredded tires permeable layer. This was overlain by a polyethylene geomembrane to allow near complete (estimated 95-99%) gas capture throughout the experiment.
- More accurate and complete landfill methane capture measurements than in any previous and comparable work.
- Use of methods and materials that would be economically practical for as high a fraction of landfills as possible, both in the United States and around the world.
- An operational sequence to reduce early or "pre-gas collection" methane emissions. This was to be achieved by a sequence of filling, then surface tire layer coverage, then membrane coverage for gas capture. Only then, once waste was capped by cover for maximum gas capture, was liquid added to enhance and maximize methane generation.

1.5.1 Overview

The following provides an overview and summary of the pilot-scale test cells. Additional detailed information may be found elsewhere, particularly Yazdani (1997). Also see other symposium texts, including Yazdani and Augenstein (2001) and Yazdani et al. (2003).

The Yolo demonstration project involved building and operating two demonstration cells, containing about 9,000 tons of MSW each. One cell received liquid addition and recirculation and was the enhancement cell, while the other was operated as a typical dry-tomb control cell. Important features included:

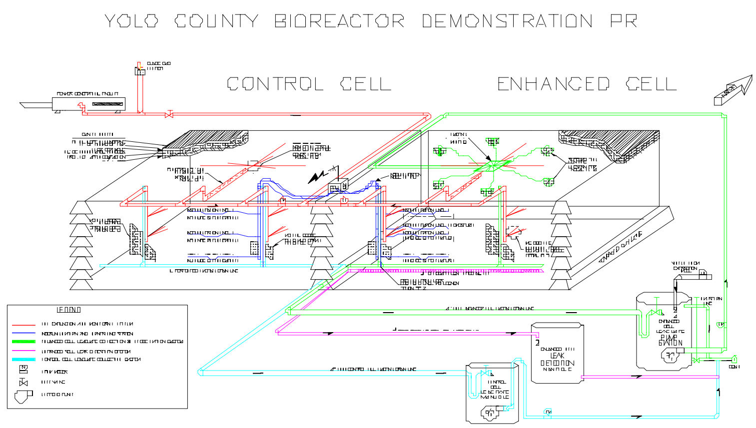
- A high-permeability leachate collection and recovery system (LCRS) under the waste to handle any likely rate of liquid leachate drainage that might be encountered.
- Multiple moisture and temperature sensors (over 50) emplaced while the pilot-scale cells were built to allow for accurate waste monitoring.
- The use of permeable greenwaste daily cover in lieu of soil to allow better liquid infiltration.
- A highly gas-conductive shredded tires layer just below the surface of the cell with permeability estimated at > 10^6 Darcys.
- A surface cover geomembrane to prevent gas emissions to the atmosphere and confine gas to the permeable shredded tire layer.
- Introduction and recirculation of liquids through multiple metered surface addition points spaced on approximately 25-ft centers to achieve (a) elevated moisture sensor readings, (b) a planned waste moisture content (around 40%), and (c) liquid outflow ratio of at least 50% of inflow.
- Gas extraction through application of slight vacuum (<0.5 inches of water) from the collection system to the permeable layer to withdraw gas as it is generated.

1.5.2 Waste Selection and Placement

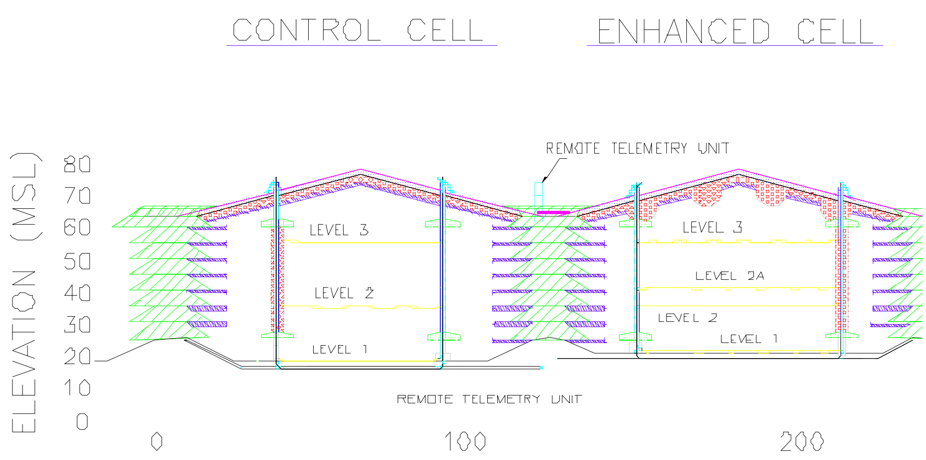
Waste were typical residential or commercial loads from packer truck collection routes serving households, small businesses, markets, etc. Tonnages were carefully logged. Loads that were inert (like wood or concrete) were diverted. Lifts were covered with greenwaste rather than more typical cover soil. This use of greenwaste for cover left waste permeable to later moisture additions, and allowed some limited initial composting, which elevated startup temperature as well. The test cells were filled between late 1994 and early 1995.

1.5.3 Important Features and Results

Specific features of the test cells, 100 ft by 100 ft by 40 ft deep are shown in the oblique view in Detail 2. Moisture and temperature sensors were located at 3 layers of the moisture added enhanced cell and 2 layers of the control cell. Cross-sections of cells with instrumentation are shown in Detail 3.



Detail 2. Yolo County bioreactor test cells demonstration project



Detail 3. Cross-section of test cells demonstration project

Both the enhanced and control cells experienced substantially elevated temperatures, around 45-55°C then falling and stabilizing to levels still well above ambient, around 40°C in the enhanced cell and 30°C in the control. Heat generation from methanogenesis is thought particularly important in the enhanced cell, which maintained its higher temperature while the control cell tended towards cooler temperatures after two years. Elevated waste temperature is a beneficial factor in enhancing methanogenesis.

The surface liquid addition method was effective based on the elevated moisture sensor readings with time and methane enhancement performance. Prior to this project, considerable modeling study had projected the need for rapid liquid additions for optimal moisture distribution into bioreactors. But, in this test, the liquid addition and recirculation were relatively conservative. Liquid addition was slow and easily manageable at 0.2-0.6 gal/ft^2-day. This helped in limiting head buildup over the base liner and minimizing waste instability effects due to liquid pore pressure, as well as limiting moisture-related factors like side seeps and increased lubricity/plasticity from increased moisture. This slow liquid addition would also minimize waste instability effects due to liquid pore pressure.

One early concern was that moisture distribution with slow additions and the multipoint distribution system would be incomplete. However, the moisture sensor readings quickly elevated at nearly all points in the waste, indicating good moisture distribution. Sensor moisture readings recorded in the interval from April 1995 to January 2003 are shown in Figure 1 below.

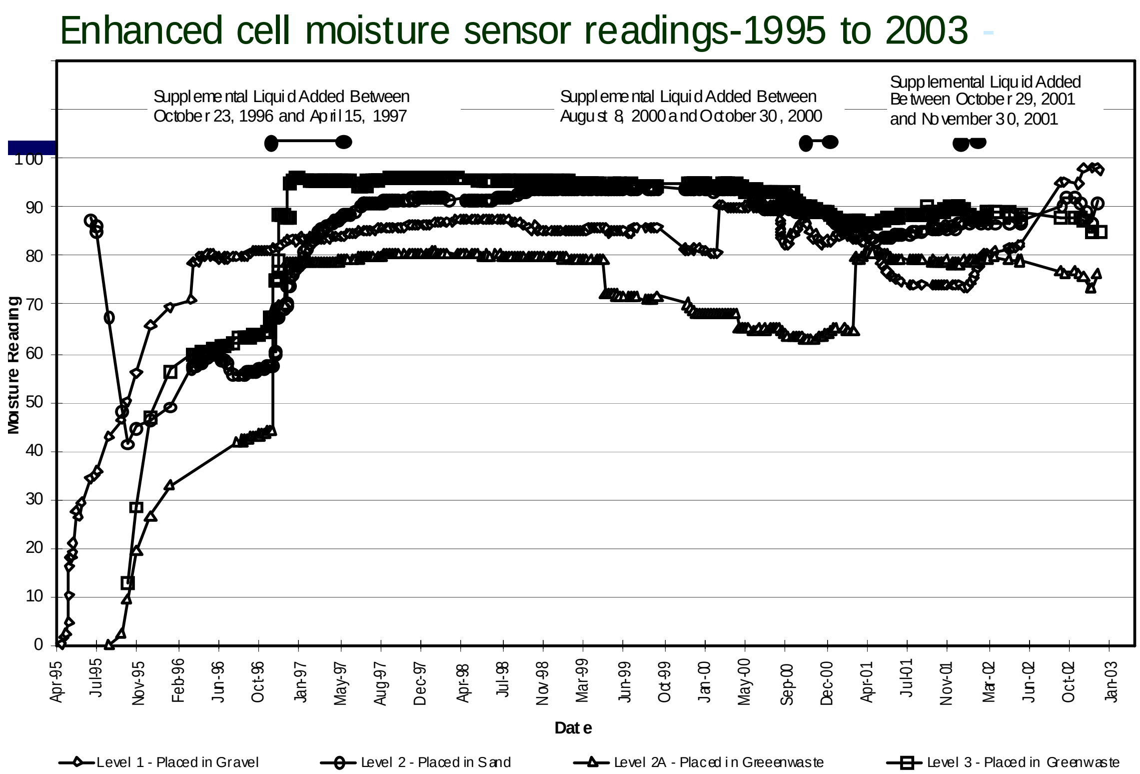


Figure 1. Moisture sensor readings versus time for moisture enhanced pilot-scale cell.

No liquid level buildup was seen in the injection pits, so liquid entered the waste easily, and most of the necessary liquid infiltration was accomplished within 3 months. Liquid permeability of the waste of over 3 x 10^{-5} cm/sec was estimated from these moisture permeation results. Core sampling data (not shown), as well as the gas results, confirmed that moisture distribution was excellent.

Figure 2 below (gas data from June 1996 to January 2005) shows the cumulated methane generation for the enhanced and control cells, with both of these compared to the normal generation expected for this mass of waste (the "normal" from the 19-landfill study of Vogt and

Augenstein (1997), and sources including EMCON). A methane recovery rate of over 5-fold that of conventional landfilling is one of the most important findings of the demonstration project. The accelerated methane recovery rates have major implications for improved methane energy recovery, and with high efficiency gas capture as in the demonstration, greenhouse gas emission and odor control.

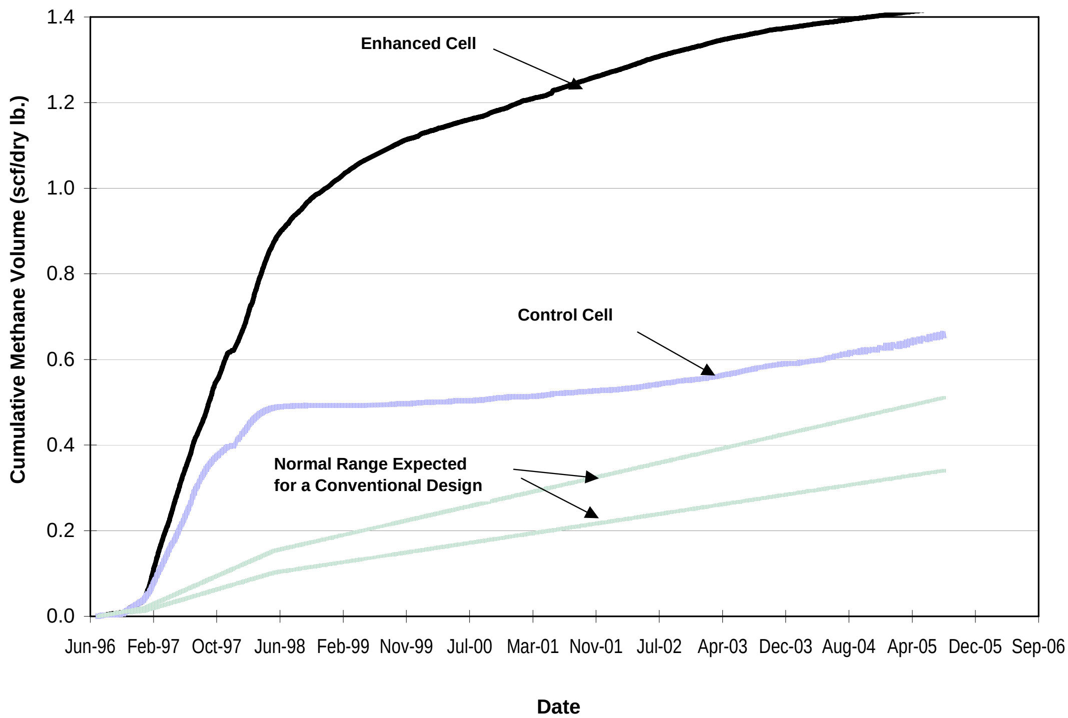


Figure 2. Cumulated methane recovery of pilot-scale 9000-ton enhanced bioreactor and control. Note the greatly accelerated methane recovery from the enhanced pilot cell relative to conventional and controls.

The methane generation behavior of the control cell started with rapid methane generation. However, the methane generation came to a near-complete stop quite suddenly, approximately a year after gas collection started. This rapid start is thought to be due to its initial elevated temperature in conjunction with its normal as-received moisture of around 18%. This observation supports the often-discussed expectation for dry-tomb landfills from which moisture is excluded. The slowing and limit to waste decomposition in the dry-tomb is confirmed by these control cell results. The confirmation of the dry-tomb phenomenon, wherein un-decomposed waste poses greater long-term risk, is another argument for the controlled bioreactor landfill.

The rapid conversion of solid material to gas in the enhanced cell is associated with rapid and pronounced reduction in waste volume. A photograph of the enhanced cell compared to the control is provided in Image 1. Volume loss of waste in the enhanced cell is pronounced, of the order of 20%. This fractional volume reduction in the moist, enhanced cell corresponded closely to the fraction of solids converted to gas. This volume loss can be extremely important inasmuch as such waste shrinkage in the fill should translate in the long term into an ability of bioreactor landfills to accept substantially more waste than a conventional landfill. This translates not only to environmental benefit, but an economic benefit to landfill operators. The economic value of volume reduction and landfill life extension is comparable to the methane energy value, and will facilitate the controlled landfill process. Another very interesting observation is that added moisture as well as waste conversion to methane both seems required for volume reduction. Solids conversion to methane by itself, without added moisture (as occurred with dry waste in the control cell) gave little apparent volume reduction. Only the enhanced 9000-ton cell with moisture added showed the volume loss that might be expected based on the waste solids converted to gas. This is another argument for bioreactor operation via moisture enhancement.

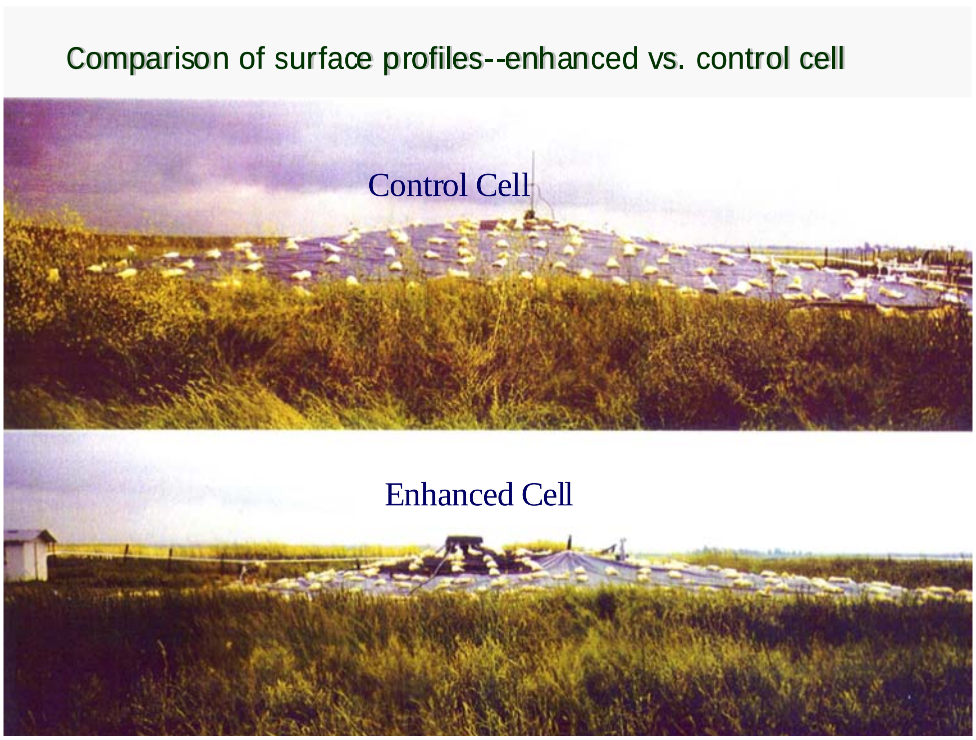


Image 1. Surface profiles of the two 9,000-ton pilot cells operated 1995 to present. Note the waste volume loss indicated by the subsidence of the methane-enhanced cell. This subsidence is due to the destruction of organic waste solids (like paper fractions and food) to form landfill gas.

The sensor readings, core moisture results, methane generation (methanogenesis), and volume reduction all indicate that it was possible for a slow, multi-point surface moisture addition approach (without deep injection wells) to give good moisture elevation throughout the mass of waste. This good moisture distribution with slow moisture percolation occurred despite studies indicating that much more rapid additions should be required. The liquid infiltration rates, even if infiltration should be slowed by compaction at greater depths, are still quite promising. And this moisture addition method is relatively economical and controllable.

The important outcomes of the Yolo pilot tests were (a) very substantial acceleration of methane recovery compared to the conventional landfill operation (Figure 2). And (b) as more waste solids were converted to methane, the volume of landfilled material lessened as seen in Image 1.

1.5.4 Conclusions

The Yolo County Bioreactor Pilot-Scale Project, still ongoing, has performed as well as hoped in virtually all respects. Among key benefits of greatest concern here was increased methane capture for energy and methane emission prevention. It is clearly evident the success here provided the basis for the scale-up to Yolo County's full-scale controlled landfill bioreactor application, which is the subject of this project report.

1.6 Other Relevant Large-Scale Demonstration Projects-- Past and Present

The following sections summarize some of the most relevant demonstration projects. The project attributes are either (a) focused on increased energy and electricity production and thus are the most closely comparable to the Yolo County Program, or (b) relevant in terms of being larger-scale demonstrations of accelerated waste decomposition in landfills.

1.6.1 Sonoma County, California

The Sonoma County project was one of the first studies on liquid addition and leachate recirculation. Summary of the Sonoma County project design can be found in Appendix A, Table 1. Five pilot-scale demonstration cells were constructed. Each cell contained about 500 tons of municipal solid waste and each had a clay cap (EMCON 1975). The cells were 49 ft by 49 ft by 10 ft deep. Various enhancement techniques were applied to each cell as shown in Appendix A, Table 1. Cell A was the project control, and therefore did not receive liquid. Cells B and E were initially brought to field capacity through the addition of water and septic pumping, but liquid additions did not continue. Cell C received daily additions of water, whereas cell D received daily additions of leachate (leachate recirculation). Between November 1971 and April 1974, leachate quality, gas composition and landfill settlement were the parameters monitored to determine the relative levels of waste stabilization. Results of the project indicated the level of waste decomposition was higher in the cells that had continual liquid addition (Leckie and Pacey 1979).

Landfill gas composition from cell C and cell D suggested favorable conditions for waste decomposition because the gas compositions stabilized at 50% methane. Unfavorable conditions for methane generation were indicated by the control cell, and cells A, B, and E. The gas composition for these cells was similar, all remained near 90% carbon dioxide (EMCON Associates 1975). Generally, gas composition indicated that liquid addition enhanced conditions for waste decomposition.

The leachate composition in both cells C and D showed declining organic strength. However, cell D provided the most rapid decline in chemical oxygen demand (Reinhart and Townsend 1997). The daily addition of water into cell C, without the recirculation of that water, generated large volumes of leachate that required treatment (Reinhart and Townsend 1997). On the other hand, the daily addition of water and the recirculation of leachate proved a beneficial means of treating the leachate in situ.

Landfill settlement showed the most significant benefits from leachate recirculation. The only leachate recirculation cell, cell D, showed a 20% reduction in height while other cells averaged only a 7.6% reduction in height (Reinhart and Townsend 1997). These settlement results, along with the gas and leachate composition results showed that while the addition of water can help decomposition, the greatest benefit was realized in this test through leachate recirculation.

1.6.2 Mountain View, California

This work started in part as a scale-up of laboratory work and engineering analysis at the Dynatech R/D Company in 1972 and was in a way an expansion on the Sonoma County project discussed previously.

The Mountain View demonstration was one of the earliest, and is still one of the most comprehensive, landfill enhancement projects. This project explored the effects of varying and optimizing those environmental components considered to affect activity of the anaerobic microorganisms. Several environmental conditions were varied including moisture, pH buffering, bacterial and nutrient supplementation with sludge amendments, and leachate recirculation.

The project's operation was managed by EMCON Associates (San Jose, CA) and a Ph. D. student, Costa Halvadakis, at Stanford University. The tests were initially funded by a consortium of stakeholders including the Pacific Gas and Electric Company, Southern California Gas and the U.S. Department of Energy. At Mountain View, six test cells were run at varying levels of moisture and amendments that included water, and varying levels of sewage sludge, and leachate (EMCON Associates 1987).

Six demonstration cells were constructed and each was filled with slightly over 5,000 tons of municipal solid waste. The cells were 100 ft by 100 ft by 47 ft deep. The amendment regime applied to each cell is shown in Appendix A, Table 2 and other findings from cell operation are included in Table 3. Cell F was the project control cell and received no amendments. Cells A, B, C, and E received sludge and buffers, and cell D received buffer only. Leachate recirculation was partial, and applied to cell A only. From June 1981 to December 1985, a variety of parameters were monitored to evaluate each enhancement regime.

Although the project is known as one of the most comprehensive of the field demonstration studies, some of the results conflict with other studies that use leachate recirculation techniques. For example, the total reported gas production rates were lower than the rates obtained in other studies. Several other anomalies were observed. One of the driest cells, D, reportedly generated the most landfill gas. Cell A produced less gas than cell C, in spite of the fact that the cells were identical except for the partial recirculation of leachate in cell A.

In contrast to the gas generation data, a BMP analysis of refuse samples showed (as expected based on fundamentals) more degradation in the leachate recirculation cell than in the control cell. Results are shown in Appendix A, Table 3. The recirculation cell had the lowest potential (0.35 standard cubic feet (scf) of methane per pound of dry refuse). The highest methane potential was found in the cell that had only negligible water infiltration, cell D, which had a potential of 1.93 scf of methane per pound of dry refuse (EMCON Associates 1987). These gas recovery and BMP results are inconsistent with one another. The temperature data showed heating above 60°C in every case where gas recovery interruptions were observed.

Thus, some difficulties and puzzling results were experienced in this project. However, final biochemical analyses of refuse samples provided evidence confirming recirculation success. Cell A, which had leachate recirculation, had relatively low volatile solids content, low cellulose content, low carbon-to-nitrogen ratios, and high carbon-to-phosphorus ratios. All of these are evidence for faster stabilization. On the basis of loss of volatile solids, waste decomposition and methane generation were enhanced by moisture, sludge addition and leachate recirculation (Reinhart and Townsend 1997).

Although some of its findings were puzzling, this Mountain View project had one extremely important outcome. From optimizing conditions for decomposition, and careful gas recovery measurements, it was possible to obtain a several-fold (3 to 10-fold) increase in methane capture compared to expectations from similar masses of waste in conventional landfills. Therefore, this project more than any other, helped set the stage for the Yolo County Demonstration Project.

The chronology of cell construction through 4 years of operation is presented in the final project report by EMCON Associates and John Pacey (1985).

1.6.3 Delaware Solid Waste Authority

The Delaware Solid Waste Authority began employing one of the first large-scale applications of liquid leachate management and recirculation on a full-scale basis at its Central Solid Waste Management Center (CSWMC) in Sandtown, Delaware. Leachate recirculation began in 1982 on cells that were built in 1980 as a method to treat the vast quantities of leachate produced from close to 30 acres of waste (Vasuki 1993). Several recirculation methods were tested at this facility including surface flooding, spray irrigation, vertical recharge wells, and tiled infiltrators. Initially, techniques were not applied in a scientific manner and the information about the project is primarily qualitative. However, the project is invaluable as a preliminary evaluation of large-scale liquid recirculation techniques.

Surface flooding was determined impractical due to odor problems and the mess that it made (Vasuki 1993). The irrigation system was employed on a closed section of landfill where it also killed the existing vegetation, as well as created odors.

Vertical recharge wells were used to allow leachate to trickle down into the landfill and act as an aerobic filter (Vasuki 1993). This attempt was efficient compared to previous attempts, however the pea gravel that was used to fill the wells clogged in the presence of leachate precipitates (Vasuki 1993). Wells were redesigned for recirculation using large stones in a four-foot diameter perforated concrete cylinder (Vasuki 1993).

An infiltration filed located below the final cap and constructed from roof tile was utilized in the next system. The system also incorporated valves that allowed control of liquid inflow (Vasuki 1993). This system has worked well.

Gas generation rates are unavailable for the Delaware work. However, favorable conditions for waste decomposition were evidenced by low organic levels after about seven years (Reinhart and Townsend 1997). DSWA concluded qualitatively that leachate recirculation increased waste breakdown, settlement, and gas generation, and decreased cost of leachate treatment.

The DSWA also ran two 10,000-ton test cells where the waste decomposition was monitored, including test lots of waste in time capsules. However, the detailed data was less than expected, due to loss of instrumentation when the wire leads to in-waste sensors broke during operations. Gas capture was incomplete and appeared to be at best a small fraction of generation (or potential). An additional issue on review of the project was that the leachate recycled from relatively dry, as-received waste was limited, so that waste moisture apparently remained well below field capacity. At the end of tests, pronounced decomposition of waste samples was seen in portions, but not all of the waste in the leachate recycle cell.

The literature on DSWA leachate recycle activities has been voluminous. A short overview of some activities was presented by Anne Germain, Head of Landfill Engineering at the DSWA, at the EPA February 2003 Workshop on Landfill Bioreactors, Arlington, VA, entitled "Bioreactors-Practical Experience".

1.6.4 United Kingdom and International Energy Agency Project and Report

Based on the results of the previous controlled landfill bioreactor studies, the objective of the Brogborough study was to further investigate the effect of waste density, air injection, waste amendments, and leachate recirculation (Croft and Fawcett 1993). The project consisted of six demonstration cells filled with between 16,000 and 22,000 tons of waste (Reinhart and Townsend 1997) (Appendix A, Table 4). Cell 1 was the project control while various enhancement techniques were applied to the remaining five. As outlined in Appendix A, Table 4, these were (a) low-density waste placement, (b) water and leachate recycle, (c) air injection, (d) sewage sludge and water addition, and (e) commercial and industrial waste addition.

Based on the landfill gas flow rate and methane composition, investigators stated that "results show that a mixture of nonhazardous commercial and industrial waste helped to promote degradation. This conclusion would, of course, depend on the typical industry waste brought to a specific landfill."

As methane production increased in each cell, the leachate composition decreased in organic strength and the pH level increased (Croft and Fawcett 1993). Settlement significantly impacted the integrity of the cap and gas recovery piping, which may have affected the gas recovery results (Reinhart and Townsend 1997).

This and other projects were further documented in the early 1990's by the International Energy Agency (IEA) Expert Working Group and Agencies in the United Kingdom Environmental Technology Support Unit (ETSU) of the UK Atomic Energy Agency for some time. These reports are available from IEA.

1.6.5 Buncombe County, North Carolina Bioreactor

Information on the Buncombe County Bioreactor was taken from the EPA Project XL website in the document "U.S. EPA Project XL Final Project Agreement" submitted in July 2000. The principal distinguishing feature of Buncombe County's approach is the alternating use of the same lines for both leachate injection and gas extraction. Other advantages and approaches are similar to those stated in other bioreactor projects, including Yolo's project XL. (Yolo County helped to advise and provide background for this project.) From recent discussions with Chris Gabel of Camp Dresser and McKee, the implementation of the Buncombe project has been delayed for reasons that were unforeseen at the outset, mainly due to existence of asbestos in old sections of the landfill. Construction of the project only began proceeding at the end 2004 as outlined in the proposal. In recent discussions with Chris Gabel, Project Manager at Camp Dresser and McKee, completion is anticipated in spring of 2005.

1.6.6 Corral Farm Landfill, Fauquier County, Virginia (from SCS Engineers website)

Fauquier County is also experimenting with bioreactor operation at their Corral Farm Landfill. The bioreactor portion of this project is managed by SCS Engineers and more information on the project can be obtained at http://www.scsengineers.com/Profiles/bioreactorprojects.html.

1.6.7 Other EPA Project XL Landfills--Virginia

Descriptions of other Virginia landfills can be found on the EPA XL project website, http://www.epa.gov/projectxl/virginialandfills/page6.htm. Reports include the following: the Prince Georges Landfill, Prince Georges County, and the Maplewood landfill, Amelia County.

Inspection of these reports showed that the design and operation of these projects were not focused so strongly on maximizing energy capture or on limiting emissions to their lowest possible level. Although these XL projects are, by regulatory standards, fully compliant with rules, data are being developed in other key areas such as liquids management slope stability analysis, etc. Gas recovery data are presented well by well but not summarized, so the report data would require further work for interpretation.

1.6.8 Other Recent Tests: Waste Management, Inc (WM) Tests: Outer Loop Landfill

Waste Management, Inc. (WM) is conducting bioreactor tests at its Outer Loop Landfill, Louisville, Kentucky. (WM reports it is conducting a number of other tests at other sites, for example the Prince Georges Landfill, Prince Georges County, and the Maplewood landfill, Amelia County (Websites for these are referenced above.) Its bioreactor program, in terms of effort, is reported by WM personnel to be the largest of any private waste company. Among important aspects of the WM program is its execution of a Cooperative Research and Development Agreement (CRADA) between WM and the U.S. EPA, which funds a great deal of supporting analytical work and work on environmental parameters of bioreactors at WM's bioreactor sites.

In its XL project information made publicly available, WM's primary focus has not been energy recovery, although this may change as the world energy picture changes. A major, overriding goal of WM to date has been waste volume reduction, which allows landfill life extension (i.e. increased capacity at existing landfills). Another goal is to develop a necessary base of operational knowledge and actual experience and effort to achieve the benefits associated with bioreactors. One approach used by WM is the "facultative landfill" in which a landfill sector is first aerated to elevate temperature to an optimum, and then allowed to produce methane anaerobically once that optimum temperature is established. A variation on this is to use wastewaters that have nitrified dissolved ammonia (treated leachate). WM has patented both the facultative landfill, and the use of nitrified, treated leachate in bioreactor landfills.

The results of the work done under the Waste Management/EPA Louisville Outer Loop CRADA are listed on the U.S. EPA website,
http://www.epa.gov/ORD/NRMRL/Pubs/600r03097/600r03097.html.

Another source of information is WM's website,
http://www.wm.com/wm/environmental/bioreactor/index.asp.

In terms of instrumentation, the Waste Management Outer Loop project is a commercial operation that is somewhat constrained for practical reasons, and it has been less intensively instrumented than was the Yolo Project. For example, from the report, temperature measurements are performed in two ways: from temperature of leachate exiting the waste and by placing a probe in waste sampled with a bucket auger. Determinations of waste moisture and other measurements were made by Dr. Morton Barlaz at North Carolina State University. These temperature and moisture measurements and other methods provide less in the way of detail on a less continuous basis than the sampling methods using embedded temperature and moisture sensors.

A strong focus of WM has been on subsidence and settlement at Outer loop, which is measured very accurately because of the monetary implications of added landfill space associated with volume loss during settlement. Data are also taken on regulatory compliance, particularly on factors such as head over the liner.

Waste management findings excerpted from their posted EPA report are summarized in Appendix A, Table 5.

As far as gas recovery is concerned, WM is overextracting on their wells, at least as suggested by methane concentrations that fell to as low as 20% because of air dilution. Instead of complete gas collection, the tests at Outer Loop have also, in part, been conducted to determine the efficacy of a surface biofilter in abating methane that approaches the waste surface, by bio-oxidation.

An approximate lower bound k value can be derived from the recorded gas recovery "time-averaged" over the entire reported measurement interval, of about 100 cubic feet per minute (CFM) of methane. The authors estimated that k is roughly 0.05 $year^{-1}$, or about 10-20% of that of the Yolo pilot-scale cell. Low k values may be a function of relatively cool waste temperature at around 25-35°C. This is much cooler than bulk waste temperature values seen in the Yolo County's Project. Temperature is extremely important, and operating at 30°C vs. 45°C would, by itself, be expected to slow methanogenic activity by over half. WM staff is well aware of this, and the intent is elevating temperature by initial aeration in its latest cells

WM has been examining methane emissions. The Outer Loop Landfill has been found generally in compliance by means of integrated surface scans. The emission of fugitive methane has been quantified by sophisticated Fourier transform infrared spectrophotometry at less than 10 CFM when tests were done, also indicating modest methane losses and that the landfill is compliant under regulations. All of this suggests that capture is efficient, and thus the fairly low value of k may be realistic.

To summarize, WM's objectives have been focused on aspects other than energy including volume loss and emissions. Additional information and overview of WM's approach can be obtained in the article by Carson and Green (2003).

1.6.9 New River Bioreactor Landfill (Florida)

The New River bioreactor involves experimental adaptations on an existing landfill, and adaptation of new landfill sections to meet research objectives. Some of the New River project's important features are:

- Vertical clusters of liquid injection wells (135 wells in 45 clusters). Piping enabled tests of both aerobic and anaerobic operation in different parts of the landfill.
- Exposed geomembrane cap.
- Gas collection from horizontal trenches beneath the cap and leachate collection system.
- Extensive moisture (resistivity based probes) and temperature instrumentation (332 thermocouples and 138 resistivity based moisture sensors).
- Ability to test shallow and deep waste permeability via liquid draining rates.
- Ability to test air permeability.

The parameters being measured at the New River Landfill are of fundamental value in understanding future operations of bioreactors. An example of one such parameter is waste permeability tests using infiltration rates of liquid from vertical wells. In terms of results on energy recovery, the landfill produces only a fraction of the gas potential that would be inherent from an 800 tons per day (TPD) waste inflow, (about 300-400 ft^3/ton vs. potential that we estimated at 3000 ft^3/ton). The situation is admittedly complicated by the partially aerobic operation. The New River project is in startup status, and much more high value data on waste management parameters and operations is anticipated to be forthcoming in future years of this project as operational experience is gained.

Recent information can be found from Reinhart et al. (2004) and the website, http://www.bioreactor.org/publications.htm, operated by the University of Florida. A presentation by the same group was made at the Third International Landfill Research Symposium, Sapporo, Japan, November 2004. Slide presentations will be available at http://lst.sb.luth.se/iclrs/web/symposia.html.

1.6.10 Anne Arundel County, Maryland

Information on the Anne Arundel County Millersville Landfill is available at the EPA Project XL web site at: http://www.epa.gov/projectxl/aarundel/index.htm. Although the project features have some general resemblance to the Yolo County project, the major focus is something other than energy.

1.6.11 Other Projects

Numerous other projects have been undertaken, but most differed from the Yolo Controlled Bioreactor Landfill operated for energy recovery. The basic lack in most operations was relevant measurements or publication of the effects of recycling.

In a multitude of projects, including past and ongoing experimental projects, examples of missing measurements and information that would be desirable included:

- Incomplete collection of landfill gas when generated.
- When leachate recycle was practiced, there were few measurements of where the added liquid actually went or how effective the addition was in terms of consequences for energy.
- Few measurements of other types, including temperature.

- In most cases no overall measurements of aspects now considered extremely important. Methane capture effectiveness and emission abatement and more recently, under subtitle D landfill rules, of leachate head over the base liner.
- The projects for energy recovery assessment were relatively short term (4 years at most) and were terminated (for a variety of reasons including lack of funding and landfill closure requirements) prior to waste degradation reaching completion.

1.7 Organization of Subsequent Sections of the Report

This report is organized into the main categories of design, construction, monitoring and data analysis, project operation and maintenance (O&M), economics, and conclusions. Where applicable, important data in the form of graphs or tables is included within the text, however, the majority of the data can be found in the appendices. Photographs, design drawings, and reports are also located in the appendices. For clarity and where data results differed, discussions of the bioreactor cells were separated into different sections.

2 PROJECT DESIGN AND CONSTRUCTION

The project was separated into three bioreactor cells, two cells were operated anaerobically and one aerobically. The cells have been designated as the northeast and west-side anaerobic cells and the southeast aerobic cell. This configuration allowed the northeast cell to be constructed and operated prior to completion of the west-side cell. In addition, experiences gained from the construction of the northeast cell were incorporated into the west-side cell.

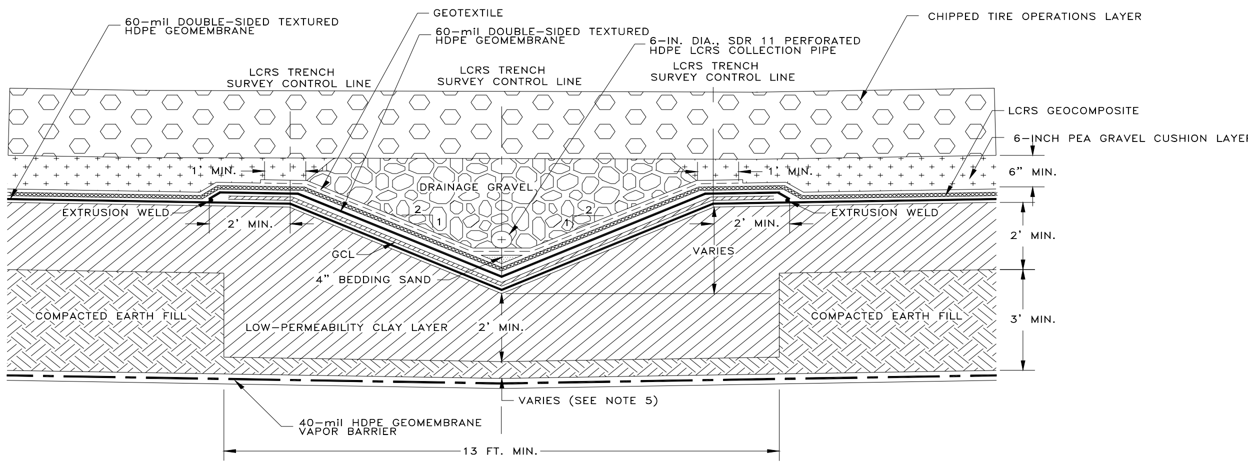
2.1 Base Liner System

All three bioreactor cells share a common composite liner system designated the Module 6D primary liner. This composite liner system was designed to exceed the requirements of Title 27 of CCR and Subtitle D of the Federal guidelines.

The base layer of Module 6D has a ridge and swale configuration, enabling the west 6-acre cell to be hydraulically separated from the northeast 3.5 and southeast 2.5-acre cells. The base layer slopes 2% inward to two central collection v-notch trenches located on the southeast and southwest side of Module 6D (Detail 4). Each of the trenches drain at 1% to their respective leachate collection sumps located at the south side of the module.

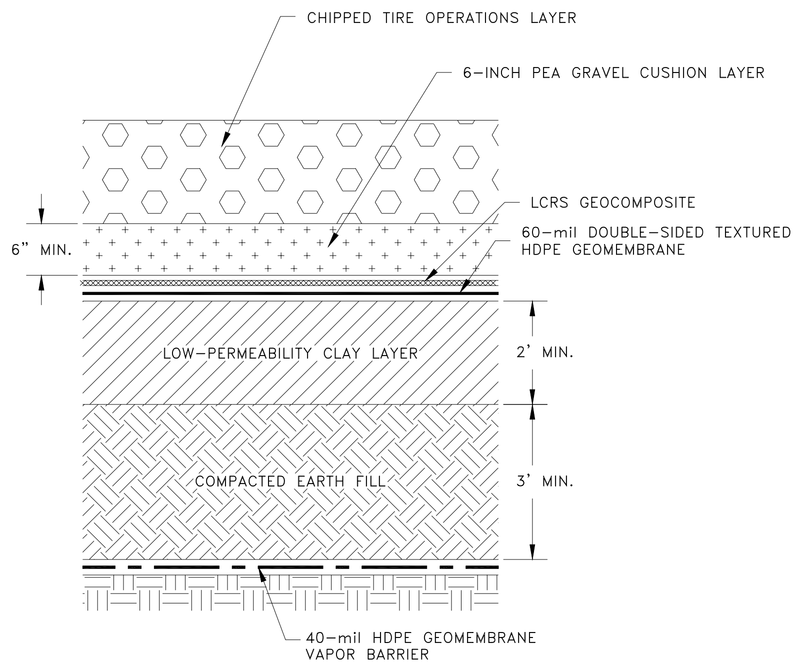
The liner system within the collection trenches and sump areas was upgraded further to a double composite liner to account for infringement on the 5-ft groundwater offset and to minimize potential leakage in these critical collection areas where head on the primary liner will be at its greatest. The liner and leachate collection system in the collection trenches and sumps consists from top to bottom of a minimum of 2 ft of gravel drainage material, a protective geotextile, a blanket geocomposite drainage layer, a primary 60-mil high-density polyethylene (HDPE) liner, a geosynthetic clay liner (GCL) ($k < 5 \times 10^{-9}$ cm/sec), a secondary 60-mil HDPE liner, 2 ft of compacted clay (k< 6 x 10-9 cm/sec), a minimum of 0.5 ft of compacted earth fill ($k < 1 \times 10^{-8}$ cm/sec), and a 40-mil HDPE vapor barrier layer (Detail 4). The thickness of the compacted earth fill varies from a minimum at the south end of the trench of 0.5 ft to a maximum of about 2.5 ft at the upper, north end of the leachate collection trench. Leachate collection pipes were also placed in the collection trenches to transport leachate immediately to the sumps for recovery, removal, and recirculation, as needed.

As described above, the more rigorous Module D LCRS and liner system will outperform the Title 27 and Subtitle D prescriptive liner. The LCRS has been designed and constructed to be free-draining throughout the life of the module and will maintain less head over the primary liner system than prescribed by Title 27, Subtitle D, or the site specific Waste Discharge Requirements issued by the California Regional Water Quality Control Board.



Detail 4. Module D bottom liner and leachate collection trench cross-section

The Module D liner and leachate collection system consists, from top to bottom, of a 2-ft thick chipped tire operations/drainage layer (k> 1 cm/sec), 6 inches of pea gravel, a blanket geocomposite drainage layer, a 60-mil HDPE liner, 2 ft of compacted clay (k<6 x 10^{-9} cm/sec), 3 ft of compacted earth fill (k< 1 x 10^{-8} cm/sec), and a 40-mil HDPE vapor barrier layer (Golder 1999) (Detail 5). The chipped tire operations layer was not placed during initial liner construction, but was placed immediately before waste placement.



Detail 5. Module D bottom liner cross-section

The permeability of the clay liner, as constructed, was on average about 6 x 10^{-9} cm/sec and the earth fill averaged about 1 x 10^{-8} cm/sec. These two layers, in effect, provide a 5-ft thick composite liner. This fact, coupled with the lower permeability, will result in a significantly more effective barrier to leachate migration than the prescriptive liner system.

For design purposes, it was estimated that the peak liquid addition would be up to 10 gallons per minute (gpm) of liquid per 10,000 ft^2 (44 gpm/acre) of disposal area. Based on the demonstration cell performance, the amount of liquid added would be in the range of 30 to 50 gal/ton of waste. According to results of the bioreactor demonstration project by Moore et al. (1997), the average leachate generated during liquid introduction peaked at about 47% of the liquid delivery rate, which would equate to approximately 20 gpm/acre for the proposed program. Given a 6-acre drainage area, the total anticipated flow into any given sump would be approximately 120 gpm (173,000 gal/day).

Based on the estimated leachate production, drainage into the leachate collection layer would be about 4.6 x 10^{-4} gpm/ft^2 of disposal area. It is approximately 200 ft between the ridge and collection trench. Using these values, the peak flow through the geocomposite would be about 0.09 gpm per linear foot of trench. The geocomposite for Module 6D has a measured capacity of 1.0 gpm/ft (Golder 1999). Therefore, the geocomposite has over 10 times the capacity required under peak flow conditions.

Although clogging of the geocomposite layer was not anticipated, the LCRS was designed under the conservative assumption that geotextile clogging may occur. In the event that the geocomposite were to become clogged or otherwise nonfunctional, the chipped tire operations layer with its high porosity would provide adequate drainage. Due to the large particle size of the chipped tires (>6 inches), the calculated effective permeability of the tires layer at the drainage slope of 0.02 was estimated to be well over 1.0 cm/sec. Given this value, it has a flow rate capacity on the order of 0.025 gpm per inch of thickness per 1-ft width. Therefore, at the calculated maximum inflow rate of 0.09 gpm per foot width, the head over the liner would not exceed 4 inches. Typically, collection systems are designed to maintain less than 1 ft of head over the liner. Therefore, this system has over three times the required flow capacity at the allowable prescriptive level of 1 ft.

In addition to the upgraded LCRS, the primary composite liner was better than the Title 27 prescriptive system. This was based on the reduced permeability, k, of the clay soil used during construction of the module. The permeability of the clay soil used in construction of Module 6D liner was significantly lower than the prescriptive 1×10^{-7} cm/sec. Based on the results of the laboratory testing performed during construction of Module 6D, the clay liner had an average permeability on the order of 6×10^{-9} cm/sec. Using standard leakage rate analyses by Giroud and Bonaparte (1989), the leakage from the Title 27 system (with 1 ft of head over a HDPE geomembrane and 1×10^{-7} cm/sec clay liner) would be 1×10^{-4} gpm from a standard 1-cm^2 hole in the liner. With the Module 6D liner (4 in of head over an HDPE geomembrane and 6×10^{-9} cm/sec clay liner), the leakage would be 5×10^{-6} gpm, less than 1/20 of the flow.

In the event leaks were to occur through the 5-ft thick primary composite liner, the vapor barrier would provide secondary containment. Secondary containment is not required by Title 27 or Subtitle D for conventional landfilling operations. As constructed, the vapor barrier would minimize further downward migration, and aid in detection of migrating leachate. The 40-mil HDPE vapor barrier was sloped to mirror the primary liner. Geocomposite strip drains were also installed diagonally across the top of the vapor barrier to act as drainage pathways to the pan lysimeter located immediately beneath each of the leachate collection sumps. The strip drains and lysimeter acted as a vadose zone monitoring system for early detection of leakage across the entire Module 6D disposal area. This added feature provided another level of protection to the groundwater that standard Title 27 systems do not have.

Monitoring of the base layer consisted of temperature, moisture, and pressure sensors placed on the liner and in the LCRS trenches. As part of the requirements specified under Waste Discharge Requirements in Order R5-2004-0134, Yolo County was required to monitor liquid buildup on the liner. Under typical landfilling, liquid buildup on a Class III composite liner system must be maintained to less than 1 ft. In order to gain approval from the California Regional Water Quality Control Board to operate Module 6D as a bioreactor, Yolo County must maintain less than 4 inches of liquid buildup on the Module 6D primary liner (CRWQCB 2000).

The majority of Module 6D primary liner system was constructed in 1999 by Nordic Construction. Construction quality oversight of the liner system was provided by Golder Engineering, who was also the design engineers. A separate third party contractor placed the pea gravel layer in 2000 and the daily waste placement contractor (B&D Geerts Construction) placed the shredded tire operations layer.

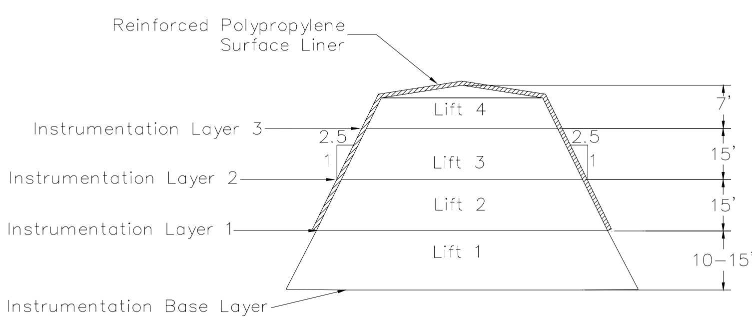
Sensors were placed on the geocomposite and covered with pea gravel prior to the placement of the chipped tire operations layer. Each sensor location on the base layer received a temperature sensor (thermistor), a linear low-density polyethylene (LLDPE) tube, and selected locations received a polyvinyl chloride (PVC) moisture sensor. Refer to Appendix D for the locations of the base liner sensors.

The Aerobic liner was constructed by first placing an approximate 10-foot lift of waste on the Module 6D liner. This first lift of waste acts as a buffer between the Module 6D primary liner and the aerobic cell. The waste was graded to promote drainage and a 60-mil HDPE geomembrane was installed to capture all leachate being generated by the aerobic cell. A sixteen-ounce geotextile was then placed on the membrane to act as a cushion for a shredded tire operations layer.

2.2 Waste Filling and Operations Layer

Waste placement in the northeast 3.5-acre cell began on January 13, 2001 and was completed on August 3, 2001. Waste was placed in four separate lifts with an approximate thickness of 15 ft (Detail 6). In general, all waste received at the landfill was deposited in the northeast cell with the exception of self-haul waste in the top two lifts. Because of the difficulties handling large volumes of self-haul vehicles in the limited area of the upper lifts, self-haul waste was not placed in lifts 3 and 4. The use of daily cover soil during waste filling was minimized to aid in the overall permeability of the waste. Whenever possible, greenwaste or tarps were used as alternative daily cover (ADC) and, in the event soil was placed (for example, access roads or tipping pad), the soil was removed prior to placing the next lift of waste. All side slopes were constructed at approximately 2.5-to-1 (horizontal to vertical) and received at least 1 ft of soil cover.

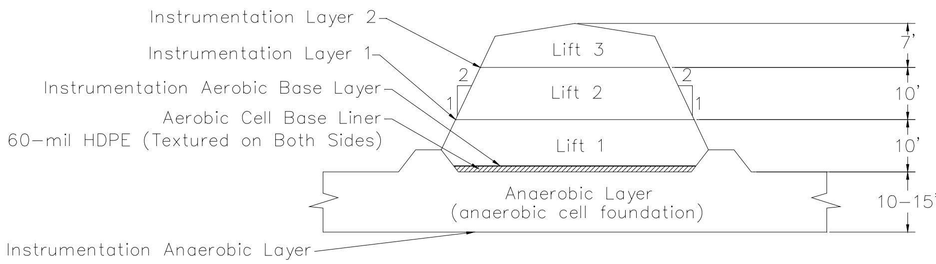
Following final placement of waste, final grading on the northeast 3.5-acre cell was performed in August and September of 2001 in anticipation of placement of the surface liner. Final grading consisted of placement of a 1-ft thick layer of soil over the waste utilizing a Caterpillar D6 LGP bulldozer.



Detail 6. Northeast anaerobic cell cross-section

Waste placement in the southeast aerobic cell first began on November 14, 2000, with approximately 10-ft lift of waste placed on the Module 6D liner. This first lift of waste acted as a buffer between the Module 6D primary liner and the future aerobic cell. The waste was graded to promote drainage and a 60-mil HDPE geomembrane was installed to capture all leachate being generated by the aerobic cell. A 16-oz geotextile was then placed on the membrane to act as a cushion for a shredded tire operations layer.

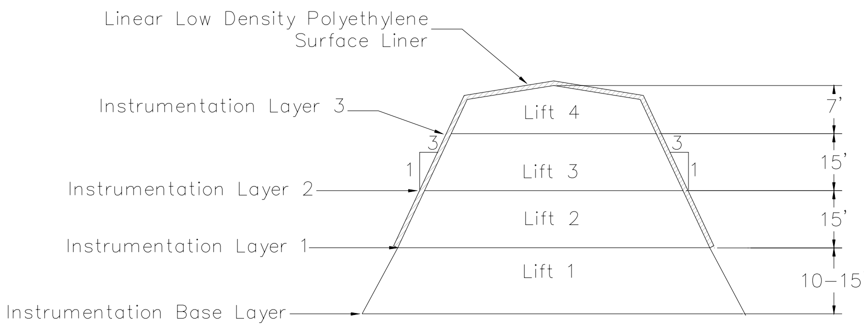
Waste placement in the aerobic cell occurred between August 8, 2001 and September 26, 2001. Waste was placed in three 10-ft lifts with 2-to-1 side slopes on the north, east, and west (internal side slopes), and a 3-to-1 side slope on the south (external side slope) as presented in Detail 7. Because of the limited tipping area of the aerobic cell, self-haul waste was excluded. The use of daily cover soil during waste filling was also minimized to aid in the overall permeability of the waste. Whenever possible, greenwaste or tarps were used as ADC and, in the event soil was placed (for example, access roads or tipping pad), the soil was removed prior to placing the next lift of waste. To further aid permeability of the waste, compaction was restricted to only 1 to 2 passes with a Caterpillar 826 compactor. Based on waste tonnage records and as-built topography, the in-place refuse density was approximately 800 lb/yd^3.



Detail 7. Cross-section of the Southeast aerobic cell

Waste placement for the west 6-acre cell began on March 8, 2001 and was completed on August 31, 2002. Waste was placed in four lifts of approximately 15-ft thickness with 2.5-to-1 side slopes on interior slopes and 3-to-1 on exterior slopes (Detail 8). All waste received at the landfill was deposited in the west 6-acre cell (i.e. no class of waste was excluded).

During the waste filling phase, it was necessary to construct an all-weather tipping pad (comprised of concrete rubble and dirt) on top of the first lift of waste along the west side of the module. When the subsequent lift of waste was placed over the pad area, rather than remove the pad material, it was incorporated in to the waste. We believe that this is one thing that led to leachate seeps, which are discussed later in Section 3.5.1.



Detail 8. Cross-section of west-side anaerobic cell

2.3 Waste Monitoring

Several parameters are important in maintaining proper operation of a bioreactor landfill. These parameters greatly influence the degradation process of the waste and the quality and quantity of the biogas produced. In order to obtain statistically valuable data, a grid was created for the distribution of sensors throughout the cell for each lift of waste. Each location received a temperature sensor, a LLDPE tube for pressure measurement, and a moisture sensor. The sensors were placed within the waste mass at each lift at spacings of 75 ft on center (Image 2). A total of 47 temperature sensors and 70 moisture sensors were placed in the northeast 3.5-acre cell. The southeast aerobic cell contained 59 temperature sensors and 52 moisture sensors. For the west-side anaerobic cell, equal numbers of temperature and moisture sensors were placed, totaling 126 sensors. Appendix A, Tables 6 and 7 give a summary of the sensors placed in the two anaerobic and the aerobic bioreactor cells, respectively. Appendix A, Table 8 gives a summary of sensors installed on the base liner

Image 2. Moisture, temperature, and tube installation

For protection, each wire and tube were encased in either a 1.25-in HDPE pipe or run inside the landfill gas (LFG) collection piping. Refer to Appendix D, Detail 1 for sensor location diagram.

2.3.1 Temperature

Temperature was monitored with thermistors (QT06005, Quality Thermistor, Inc., Boise, ID) with a temperature range of 0°C to 100°C to accommodate the temperature ranges expected in the anaerobic cells. To prevent corrosion, each thermistor was encased in epoxy and set in a stainless steel sleeve. All field wiring connections were made by first soldering the connection, then covering each solder joint with adhesive lined heat shrink tubing, and then encasing the joint in electrical epoxy. Changes in temperature were measured by the change in thermistor resistivity (ohms). As temperature increased, thermistor resistance decreased.

Sensors were placed within the waste on either a bedding of greenwaste (shredded yard waste), wood chips (chipped wood waste), bin fines (fine pieces of greenwaste), or pea gravel to protect against damage from the underlying waste. Sensors installed on the primary liner (prior to any waste placement) were placed on geocomposite and covered with pea gravel prior to the placement of the chipped tire operations layer.

As-built drawings showing the locations of the temperature sensors are located in Appendix D.

2.3.2 Moisture

Moisture levels were measured with PVC moisture sensors and gypsum blocks. Both the PVC moisture sensors and gypsum blocks were read utilizing the same meter (MM4, Electronics

Unlimited, Sacramento, CA). Moisture sensors were installed adjacent to temperature sensors and were placed in the same bedding material as the temperature sensors were.

The PVC sensors were designed by Yolo County and used successfully during the pilot-scale project (Yazdani et al. 1998). The design of the sensor consisted of perforated 2-in diameter PVC pipes with two stainless steel screws spaced 8 inches apart and attached to wires to form a circuit that included the gravel filled pipe. The sensor provided a general, qualitative assessment of the waste's moisture content. A reading of 0 to 40 equated to no free liquid, 40 to 80 equated to some free liquid, and 80 to 100 meant complete saturation.

The gypsum blocks are manufactured by Electronics Unlimited (Sacramento, CA) and are typically used for soil moisture determinations in agricultural applications. Gypsum blocks establish equilibrium with the media in which they are placed, and thus are reliable at tracking increases in the soil's moisture content. However, the gypsum block can take considerable time to dry, which may not reflect the drying of the surrounding environment. Gypsum blocks were only used in layer 2 of the northeast anaerobic cell.

As-built drawings showing the location of the moisture sensors are located in Appendix D.

2.3.2.1 Partitioning gas tracers

Measuring water in situ has proved to be difficult and expensive with existing technologies. While well drilling and analysis of solid waste samples can be used, this is an expensive, time consuming, and destructive procedure. The objective of this work was to evaluate the utility of the partitioning gas tracer test (PGTT) for measuring water. This was done using the southeast aerobic bioreactor. This technology may play a major role in advancing acceptance of bioreactor landfills and the associated reduction in greenhouse gas emissions.

2.3.3 Pressure

Pressure within cells was monitored with ¼-in inner diameter and 3/8-in outer diameter LLDPE sampling tubes. Each tube can be attached to a pressure gage and supplemental air source. By first purging the tube with the air source (to remove any liquid blockage), and then reading the pressure, an accurate gas and/or water pressure can be measured at each sensor location.

The installation was similar to that for the pilot-scale cells as described in project history. For protection, each wire and tube were encased in either a 1.25-in HDPE pipe or run inside the LFG collection piping.

Three LLDPE pressure-sensing tubes were installed in each of the leachate collection trenches. The tubes were installed inside a 2-in diameter PVC pipe for protection, and terminated at different points along the trenches.

Pressure transducers (Model PTX 1830, Druck, Inc., New Fairfield, CT) were installed at three locations adjacent to each leachate collection trench in the northeast and west-side anaerobic cells, and at two locations in the southeast aerobic cell. Additionally, tubes were installed that terminated adjacent to each of the pressure transducer locations. The pressure transducers provided an output current between 4 and 20 mA, which was directly proportional to pressure. Their pressure range was 0-1 pounds per square inch (psi) and had an accuracy of ±1% full-scale.

Pressure sensing tubes were installed at the same locations as temperature and moisture sensors on the base liner and within the northeast anaerobic and southeast aerobic cells, minus a few locations on the first and second lift. A total of 41 tubes were installed in the northeast anaerobic and 54 tubes in the southeast aerobic cell. Tubes were also installed in the west-side anaerobic cell, but only at select locations in each layer. A total of 13 tubes were installed in the west-side cell.

As-built drawings showing the location of pressure transducers and tubes are located in Appendix D.

2.4 Supervisory Control and Data Acquisition (SCADA) System

Efficient data monitoring and operation of the bioreactors were accomplished by using the SCADA system. All sensors were linked to the SCADA system for near real-time data collection and control. Data were transferred to a computer at the Woodland office by high frequency radio.

Major components of the SCADA system included two Allen-Bradley Model 5/05 small logic controllers (SLC), which controlled and monitored the raw data acquisition. Each SLC had a 10-slot rack capable of receiving up to ten different input or output (I/O) cards. Analog output cards (Allen-Bradley Model 1746-NI8, Rockwell Automation, Milwaukee, WI) were used to monitor flow meters, pressure transducers, temperature, and moisture sensors, all of which provided a signal of 0 to 5 V that was proportional to their reading. Because the large number of moisture and temperature sensors would have required a significant number of analog output cards (each card can accept 8 readings), Campbell Scientific multiplexers (Model AM416, Campbell Scientific, Inc., Logan, UT) were utilized to allow up to 16 temperature or moisture sensors to be connected to each analog output. Digital output cards (Allen-Bradley model 1746-OW16, Rockwell Automation, Milwaukee, WI) were used to power the multiplexers as well as control the leachate injection solenoid valves (both of which require 12 volt direct current (VDC) power. Finally, a digital input card (Allen-Bradley 1746-IB16, Rockwell Automation, Milwaukee, WI) was used to monitor leachate pump status and run time.

The user interface for the SCADA system was provided through a customizable program called Wonderware InTouch (Wonderware, Lake Forest, CA). This program received the raw data from the SLC and converted it to real world values such as "°C", "range of wetness", "flow rate in cubic ft/min", etc. The program also provided the interface for the user to change system components, such as valve position and alarm value levels.

At the heart of the system is a graphical display of the current status and readings of all of the sensors installed for the project. Display screens were first divided into modules (northeast, southeast, or west-side) and then into a separate screen for each lift of sensors. By clicking on the module and lift you are interested in, a screen is displayed providing current (within 15 min) data on both the temperature and moisture status of that lift. Additional screens exist to monitor the flow of leachate and landfill gas, liquid buildup on the liner, and leachate pump status. Various screens from Wonderware are included in Appendix C.

As data from the bioreactor were collected and stored on the SCADA computer, a file was created with all of the data for each day. These data can then be viewed in various graphing screens so that the operator can determine trends or analyze problems. Data collected by the

SCADA system can be exported to a spreadsheet program such as Excel for manipulation and graphing.

With each parameter, alarm values were set to indicate unusually high or low levels. In the event a particular sensor reached an alarm level, the color of that sensor, as displayed on the computer screen, changed to either orange or red, and the alarm condition was recorded in a separate alarm file.

Hardware installation for the northeast and southeast cells began in December 2001 and continued through March 2002, with system troubleshooting continuing through May 2002. Hardware installation for the west-side cell began in December 2002 and continued through January 2003, with system troubleshooting continuing through February 2003. All hardware components were installed in a shed located along the southern edge of Module 6D.

As-built drawings of the SCADA system are included in Appendix D.

2.5 Landfill Settlement Study and Surveying

Settlement in the waste cells was monitored on an annual basis to determine the amount of airspace recovery possible with bioreactor operation. This airspace recovery is extremely important because any increase in overall landfill capacity will not only increase the revenue potential of the landfill (because more waste can be put into a fixed volume), but also increase the life of the landfill by postponing (or even negating, should mining of the decomposed waste prove feasible) the need to construct a new landfill site.

This initial survey for the northeast anaerobic and southeast aerobic cell was performed on November 15, 2001, which was used as the reference for calculating the total settlement volume achieved. The second and third surveying events of the two cells were completed on January 16, 2003, and January 28, 2004, respectively. Both surveys included the generation of a topographic map with 1/2-ft contours for the second survey and 1-ft contours for the third. Both surveys had 4 cross-sections, and the re-surveying of 22 separate control points established on the surface liner for the northeast cell, and 14 control points for the southeast cell.

The first surveying event of the west-side cell was completed on January 16, 2003 and the second on January 28, 2004. Each survey included the generation of a topographic map with 2-ft contours, 8 cross-sections, and re-survey of 30 separate control points established on the liner.

Copies of settlement surveys are located in Appendix D.

2.6 Waste Field and Laboratory Analysis

2.6.1 Leachate

Leachate was monitored for the following field parameters: pH, electrical conductivity (EC), dissolved oxygen (DO), oxidation-reduction potential (ORP), total dissolved solids (TDS), and temperature. The following parameters were analyzed by a laboratory: dissolved solids, 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), organic carbon, nutrients (ammonia (NH_3), total Kjeldahl nitrogen (TKN), total phosphate (TP)), common ions, heavy metals and volatile organic compounds (VOC). For the first year, monitoring was conducted monthly during the first six months and quarterly for the following six months. After the first year, monitoring was conducted semi-annually (pH, conductivity, and flow rate continued to be monitored on a monthly basis as required by the State of California's Waste Discharge Requirements in Order R5-2004-0134).

The parameters and frequency of leachate monitoring was developed based on prior experience gained at Yolo County during the operation of the pilot-scale project. A complete list of leachate monitoring parameters and frequencies can be found in Table 3 of the FPA, which is located in Appendix F.

2.6.2 Landfill Gas

For field-testing, landfill gas composition and flow were measured from the wellheads utilizing a GEM-500, and then later a GEM-2000 combustible gas meter (CES LANDTEC, Colton, CA). The GEM-500 and GEM-2000 are capable of measuring methane (CH_4) (either as a percent by volume or percent of the lower explosive limit), carbon dioxide (CO_2), and oxygen (O_2). A reading for balance gas was also provided, which was assumed to be nitrogen. Gas flow was measured by differential pressure across an orifice plate for both the northeast anaerobic and southeast aerobic cells, and with a 1/8-in pitot tube (Dwyer Instruments Inc., Michigan City, IN) for the west-side cell. A thermal gas flow meter installed in the main header pipelines on each bioreactor cell recorded the total flow and flow rate from each cell (8240MP (northeast cell) and 8840MP (southeast and west-side), Eldridge Products, Inc., Monterey, CA). The meters were calibrated for landfill gas and automatically corrected for temperature. Field-testing was performed on a weekly basis for both the northeast and west-side anaerobic cells, and the southeast aerobic cell.

Laboratory testing was performed quarterly with gas sampled using summa type canisters from the main header line. The following parameters were tested: fixed gases using Method CFR60A EPA 3C for methane, carbon dioxide, carbon monoxide, oxygen, nitrogen, Method EPA 15/16 for sulfur compounds, Method CFR60 EPA 25C Modified for non methane organic compounds (NMOC), and Method EPA-2 TO-15 for VOC. A complete list of LFG monitoring parameters and frequencies can be found in Table 3 of the FPA, which is located in Appendix F.

2.6.2.1 Biofilter fugitive emission testing

An issue of regulatory and other interest is how to accomplish the abatement of methane that can be emitted in fugitive gas from landfill operations. Of greatest relevance here is methane present in the gas emitted to the atmosphere from aerobic bioreactors. This is because the decomposition of waste in aerobic landfills has turned out to be, in significant part, anaerobic, and the exit gas contains a substantial quantity of methane.

One approach with promise is biofiltration. Gas is passed through a matrix, very often compost, supporting bacteria that can metabolize and remove undesired organic components such as methane in the gas. This is an accepted technique for removal of odorants and pollutants from exit gases from processes such as wastewater processing and industrial processes.

A biofilter was constructed in order to treat and further reduce methane content of the gas emitted from the 15,000-ton aerobic bioreactor cell. In summary, the biofilter consisted of a pile of compost about 5 ft deep and two areas each 2,000 ft^2 in surface area. Total biofilter volume was about 20,000 ft^3. The biofilter was moistened with surface sprinklers and buffered with limestone. The exit gas stream from the aerobic bioreactor was distributed into the base layers of the biofilter and exited through the top. Gas introduction was via perforated piping designed in accordance with recommendations from Perry's Chemical Engineers' Handbook (2000), to ensure uniform flux and distribution of gas being treated over the biofilter footprint. The design was such that the retention time of gas within the biofilter was about 15 min. (Residence time depends on porosity and depth, which changed slowly with time.) A simplified schematic is shown below in Figure 3.

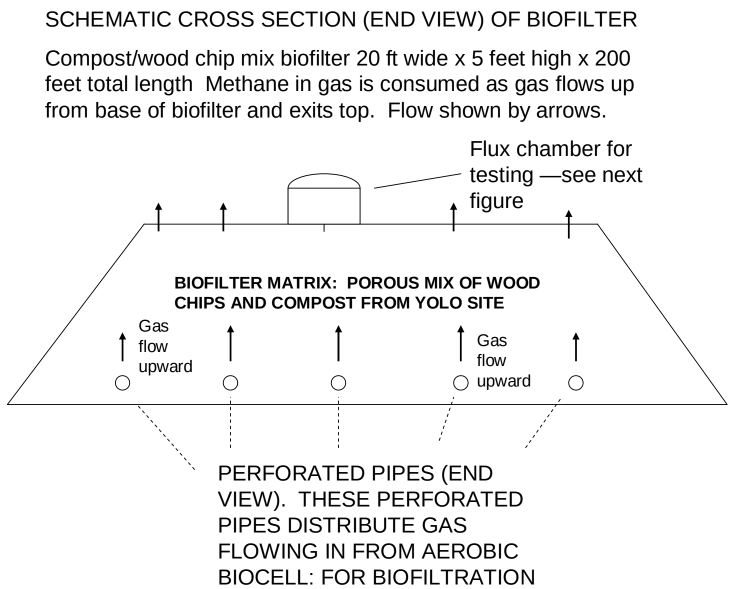


Figure 3. Typical biofilter cross-section

The testing of the efficiency of the biofilter was straightforward in principle. The efficiency was determined from the loss in methane from gas passing through the biofilter, by measuring the methane reduction in the exit gas compared to its concentration in the entrance gas. The primary testing method used and intended as definitive was that specified by the California Integrated Waste Management Board. This method used a flux chamber placed over the surface of the waste as shown in Figure 4. A flux chamber is lowered with edges sunk into the surface whose flux is to be tested. Pure sweep air was introduced into the flux chamber from a cylinder, at a rate, Q, that is several-fold (preferably 5 times or more) greater than the flux from the surface. The surface flux from the biofilter due to (about) 1,100 CFM blower air entering the nearly 5,000-ft^2 biofilter was about 2.9 in/min (7.5 cm/min by an on-the spot calculation). Air was introduced at a rate several times the surface flux, Q. See Appendix F for a detailed report.

This test procedure did not give results that looked sensible. The methane in the exit gas, as determined by the flux chamber method, exceeded the input to the biofilter. This result was clearly not possible. A composition test was also run on the compost to determine if low nutrient levels could account for apparently low conversion. Nitrogen levels were found to be low. Other potential reasons for the puzzling flux box test results are discussed later in section 3.6.7.

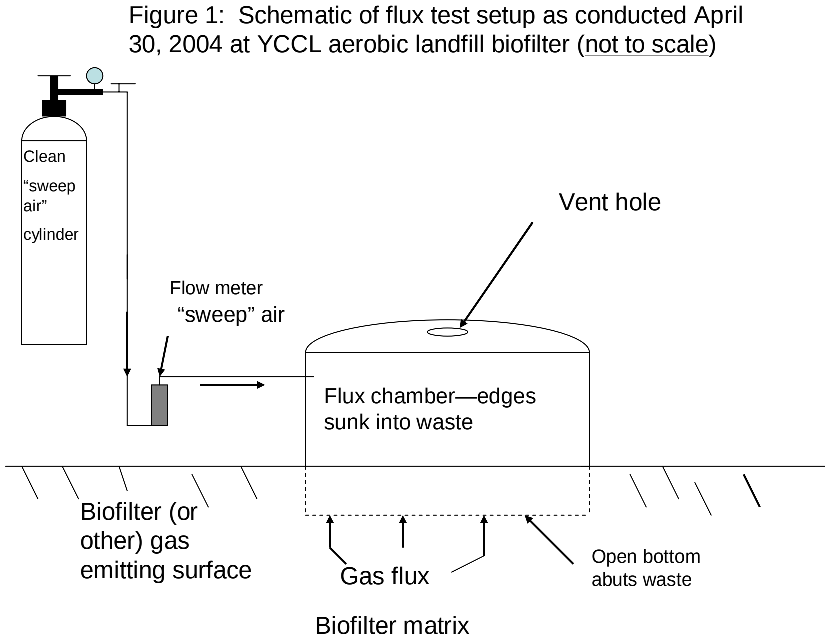


Figure 4. Flux test setup

Instead, test results that made more sense than flux box tests were those using Yolo County's own data obtained from the GEM methane meter. The methane meter showed concentrations of methane of over 2% in the header entering the injection line, and exit methane concentrations closer to 1%. The protocol was as follows:

Initial (early morning) tests on April 30, 2004. Using the GEM 500, the methane concentration in the header (inlet) pipe was measured. At the time of initial measurement, around 8 AM, the concentration was 2.5%. The subsurface readings of the GEM, over 1 ft down from the top or side surface of the biofilter, were within measurement accuracy possible, 2% by volume of the measurements. These measurements were conducted at three points considered representative, along the long surface of the biofilter. The GEM readings implied that the header was introducing about 2.5% methane gas into the biofilter. With over 2% methane in the gas 1 ft beneath the surface, (having traveled up over 80% of the way to the top of the biofilter) the biofilter would appear to be abating less methane than desired, probably under 20%,

$$= \frac{(2.5\% - 2.0\%)}{2.5\%} \qquad (1)$$

=20%.

Notes showed that later, at about 11 AM, a concentration of 1.1% methane was measured at 1 ft subsurface in the biofilter at measuring stations along the length of the biofilter. Given unchanged inlet concentration, this would imply that the abatement was more effective, from

2.5% down to 1.1%, or abating about half of the methane in the gas from the bioreactor in the later measurements. However, the results must be regarded as preliminary. Some of the variability in results was undoubtedly attributable to early startup status, after only a few days of exposure to exit gas from the aerobic bioreactor. Another source of variation was that temperature varied through the course of testing. Other sources of uncertainty included high biofilter porosity and air intrusion, which are discussed in section 3.6.6. A lessons-learned review has been carried out and approaches to better testing are planned as discussed in section 3.6.7.

Results of the three laboratory tests on liquid samples from the site, gas analysis, and a sample of the compost are presented in Appendix F. The laboratory test of the biofilter matrix showed that nitrogen-to-carbon ratio was low, and thus nitrogen may have been a limiting nutrient that could have been increased.

2.6.3 Waste Solids Sampling

Waste samples were collected prior to liquid addition and annually following liquid addition in each of the cells. The intent was to measure initially what the methane potential of the waste was and then, following liquid addition, to measure the progress of decomposition. The amount of samples to be collected was primarily based on cost. To get a statistically significant number of samples given the sizes of the bioreactor cells would have been extremely costly, and thus it was decided only limited sampling would occur.

Samples were sent to North Carolina State University (NCSU) for analysis to determine the amount of decomposition possible under accelerated anaerobic conditions.

Sampling was performed by drilling a bore using a 2-ft diameter solid stem auger. Samples were collected roughly at every 1.5-m (5-ft) vertical interval. However, there were times when the refuse began to fill in the hole during drilling, so there was the possibility of some commingling of the waste.

Excavated refuse was placed on a sheet of geomembrane liner and then multiple grab samples were collected from each pile for field measurement of pH and collection for laboratory analysis. Waste samples were placed in plastic bags that were packed in 113-L (30-gal) plastic drums for overnight shipment to the environmental engineering laboratory at NCSU. Once received at NCSU, samples were stored at 4°C until they were shredded with a slow-speed, high-torque shredder. After shredding, samples were stored at 4°C until moisture analysis by drying to constant weight at 65°C was performed.

Once samples were dried, they were analyzed for the concentrations of cellulose, hemicellulose, lignin, volatile solids (VS), and BMP. Cellulose and hemicellulose represent the major degradable components of refuse. In contrast, lignin is essentially recalcitrant under methanogenic conditions (Colberg 1988). Thus, its concentration will increase as cellulose and hemicellulose decompose. The BMP assay measures the methane potential of a sample under optimal conditions. Thus, the BMP decreases as refuse decomposition proceeds.

2.7 Surface Emissions

Under current federal guidelines (40 CFR 60.752), landfills exceeding a specific size must monitor for methane surface emissions and any reading in excess of 500 parts per million (ppm) requires corrective action to be taken. The Yolo County Central Landfill is not currently required to test for methane surface emissions, however, as part of the FPA, the County has proposed to conduct quarterly surface scans to demonstrate the emissions from a controlled bioreactor landfill.

Methane emissions were monitored with a TVA-1000 Flame Ionization Detector (FID)/Photo Ionization Detector (PID) or similar instrument rented from Total Safety Inc. (Houston, TX). Under the FID setting, the TVA-1000 measures total organic compounds (measured as methane) in air in the parts per million and has a range of 1 to 10,000 ppm and an accuracy of plus or minus 25% of the reading or 2.5 ppm, whichever is greater.

Monitoring methods and procedures were conducted in conformance with 40 CFR 60.755, with the exception that a closer (more rigorous) monitoring traverse was utilized. Methane surface concentrations were monitored between five and ten centimeters above the surface cover along the perimeter of each cell and along a pattern that traverses the landfill at 15-m intervals (by comparison, 40 CFR 60.754 requires the traverse to be conducted at 30-m intervals). Background methane readings were taken 30 m upwind and 30 m downwind of the cell perimeter. Wind speed, wind direction, and air temperature were recorded by a Kestrel 2000 hand held meter at the time and location of the surface scans or obtained from the Davis weather station of the California Irrigation Management Information System (CIMIS). Barometric pressure was obtained from CIMIS and was the average barometric pressure of that day.

2.8 Liquid Addition and Pumping System

A liquid pumping system was designed for the addition, recirculation, and removal of liquid. A multiple pump system was used for both the northeast and west-side anaerobic bioreactors to allow for continued operation should one of the pumps fail, whereas a single pump was used for the southeast aerobic cell. Reliable operation of the pumps installed in the leachate collection sumps was critical to ensure no liquid build-up on the primary liner system. The operation of each of the pumps and their associate flow meters was linked to the SCADA system.

Within each leachate collection sump, two separate pumps were used. Each of the pumps was conservatively designed to remove twice the amount of liquid anticipated by each bioreactor cell. Under normal operation, the pumps were programmed for an alternating cycle to maintain similar duty cycles. However, if leachate flows increased above the capability of one pump, the second pump would automatically start to allow the rapid draining of the leachate collection sump.

The leachate addition pumps are located just to the south of the bioreactor cells at the leachate surface impoundments (leachate ponds). The leachate ponds were constructed several years ago to contain all of the leachate generated at the YCCL. As part of the original design and construction of these leachate ponds, a series of pumps and sprinkler emitters were installed to allow the evaporation of stored leachate. During the design of the bioreactor cells, these evaporation pumps were evaluated to determine if they would be adequate for providing supplemental liquid to the cells. The pumps flow and pressure capabilities were determined to be ideal for liquid addition, and thus were employed in the bioreactor project.

The injection system was designed for maximum leachate distribution by incorporating horizontal injection lines within each lift of waste in the northeast and southeast cells, and only between lifts 2 and 3, and 3 and 4 in the west-side cell Injection lines were spaced every 40 feet within each lift of waste with an additional line installed around the perimeter of the top deck of the module. Each injection lateral was connected to a 4-inch-diameter HDPE injection header. See Appendix D for drawings of the leachate injection lines.

Field tests were performed on the leachate injection laterals using one of the recirculation pumps and 3/32-in diameter holes. Based on these tests, the average flow rate per hole was approximately 1 gpm. In practice, actual flow rates achieved in individual laterals varied significantly and were sometimes significantly less than the original design values. The discrepancy between the design and actual achieved flow rates could be due to the backpressure exerted by the gravel and tires that were placed over the pipe or clogging of the holes with sediment. On several occasions the injection laterals were flushed, which did increase the flow substantially but still did not increase the flow rate to the original design value. It is possible that the flushing did dislodge some sediment, but some particles remained lodged in the perforations (holes drilled as described above) in the lateral injection line. Following this experience, hole diameter was increased to 1/8 or 1/4 in and spacing was decreased to 10 ft from spacing of 20 ft in the upper lifts of the west 6-acre cell.

An additional test was performed to determine the durability of the HDPE pipe under waste loading. To simulate waste conditions, a test pad was constructed with roughly 6 inches of greenwaste alternative daily cover (ADC) as bedding. A section of pipe was then covered with 2 ft of shredded tires and a D-8 size dozer was left on top for approximately 72 hours. The dozer was then removed and upon visual inspection, two slight depressions were observed on the sections of pipe that were directly under the tracks of the dozer. However, no other cracks or deflections were seen on the rest of the pipe. Calculations using Driscopipe Design software also confirmed that the HDPE pipe was acceptable for use under our expected waste load.

Throughout the course of the project, injection laterals have been periodically flushed (which is possible because the laterals extend completely through the waste) and to-date, all of the laterals remain functional and have not crushed.

Existing pumps and storage ponds were utilized for the addition of liquid to the cells. Construction of the leachate storage ponds (designated Waste Management Unit H (WMU H)) and a pumping system originally designed to evaporate leachate was completed in 1999. Subsequently, during the installation of the surface liners over each of the cells, a 4-in diameter HDPE header line was installed linking the leachate ponds to the injection laterals.

As-built drawings of the liquid pumping systems are located in Appendix D.

2.8.1 Horizontal Liquid Injection Lines

For the northeast 3.5-acre cell, horizontal liquid injection lines were installed in each lift of waste. Injection lines within the waste (between lifts 1 and 2, 2 and 3, 3 and 4) were placed approximately every 40 ft. Injection lines installed on top of lift 4 were installed every 25 ft, with an additional injection line following the perimeter of the top deck. Each injection line consisted of a 1.25-in diameter HDPE pipe placed horizontally (north to south), which extended completely through the waste. Each line was perforated by drilling a 3/32-in hole every 20 ft. A total of 8,130 ft of piping was installed with a total of 342 injection holes.

For the west 6-acre cell, horizontal liquid injection lines were installed between lifts 2 and 3, and 3 and 4 approximately every 40 ft. In addition, three injection lines were installed on top of lift 4, spaced every 25 ft. The pipes were placed horizontally (east to west), which extended completely through the waste. Each injection line was perforated by drilling 1/8 or 3/32-in holes every 10 or 20 ft (depending on which line). A total of 7,185 ft of injection piping was installed with a total of 321 injection holes.

Horizontal liquid injection lines in the southeast aerobic cell were also installed in each lift of waste. Injection lines within the waste (between lifts 1 and 2, 2 and 3) were placed horizontally (north to south) every 20 ft. Injection lines on top of lift 3 were placed east to west every 20 ft. Various combinations of 1¼-in-diameter chlorinated polyvinyl chloride (CPVC) and 1¼-in-diameter HDPE pipe were installed and perforated with 3/32–in-diameter holes spaced every 10 ft. Because of the elevated temperatures expected in the aerobic cell, CPVC was installed at selected locations as a redundancy in the event the HDPE piping fails failed (CPVC is rated for service at temperatures up to 200°F, however it is was approximately 4 times as expensive). A total of 4,780 ft of injection piping was installed with a total of 326 injection holes.

The area to receive the injection lines were first graded and then bedded with greenwaste to create a relatively smooth surface on which to install the lines. The lines were then installed and snaked to allow for future settlement. Injection holes were drilled in the pipe and each hole was covered with pea gravel to help prevent clogging. Finally, the line was covered with shredded tires to protect it from waste placement (as well as facilitate landfill gas collection).

Each of the injection laterals was connected to a 4-in-diameter HDPE injection header. For the southeast aerobic and northeast anaerobic cells, flow was controlled with solenoid valves. However, the solenoid valves in the northeast cell were removed due to leaks at the valves as well as the mechanical saddle connections between the laterals and the header (discussed further in section 4). For the west-side cell, flow was controlled through manual valves and individual rates and the total were monitored at each lateral with a meter. Each of the cells has a flow meter to monitor the total flow into the cells.

As-built drawings of the liquid injection lines are located in Appendix D.

2.9 Landfill Gas Collection and Removal System

A landfill gas LFG collection system was designed to enable maximum gas recovery from the bioreactor cells. The gas collection system incorporated horizontal LFG collection lines between each lift of waste and directly under the surface liner. LFG collection lines consisted of various combinations of alternating 4 and 6-in diameter schedule-80 PVC pipe as well as several variations of corrugated HDPE pipe. In each case, shredded tires were used as the permeable medium. Gas collection lines between layers were spaced approximately 40 ft apart and lines directly under the surface liner were spaced at 25-ft intervals. Design drawings of the LFG system are located in Appendix D.

Sizing of the main header line for each of the cells was done based on the following assumptions:

- The minimum required vacuum at well was 10 inches of water.

- The maximum available vacuum was 25 inches of water for the northeast cell, 27.5 inches of water for the west-side cell (which is roughly half the actual available vacuum from gas-to-energy facility).
- The maximum flow rates expected from each of the cells were proportional to the original pilot-scale project. This corresponded to a design flow rate for the northeast cell of 350 CFM, west-side cell of 831 CFM.

The results of the sizing analysis indicated that a 6-in-diameter header line would be required for the northeast cell and a combination of an 8-in and 6-in pipe would meet the requirements of the west-side cell.

Additional design constraints and considerations included the use of selected anchorage points and expansion fittings to allow movement of the pipe due to thermal expansion and contraction. In addition, the piping layout was designed to allow any condensate to drain back into the landfill or towards the gas-to-energy facility, thus there was no need for condensate sumps.

The bioreactor LFG removal system was connected to the existing gas collection network at the landfill. The connection point was located at the southwest corner of the west-side cell. From that point, gas was conveyed a short distance to the gas-to-energy facility.

Each LFG collection line was connected to an LFG collection header that conveyed the gas to the on-site LFG-to-energy facility (Image 3). Each LFG collection line incorporated a valve capable of controlling flow and a port for monitoring gas composition, temperature, pressure, and flow rate.

The gas collection system associated with the northeast cell was constructed concurrently with the installation of the surface cover system by the same contractor. Construction occurred during the fall of 2001.

The gas collection system associated with the west-side cell was completed by Yolo County staff following the installation of the surface cover system in December 2002.

The gas collection system for the aerobic cell was designed such that gas could be collected and routed to the gas-to-energy facility (if operated anaerobically) or collected through the use of a separate blower and routed to a biofilter for odor control (if operated aerobically). The aerobic blower station and main header collection pipe was designed to operate at approximately 1000 scfm with a suction vacuum of 90 inches of water and a discharge pressure of 10 inches of water. Construction of the blower station was completed in June 2003 (Appendix C), and the biofilter was completed in September 2003.

As-built drawings of the gas collection system are located in Appendix D.

Image 3. LFG collection lines connected to the main header on the west 6-acre cell.

2.9.1 Horizontal Landfill Gas Collection System

For the northeast cell, horizontal LFG collection lines were installed between each lift of waste and directly under the reinforced polypropylene geomembrane (RPP) geomembrane cover. LFG collection lines consisted of various combinations of alternating 4 and 6-in–diameter, schedule-80 PVC pipe as well as several variations of corrugated HDPE pipe. A total of sixteen LFG collection lines were installed.

For the west-side cell, LFG collection lines were installed between lifts 2 and 3, 3 and 4, and on top of lift 4 in the cell. The LFG collection lines consisted of various combinations of alternating 4 and 6-in diameter schedule-80 and schedule-40 PVC pipe, as well as several variations of corrugated metal pipe and electrical conduit. A total of eighteen LFG collection lines were installed.

The southeast aerobic cell air collection lines consisted of various combinations of alternating 4 and 6–inch-diameter CPVC pipe and 6 and 8–in-diameter corrugated metal pipe. A total of 11 horizontal air collection lines were installed.

Each air collection line was connected to a 12-in-diameter air collection header that conveyed the gas to an on-site blower and biofilter. Each air collection line incorporated a pre-manufactured wellhead capable of controlling flow and monitoring flow rate, temperature and pressure.

A summary of gas collection lines for the northeast, west-side, and southeast cells are provided in Appendix A, Tables 9 through 11. As-built drawings are located in Appendix D.

2.10 Surface Liner Cover System

A final cover system for the northeast and west-side bioreactor cell was designed to allow for maximum landfill gas recovery and emissions control. Yolo County retained the services of Vector Engineering (Vector) to design the surface membrane covers for each of the bioreactor cells. A complete copy of Vector's design report is included in Appendix E.

Based on the life expectancy of the project, it was determined that the surface liner materials would be exposed for at least 5 years. The selected liner material must be able to withstand ultraviolet (UV) exposure as well as other climatic and operational conditions such as wind uplift, rain, temperature fluctuations, foot traffic, and billowing of off-gases. Based on the findings, Vector recommended a 36-mil RPP as the preferred choice for an exposed geomembrane cover (Vector 2001). Reinforced polypropylene offered distinct advantages over the other potential material including long service life (a 20-yr warranty was obtained), superior strength due to the nylon reinforcement, and low thermal expansion and contraction.

Because the west-side cell was built following the northeast cell, experience from the northeast cell determined that a more cost effective geomembrane would be sufficient. Thus, a 40-mil LLDPE geomembrane material was selected for the west-side cell.

Each of the surface covers was designed to incorporate a series of anchor trenches at the top and bottom of the cells in addition to a surface ballast system (ropes and sandbags) to ensure the stability of the liner against a design wind speed of 90 miles per hour (mph).

Since the operation of an aerobic bioreactor at the Yolo County Central Landfill was first considered, two methods of air management for oxygen delivery have been discussed. One method was to push air into the landfill and the other was to apply a vacuum and draw air through the landfill. Both methods have advantages and disadvantages. However, Yolo County decided that the best alternative was to leave the aerobic cell covered with soil and greenwaste (shredded yard waste), but without an impermeable geomembrane, so that air could be drawn through the waste by applying a vacuum. In this way, air will enter through the cell surface and migrate to horizontal pipelines to which a vacuum is applied. Alternate operations plans could include using some of the installed pipelines as vents and others for vacuum.

Yolo County had intended to cover the aerobic cell with an exposed geomembrane with a biofilter at the top of the cell to provide some treatment of the off-gas. However, the weight of the geomembrane that would have been placed on the aerobic cell along with the weight of a sandbag surface ballast system would result in a pressure equivalent to only 0.17 inches of water. Calculations indicated that the required pressure present in the cell to force the air through the waste, to the top of the cell, and through the biofilter would result in a great deal of ballooning of the surface liner. Additionally, the expected high settlement rate would create a great deal of maintenance difficulties for the geomembrane surface liner.

Yolo County developed a design for a geomembrane surface liner for the aerobic cell and advertised for bids on the construction. The bids received were very expensive and not within the budget of the project. As a result of both the technical and economic difficulties encountered, it was decided that leaving the aerobic cell without a geomembrane liner was the preferred approach.

2.11 Landfill Slope Stability Analysis

Vector Engineering performed the Landfill slope stability analysis. Stability was modeled using the program PCSTABL5M for a saturated waste density of 85 lb/ft^3. Results of the analysis indicated that the slopes of the bioreactor cells could be constructed with up to a 2-to-1 (horizontal to vertical) slope and still have a factor of safety of 1.4. A complete copy of the stability report is included in Appendix G.

2.12 Aerobic Cell Biofilter

Two separate biofilters were constructed, each approximately 100 ft long and 20 ft wide. Piping to convey the aerobic cell gas was installed directly on the biofilter base, which was composed of approximately 1 ft of wood chips. Two 1-ft lifts of biofilter media, composed of approximately six parts wood chips to one part compost, were placed above the base. Between each of these lifts, 10 temperature sensors and 10 moisture sensors were installed. A final 2-ft lift of biofilter media was placed on top the biofilter. Limestone was sprinkled between each lift as a buffering agent to balance the pH of the biofilter media, which will tend to become more acidic during operation.

2.13 Quality Assurance Procedures

Quality assurance procedures are necessary for maintaining the integrity of the data. All data were obtained and analyzed following strict guidelines discussed in the following sections.

2.13.1 Laboratory QA/QC and Instrument Calibration

Gas and leachate laboratory analyses are currently performed by Sequoia Analytical and were previously performed by Sevren Trent Laboratory. A quality assurance program was developed by the laboratory, which was designed to ensure that the data produced conformed to the standards set by the state and/or federal regulations. Important documentation of the samples from their collection to their analysis is achieved through the Chain-of-Custody form, which remains with the sample throughout the process. Sample handling, analytical methods, and instrument calibration are discussed in their assurance program manual, which can be found at the following link, http://www.sequoialabs.com/Content/Sequoia-QAM.pdf.

2.13.2 Field QA/QC and Instrument Calibration

Field quality assurance/quality control (QA/QC) and instrument calibration for all environmental monitoring of leachate followed protocol outlined in the Yolo County Division of Integrated Waste Management, Sampling and Analysis Procedures for Water Quality Monitoring.

Before each use, the GEM 500 (or GEM 2000) was field calibrated following the instructions outlined by the manufacturer. Calibrations were documented and kept at the same storage facility as the equipment. In an event an odd (defined as values outside the normal range seen) gas reading was measured, the instrument was recalibrated. In addition, the GEM was also annually sent back to the manufacturer for factory recalibration.

Prior to shipment of the TVA-1000, Total Safety, Inc. calibrated their rental equipment. No field calibration of the equipment was necessary, and readings were taken following the instructions manual accompanying it.

2.13.3 Record Management

All data collected for the project were stored on the main server for Yolo County, Integrated Waste Management. This is to ensure no loss of data since backup systems for the server were always active.

Data collected using the SCADA system were recorded onto two computers; one was located at the landfill and the other at the Woodland office. Data were downloaded from the SCADA files and managed in Excel. This process was facilitated by a software program known as Report Builder, which allowed for easy transfer of the data.

Weekly gas field readings were downloaded from the GEM 500 (or GEM 2000) and saved onto the computer at the landfill. A copy was saved onto a 3.5-in floppy and downloaded onto the computer at the Woodland office, where it was then integrated into a main Excel spreadsheet created for gas readings for each of the bioreactor cells.

Leachate field readings were manually recorded and entered into the main Excel spreadsheet for leachate. Laboratory analysis data obtained from the laboratory were also manually entered into the spreadsheet. All leachate data entered were inspected for errors by Yolo County staff. A main database known as Adept was also used for organizing and validating all leachate data.

Surface emission data were directly downloaded from the equipment and stored on the computer at the Woodland office.

3 PROJECT RESULTS AND DISCUSSION

3.1 Tonnage, Composition, and Compaction

Wastes accepted by the YCCL include residential, commercial, industrial, demolition, agricultural, dewatered sewage sludge, grits and screenings, treated medical waste, non-friable asbestos, inerts, and shredded tires. An itemized list of waste types and amounts placed in each of the bioreactor cells can be found in Appendix A, Table 12. Waste placement commenced in the northeast 3.5-acre bioreactor on January 13, 2001 and was completed on August 3, 2001. Waste placement commenced in the west 6-acre bioreactor on March 8, 2001 and was completed on August 31, 2002.

Table 1 below provides a summary of the amount of waste placed in each cell, along with the initial waste density and the effective waste density as of the last complete topographic survey conducted on January 28, 2004. It was the intent of this project to test bioreactor operation at a field-scale level and as such, typical standard of practice procedures were used to compact the waste. Waste were placed in loose lifts not exceeding 2 ft with either a Caterpillar D-7 or D-8 dozer, and then was compacted with 3 to 5 passes for the two anaerobic cells, and 1 to 2 passes for the aerobic cell, using a Caterpillar 826C sheep foot compactor.

As presented in Table 1 below, the initial density of the northeast 3.5-acre cell was less than the west 6-acre cell, although the same waste filling procedures were utilized in both. The lower initial density of the 3.5-acre cell was most likely due to the geometry of the cell that incorporated more side slopes (which are harder to compact) to interior area than did the west 6-acre cell. This lower initial density may have added in the more effective liquid permeation of the 3.5-acre cell. Wastes accepted by the YCCL include residential, commercial, industrial, demolition, agricultural, dewatered sewage sludge, grits and screenings, treated medical waste, non-friable asbestos, inerts, and shredded tires. Waste placement commenced in the northeast and west-side anaerobic bioreactors on January 13, 2001 and March 8, 2001, respectively. The northeast was completed on August 3, 2001, and the west-side on August 31, 2002. Waste placement in the southeast aerobic cell occurred between August 8, 2001 and September 26, 2001.

Table 1. Summary of waste tonnage and compaction

Module	Total waste placed (tons)	Total greenwaste ADC used (tons)	Initial volume of cell (yd^3)	Initial density of waste (lbs/yd^3)	Volume of cell as of 1/28/04 survey (yd^3)	Density of waste as of 1/28/04 survey (lbs/yd^3)
Northeast anaerobic cell	65,104	11,060	132,295*	984	123,760	1052
West-side cell	166,294	27,570	324,209**	1026	315,290	1055
Southeast aerobic cell	11,942	2,169	35,529*	672	32,597	733

* Initial survey was conducted on 11/15/2002
** Initial survey was conducted on 1/16/2003

3.2 Waste Temperature Over Time

Temperatures were monitored through an array of thermistors placed throughout the waste. Thermistors respond to changes in temperature through changes in resistance with increasing temperatures corresponding to decreasing resistance. Measured resistance can be converted to temperature through a calibration equation provided by the manufacturer. Following initial installation, sensors were read manually utilizing a Model 26 III Multimeter manufactured by Fluke Corporation (Fluke Corporation, Everett, WA). Beginning in March 2002, readings were collected through the SCADA system.

The average temperature for the northeast 3.5-acre cell over time is provided in Appendix B, Figure 1. The drops and subsequent rebound in temperature (for instance Layer 3 around March 2003) is the typical response to liquid addition to that layer. Typical waste temperatures have remained between 40 and 50°C (with the exceptions of some drops corresponding to liquid addition) for the last several years. Temperatures in this range are typical of anaerobic decomposition.

The average temperature for the west 6-acre cell over time is provided in Appendix B, Figure 2. Typical waste temperatures have remained between 40 and 50°C for the last several years. Temperatures in this range are typical of anaerobic decomposition.

Both the northeast 3.5-acre and west 6-acre cell temperatures, ranging from 40-60°C in Figures 1 and 2 (Appendix B) are well above the ambient air outside the cells. Such elevated temperatures are consistent with many other bioreactor results. The temperature elevation is due to exothermic (heat-generating) biochemical reactions that take place as waste decomposition proceeds. These reactions begin during filling when there is some limited initial open-air composting and are followed by exothermic anaerobic reactions.

An important feature of the measured temperatures is their independence over time from the surrounding ambient temperature. This is a prediction of the basic heat transfer equations governing temperature loss and temperature deep within large masses of any type that are exposed to varying temperatures at their surface. These correlations predict that the interior temperatures of such large bodies will change only slowly, exactly as seen in Figures 1 and 2 (Appendix B), and do not vary significantly from lift to lift (with the major gap of 10°C at most in the northeast cell).

The rate of waste decomposition to methane is well known to be strongly temperature dependent. For example, a temperature elevation from 20 to 40°C, with all other things being equal, can in and of itself raise decomposition rates by over 3-fold. The stability of the deeper internal temperature means that methane generation perturbations due to ambient temperature fluctuations will be minimal. A uniform temperature throughout the cells will be helpful in reducing temperature related variations in methane generation within the cells.

Appendix B, Figure 3 is aerobic cell's temperature versus time plot. As presented in this plot, the temperature of the aerobic cell has generally decreased over time. This is due to the very limited aerobic operation of the cell (due to difficulties discussed in Section 3.12). If significant air were to be entrained into the waste we would expect temperatures to become elevated to within the range of 50 to 60°C.

3.3 Waste Moisture Content & Uniformity of Water

Moisture distribution within the cells was monitored through an array of moisture sensors that were installed during the waste placement phase. The majority of moisture sensors utilized were of the PVC type with a few gypsum sensors installed in layer 2 of the northeast 3.5-acre cell.

During the pilot-scale project, Yolo County conducted laboratory tests with the PVC sensors to determine the relationship between the multimeter readings and the presence of free liquid in the PVC sensor. These sensors were not designed to measure that actual moisture content of the waste but rather give an indication of moisture arrival at each location. It was determined that a meter reading of less than 40% corresponded to an absence of free liquid. A reading between 40 and 80% corresponds to the presence of free liquid in the PVC pipe but less than saturated conditions. Readings of greater than 80% indicate saturated conditions; i.e. the PVC sensor is full of liquid.

Following initial installation, sensors were read manually. In March 2002, automated data collection began with the SCADA system.

3.3.1 Northeast anaerobic cell

Since the start of full-scale liquid addition in June 2002, the average moisture levels in all layers have increased to the some free liquid or completely saturated zones as presented in Appendix B, Figure 4.

Optimum operation of a bioreactor landfill requires the moisture content of the waste be raised to near field capacity. Based on the previous pilot-scale project, the addition of 55 gallons of liquid per ton of waste resulted in greatly accelerated anaerobic activity. Through the end of October 2004, a total of 2,809,490 gal of supplemental liquid has been added to the northeast 3.5-acre cell. With a total of 65,104 tons of waste in the cell, about 43 gal/ton of waste has been added. Table 2 below provides a summary by layer for the amount of liquid added.

Table 2. Northeast cell moisture addition by layer

Layer	Amount of waste (as received tons)	Volume of liquid added (gal)	Volume of liquid added per ton (gal/ton)
1	22,984	1,119,179	48.7
2	21,935	930,876	42.4
3	14,657	516,657	35.2
4	5,528	282,888	51.2

The moisture content of the waste can be calculated with the above information and initial waste moisture data gathered from the first sampling event. From the first waste sampling event (see section 3.8), conducted on June 4-5, 2002, the initial moisture content of the waste prior to liquid addition was measured at an average of 18.37%. The simplified equation for calculating moisture content on a wet waste basis is:

$$PMC = \left(\frac{L_0 + P + LA - LCH}{M + LA + P - LCH} \right) \times 100 \qquad (2).$$

Where:

PMC = estimated potential moisture content of waste mass (%)

L_o = initial weight of water (lbs)

M = total waste mass on an as received basis (lbs)

P = total precipitation (lbs)

LA = total liquids added to the waste mass, including recirculated leachate (lbs)

LCH = total leachate collected (lbs)

Assumptions:

1. Precipitation was assumed to be zero for the northeast anaerobic cell because the waste sampling event for which L_o was based occurred after the module was covered with a geomembrane liner, thus no precipitation has entered the waste.
2. All of the leachate that has been collected from the cell was recirculated. Therefore, the term “LA-LCH” can be simplified to be only the liquid added to the cell, L.
3. Because alternative daily cover (greenwaste) was utilized in the cell and will also absorb liquid, “M” must include the mass of the waste as well as the greenwaste ADC.

Givens:

1. Total waste in the northeast cell = 65,104 tons
2. Total greenwaste ADC in northeast cell = 11,060 tons
3. Total waste + greenwaste = 76,164 tons = 152,328,000 lbs
4. Initial moisture content of waste = 18.37%
5. Initial weight of water = (152,328,000*0.1837) = 27,982,653 lbs
6. Amount of water added = 2,849,601 gal = 23,756,671 lbs

Solution:

Given the above assumptions, the equation can be simplified to:

$$PMC = \left(\frac{L_0 + L}{M + L} \right) \times 100 \qquad (3)$$

$$= \left(\frac{27{,}982{,}653 \;\; + 23{,}756{,}671}{152{,}328{,}000 + 23{,}756{,}671} \right) \times 100$$

= 29.38%.

The calculated moisture content is 29.25%, (rounded, 29.3%). Other very small corrections would be required to account for solids loss by digestion, and water loss by consumption and evaporation. At present early in operation, it is calculated that corrections for all reasons are well under 1% i.e. moisture content lies between 28 and 29%. However, corrections will become more important as conversion proceeds.

This moisture content is low compared to the results from the CEC pilot-scale cell, which by core samples (considered a reliable indicator) averaged 35%. However, the embedded sensors for the northeast 3.5-acre cell showed (Appendix B, Figure 4) that moisture reached nearly all sensors. The explanation for these low moisture uptakes in combination with good moisture distribution has been considered by the project team. First, all of the sensors were located in the tires layer right next to the leachate line. Faster moisture flow to sensors in this area compared to the rest of the waste would not be surprising. In addition, it seemed very likely that more compacted, and deeper waste would have lower interstitial pore volume than the shallower waste in the earlier pilot-scale cells. Simply put, in the full-scale cells, there were less pore volume per ton due to higher compaction. It takes less liquid per ton to fill what is likely a lower pore volume, in other words a given moisture addition “goes farther”. Landfill gas would be expected to displace liquid occupying the pore space, spreading the added liquid further. This behavior of added liquid is an important topic as it relates to how much liquid is needed, and relates to liquid addition “targets” such as required additions (for example in gallons per ton) that should be the goals for methane enhancement. Although there have been modeling efforts elsewhere by the University of Florida and Geosyntec, among others, needs for liquid are hard to model. For this project, observation of the actual liquid uptake of the waste, in gallons per ton, is valuable information that cannot be predicted by any present modeling exercise.

3.3.2 West-side anaerobic cell

Since the start of full-scale liquid addition in June 2003, the average moisture levels in all layers have increased to the "some free liquid" or "completely saturated" zones as presented in Appendix B, Figure 5. The "completely saturated" moisture content at which some free liquid just starts to drain from the waste is defined as moisture at "field capacity".

Through the end of October 2004, a total of 3,436,946 gal of supplemental liquid has been added to the west 6-acre cell. With a total of 166,294 tons of waste in the cell, about 20.7 gal/ton of waste has been added. Table 3 below provides a summary by layer for the amount of liquid added. Note that waste tonnage per lift was not tracked for the 6-acre cell; therefore volume per lift is not calculated.

Table 3. West-side cell moisture addition by layer

Layer*	Volume of liquid added (gal)
2	656,823
3	917,008
4	2,141,535

*No liquid injection piping was installed in layer 1

From the first waste sampling event (see section 3.8) conducted on June 4-5, 2002, the initial moisture content of the waste prior to liquid addition was 22.54%. The same equation and assumptions as for the northeast cell were used to calculate the potential moisture content in the west 6-acre cell. For assumption 1, though the waste sampling event for which Lo was based upon occurred prior to the module being covered with a geomembrane liner, the sampling did occur during the summer and the unit was covered that fall. In addition, the CIMIS weather database for Davis was checked and the precipitation during that time was negligible. Thus, the assumption of zero precipitation was still valid.

Givens:

1. Total waste in the west-side cell = 166,294 tons
2. Total greenwaste ADC in west-side cell = 27,570 tons
3. Total waste + greenwaste = 193,864 tons = 387,728,000 lbs
4. Initial moisture content of waste = 22.54%
5. Initial weight of water = (387,728,000*0.2254) = 87,393,891 lbs
6. Amount of water added = 3,562,414 gal = 29,710,532 lbs

Solution:

$$PMC = \left(\frac{L_0 + L}{M + L} \right) \times 100 \qquad (3)$$

$$= \left(\frac{87{,}393{,}891 \ \ + 29{,}710{,}532}{387{,}728{,}000 + 29{,}710{,}532,} \right) \times 100$$

= 28.05%.

3.3.3 Southeast aerobic cell

Since the start of full-scale liquid addition in November 2003, the average moisture levels in all layers have increased to the "some free liquid" or "completely saturated" zoned as presented in Appendix B, Figure 6.

Through the end of March 2005, a total of 322,931 gal of supplemental liquid has been added to the southeast aerobic cell. With a total of 11,942 tons of waste in the cell, about 27.0 gal/ ton of waste has been added. Table 4 below provides a summary by layer for the amount of liquid added.

Table 4. Southeast aerobic cell moisture addition by layer

Layer	Volume of liquid added (gal)
1	172,907
2	115,699
3	34,326

From the first waste sampling event (see section 3.8), conducted on June 5, 2002, the initial moisture content of the waste prior to liquid addition was measured at an average of 17.91%. Equation 3 and assumptions as for the northeast cell were used to calculate the potential moisture content in the southeast aerobic cell.

Givens:

1. Total waste in the southeast aerobic cell = 11,942 tons
2. Total greenwaste ADC in the southeast aerobic cell = 2,169 tons
3. Total waste + greenwaste = 14,111 tons = 28,222,000 lbs
4. Initial moisture content of waste = 17.91%
5. Initial weight of water = (28,222,000*0.1837) = 5,184,381 lbs
6. Amount of water added = 322,931 gal = 2,693,244 lbs

Solution:

$$PMC = \left(\frac{L_0 + L}{M + L} \right) \times 100 \qquad (3)$$

$$= \left(\frac{5{,}184{,}381 \ \ + 2{,}693{,}244}{28{,}222{,}000 + 2{,}693{,}244} \right) \times 100$$

= 25.48%.

3.3.3.1 Partitioning gas tracers

Field trials of the PGTT technology were conducted in May 2004 in the Yolo County aerobic bioreactor. The tracer gases (helium, conservative; and difluoromethane, partitioning) were injected at 104.4 L/min (Test #1) and 121.5 L/min (Test #2) through pre-existing monitoring tubes emplaced in the landfill. Gases were extracted in nearby horizontal gas collection lines, and samples collected in borosilicate glass bottles and transported to the University of Delaware for analysis. Gas chromatography was used to measure difluoromethane (DFM) (flame ionization detector) and helium (thermal conductivity detector) in gas samples. The locations of two tracer tests are shown below in Figure 5. Both tests sampled were approximately 250 ft^3 of solid waste located 10 to 17.5 ft below the topmost surface of the landfill.

Measured tracer breakthrough curves are shown for both PGTT in Figure 6. For Test #1, there was an obvious lag in the transport of DFM with respect to helium. This DFM tracer, which partitions into water, was slowed and attenuated by water in the solid waste. The lag in DFM travel and reduction in DFM peak concentration is barely perceptible in the raw data from Test #2, suggesting less water in the solid waste sampled during this tracer test.

Based on the data shown in Figure 6 and measured landfill temperatures, the water saturation in the solid waste was estimated using the mean tracer arrival times determined from the moment of analysis (Imhoff et al. 2003). For Test #1, the fraction of the pore space filled with water was 29%, while the moisture content, the mass of water divided by total wet mass of solid waste, was estimated to be 28%. To compute the moisture content, the porosity and bulk density of the solid waste were estimated to be 0.5 and 510 kg/m^3, respectively. For Test #2, the fraction of the pore space filled with water was 7.1%, while the moisture content was estimated to be 6.9%, using the same estimates for porosity and bulk density used for Test #1. Thus, the solid waste was relatively moist in the region sampled for Test #1, but much drier in the Test #2 region.

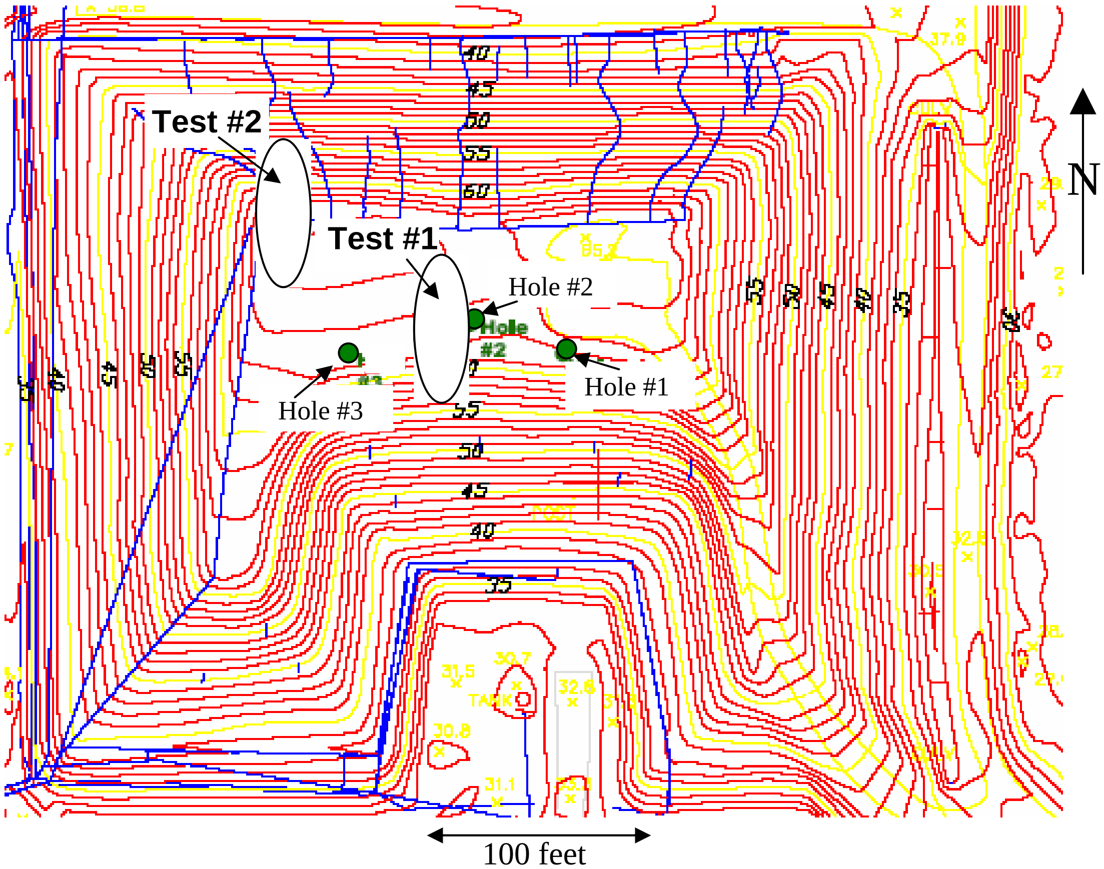


Figure 5. Plan view of Yolo County aerobic bioreactor cell. Circled regions indicate regions sampled during PGTT #1 and #2. Locations of three vertical cores (hole #1, #2, and #3) for measuring moisture content gravimetrically are also shown.

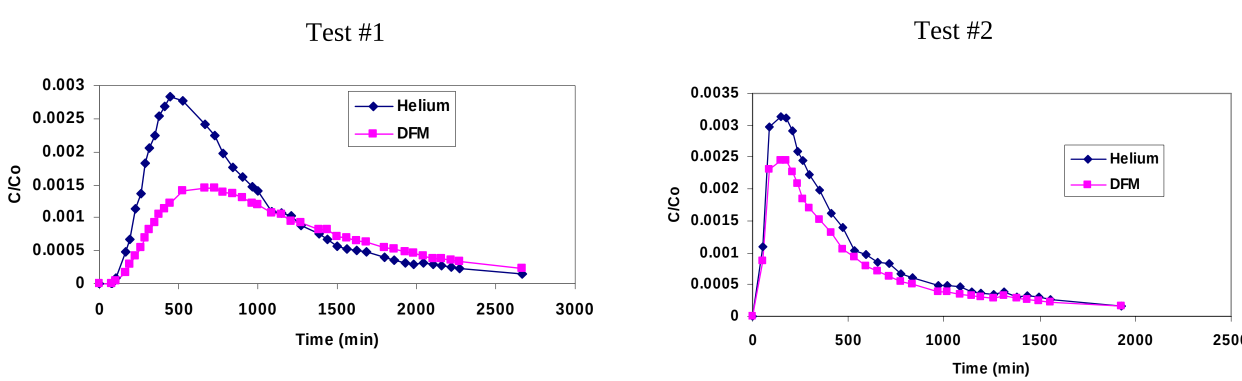


Figure 6. Tracer test results from Tests #1 and #2.

Following the PGTTs, cores were removed at three locations shown in Figure 5. Moisture contents were determined for solid waste samples collected from 10 to 15 ft below the topmost surface of the landfill, which is similar to the depth sampled by the PGTTs. The moisture contents for the solid waste sampled from these three cores at this depth were 32%, core #1; 27%, core #2; and 6%, core #3.

Because core #2 was located on the edge of the region sampled by Test #1, it was reasonable to compare core #2 results with Test #1. The moisture content from core #2 was almost identical to that from Test #1: gravimetric moisture content of 27%, core sample, versus 28%, PGTT. While Test #2 was not close to any of the three cores, it was on the west side of the bioreactor cell and was most similar in location to core #3, which was also located on the edge of the landfill. Both Test #2 and core #3 measured small moisture contents: gravimetric moisture content of 6%, core sample, versus 6.9% PGTT. Thus, the waste was not nearly as moist on the west side of the landfill as it was in the center or on the east side. The waste was also much drier than anticipated, since leachate was actively recirculated in the bioreactor before the field tests.

The variability of moisture content measured by PGTT was consistent with variability determined from three cores at the same depth. Core samples from 10 to 15-ft depth showed moisture contents varying from 6 to 32%, while the two tracer tests in different regions of the bioreactor showed moisture contents of 6.9 and 28%. Moisture contents of the cores and from PGTT were both lower on the west side of the cell. Thus, the distribution of water determined by PGTT was reasonable and was consistent with the gravimetric measurements.

3.4 Liquid Levels Over the Base Liner

To date, liquid build-up on the base liner has not been insignificant. The base liner under the bioreactor cells is continuous, however it is hydraulically separated such that leachate draining from each of the cells cannot commingle (see Section 2.1). The California Regional Water Quality Control Board (CRWQCB) has limited the liquid level over the base liner to less than the typically allowed 12 inches. If liquid levels on the base liner exceed 4 inches, the County must inspect the leachate pumps for correct operations and/or make adjustments to the injection system to reduce the level to below 4 inches. If liquid levels exceed 10 inches, liquid addition must cease. Liquid level over the aerobic liner is also monitored, however, since this is a secondary liner, no level restrictions have been imposed by the CRWQCB.

Figures 7 and 8 in Appendix B provide graphs of the liquid level over the base liner . To date, the highest leachate level recorded has been just under 2 inches in each of the cells. It, however, must be noted that only minimal leachate has been generated by the west cell and as such, the capacity of the LCRS has not truly been tested.

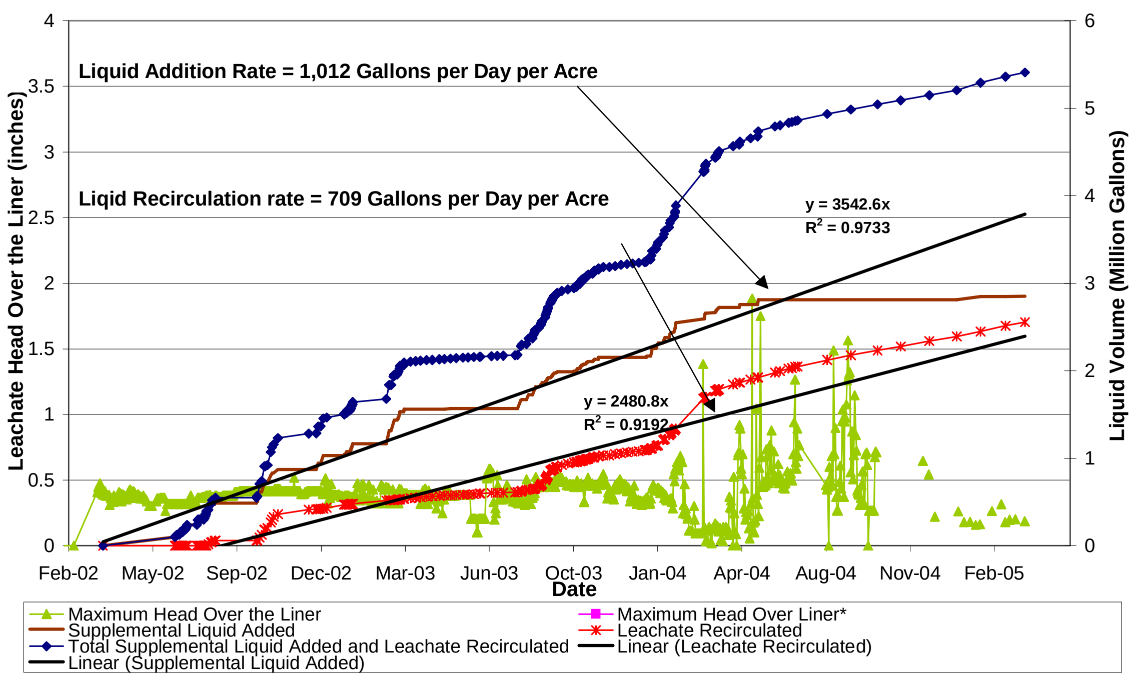
The graph of the liquid level on the aerobic liner in presented in Figure 9 of Appendix B. As presented in this graph, liquid levels on the aerobic liner have been greater than that of the primary base liner. This is attributed to two factors. First, because the aerobic liner was constructed on waste, which has a tendency to settle, the LCRS trench is likely to have settled and does not provide the same drainage capacity as when it was constructed. Secondly, a u-trap was installed in the LCRS pipe to prevent air intrusion into the cell and several instances were observed when an air lock had developed in this u-trap that prevented the pipe from draining until sufficient liquid had built up to overcome the air lock. It is suspected that the periodic peaks in liquid level observed is due to the air lock phenomenon.

In August 2004, two out of the three pressure transducers located on the base liner began indicating large, random, fluctuating pressure readings. We suspected that these pressure transducers had failed. Pressure was monitored from the tubes that were installed adjacent to the pressure transducers and was found to be stable and significantly less than the pressure transducers. The pressure transducers were attempted to be removed, however the cable that the transducers were attached broke and we were not able to remove the transducers. The County is currently looking at options to perform a video inspection of the pipe and confirm the lack of liquid buildup and cause of the cable break.

3.5 Leachate

3.5.1 Addition and Recirculation

Figure 7 below presents the cumulative leachate addition and recirculation volumes to the northeast 3.5-acre cell. Figure 10 in Appendix B presents the average daily recirculation (which is equivalent to the flow through the LCRS system). Based on the results of the original CEC pilot-scale cells, the County predicted in the FPA that the maximum leachate recirculation for the bioreactor could be as high as 20 gpm/acre. It is useful to note for reference here that this represents a liquid infiltration rate of 3 x 10^{-5} cm/sec, and obviously requires an average waste permeability of at least this. Showing workability of any infiltration rate (in terms of how well and how fast moisture distributes) also represents very useful information. Given the 3.5-acre size of the cell, this 20 gpm/acre would correspond to a maximum flow potential of 70 gpm. As presented in the graph, the average flow to-date was approximately 1,031 gal/day-acre (2.5 gpm).



In August 2004, two out of the three pressure transducers began giving erratic readings that were not supported by pressure tubes, and in October 2004, the third pressure transducer reported readings above 10 in of H20. Maximum Head Over Liner* curve was created using data from the pressure tubes.

Figure 7. Northeast anaerobic cell liquid recirculation and addition volumes

Figure 8 below presents the cumulative leachate addition and recirculation volumes to the west 6-acre cell. Figure 11 in Appendix B presents the average daily recirculation (which is equivalent to the flow through the LCRS system). Given the 6-acre size of the cell, this would correspond to a maximum flow potential of 120 gpm.

Liquid addition to the west 6-acre cell was initially begun at an aggressive rate to determine if there was an upper limit to liquid addition. During this first phase, addition averaged approximately 17,000 gal/acre-day (or 71 gpm for the entire cell). Following this initial addition, leachate seeps (i.e. liquid exiting the side slopes) were discovered along the west side of the cell in July of 2003. Leachate addition was stopped and a drainage trench was installed along the toe of the slope in the area where the seep had occurred. The function of the trench was to allow any leachate that drained down the side of the cell, a path to the Module 6D LCRS. Leachate addition was then restarted, however additional seeps appeared. Eventually, it was necessary to install a drainage trench along the entire west side of the west 6-acre cell.

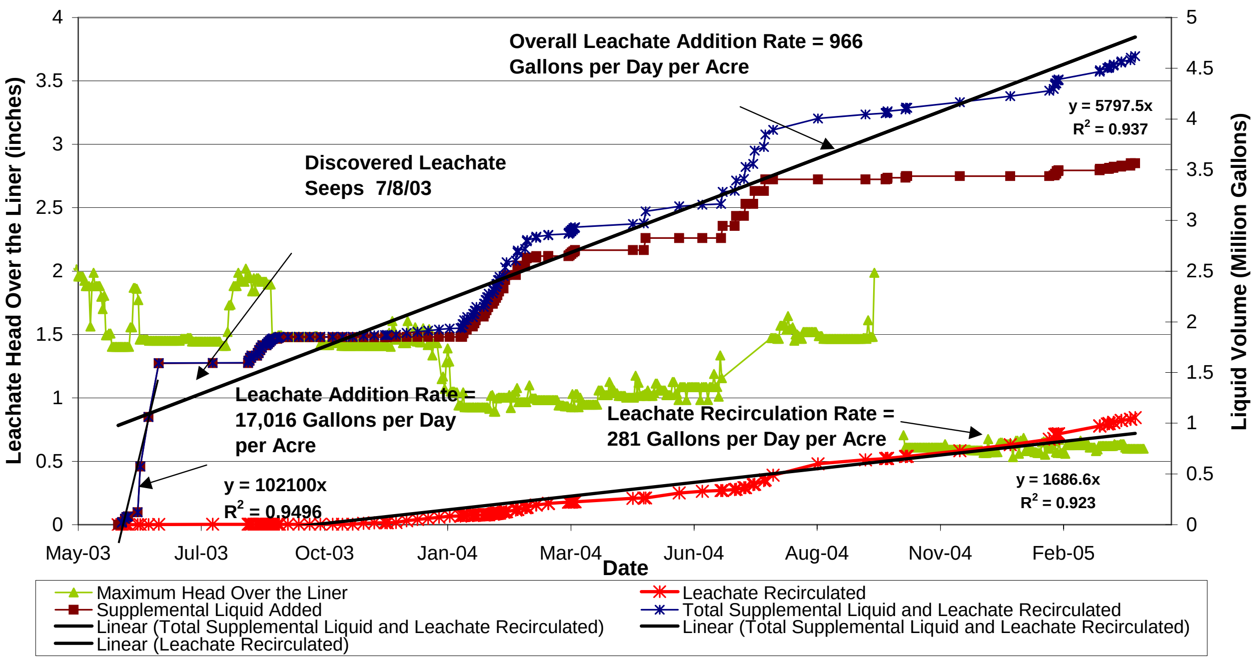
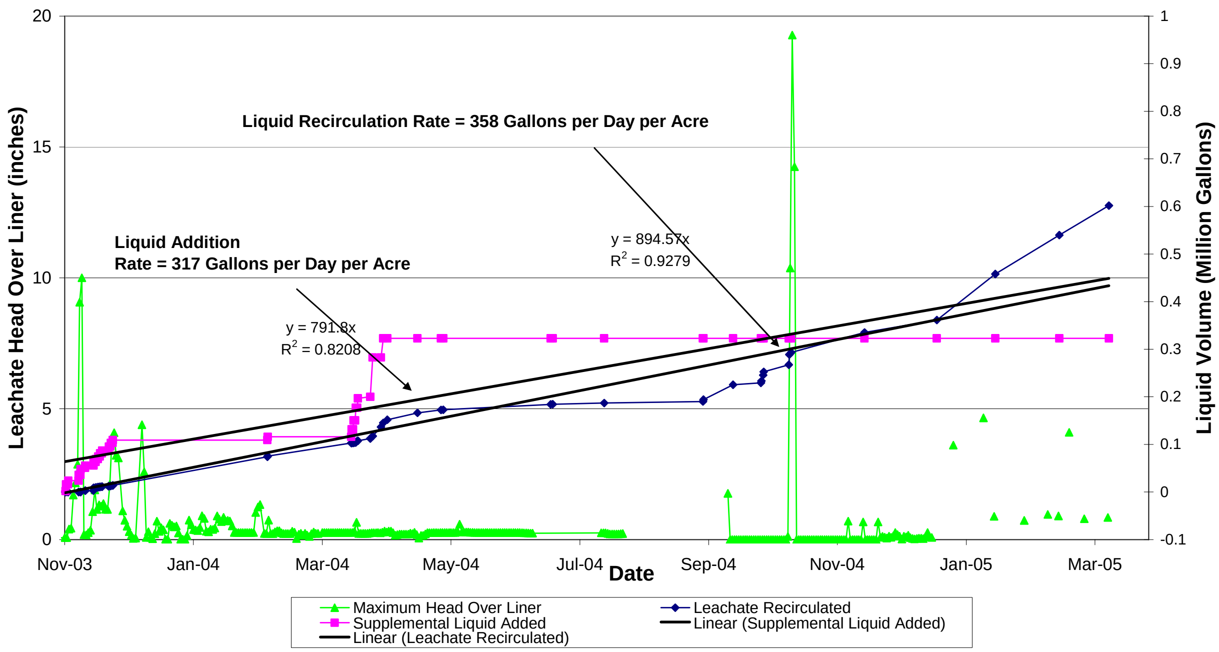


Figure 8. West-side cell liquid recirculation and addition volumes

Figure 9 below presents the cumulative leachate addition and recirculation volumes to the southeast aerobic cell. Figure 12 in Appendix B presents the average daily recirculation for the southeast aerobic cell. Given the 2.5-acre size of the southeast cell, this would correspond to a maximum flow potential of 50 gpm.



Note: In March 2004, one out of the two pressure transducers under the southeast cell began giving erratic readings that were not supported by pressure tube readings. In August 2004, both pressure transducers were removed and recalibrated. The one that was previously giving erratic readings was determined to have failed and removed from the system. In January 2005, the other sensor failed, thus maximum head over liner curve was created using pressure tube data.

Figure 9. Southeast aerobic cell liquid recirculation and addition volumes

Leachate addition and recirculation rates and volumes for the bioreactors cells have been lower than originally predicted during the development stage of the FPA. Two main factors have attributed to this, the first being remnant soil cover impeding the vertical permeability, and the second was the physical geometry of the cell and the natural tendency for horizontal permeability to be greater than vertical.

During the construction of the bioreactor cells, it was necessary to place daily cover soil in areas of traffic or where subsequent lifts of waste would not be placed for more than 7 days. Because the cover soil, which was on-site clay, would have a tendency to limit liquid movement, every attempt was made to remove or break up the soil layer prior to placement of the next lift of waste. In addition, a large wet-weather deck constructed of soil and concrete rubble was installed on top of the first lift of waste in the west 6-acre cell. This wet-weather deck was also not removed, but was broken up and incorporated into the waste.

It was hoped that the measures taken to break up the cover soil would be sufficient, however we suspect that the remains of the wet-weather deck constructed in the west 6-acre cell contributed significantly to the leachate seep problem discussed in section 4.1.1.

The other significant factor that has limited the rate at which liquid can be added was the geometry of the cells. Because of factors unique to the YCCL, the base liner for the cells was essentially installed at the existing surrounding grade of the site (rather than being an excavated pit). As a result of this, the waste cells, are in essence, an above ground pyramid. It was well established that the horizontal permeability of waste was greater than the vertical permeability and as such, the geometry of the cells lends itself to the possibility of leachate seeps. At sites where cells were excavated below ground, seeps would not be an issue because any horizontal movement of liquid would be intercepted by the sidewalls of the primary liner and would then drain to the LCRS.

3.5.2 Field Parameters (pH, EC, ORP, DO, TDS, and Temperature)

Leachate characteristics depend on the composition of waste, age of waste, rate and chemistry of water added, and the waste buffering capacity. The pH of leachate from the northeast 3.5-acre area has remained between 7.02 and 8.16 within the last year, which is considered in the optimum range. The optimum pH environment for methanogens is within the range of 6.8 to 8.5. The high pH source liquid added in this project is generally not typical of most landfills, but is rather site specific to the YCCL due to high pH of groundwater and leachate. At landfills with different source liquid characteristics, in particular buffering ability (i.e. alkalinity of liquids used), the pH of bioreactor leachate could be different.

Graphs of the leachate field parameters for the anaerobic and aerobic bioreactor cells can be found in Appendix B, Figures 13 and 15.

For both bioreactor cells, the pH at above 7.0 suggests minimal presence of organic acids, acetic, propionic and butyric acids, etc. These acids are first formed early in the breakdown of solid organic materials and are intermediates in the digestion (methane conversion) process. The acids are then consumed and converted to methane. Low acid levels and pH above 7 indicates a healthy, well functioning digestion process. A pH above 7 also means that these organic acids, which are potential leachate pollutants, are being successfully remediated.

A steadily rising leachate temperature simply reflects the transfer of heat from the waste as the leachate passes through. The leachate temperatures are much lower relative to the waste, but this is due to the contact with the cool base liner and underlying soil.

The significant dissolved oxygen levels in leachate indicated low leachate respiratory activity, likely due to low levels of aerobic organisms combined with the refractory nature of organics in the leachate. The dissolved solids and conductivity in any pre-existing liquid (like construction water) in the LCRS would be expected to be low. As liquid leachate begins to drain from the bulk of the waste, the leachate will carry with it dissolved salts and soluble solids from the waste, causing the dissolved solids and conductivity of the leachate to increase. This expected rise in dissolved solids and conductivity as a function of time can be seen in Appendix B, Figure 13. A rise in ORP was also observed (Appendix B, Figure 13).

Normally in wastewater treatment processes, the ratio of BOD_5/COD is used as a measure of wastewater biodegradability (Tchobanoglous et al. 1993). Ratios of BOD_5/COD below 0.10 are generally associated with leachate from properly decomposing landfills, and indicate that the remaining leachate soluble organics are not readily biodegradable. The ratio of BOD_5/COD for the northeast 3.5-acre cell is presented in Figure 10 below and is typical of a landfill in this phase. The BOD_5/COD ratios below 0.1 are to be expected; even when waste decomposition is not complete as is the case with the northeast 3.5-acre cell. The best available indicator, landfill gas produced, suggests that waste decomposition is proceeding in a satisfactory manner. Another important indicator, leachate pH, as noted above, likewise suggests that decomposition is proceeding in a satisfactory manner.

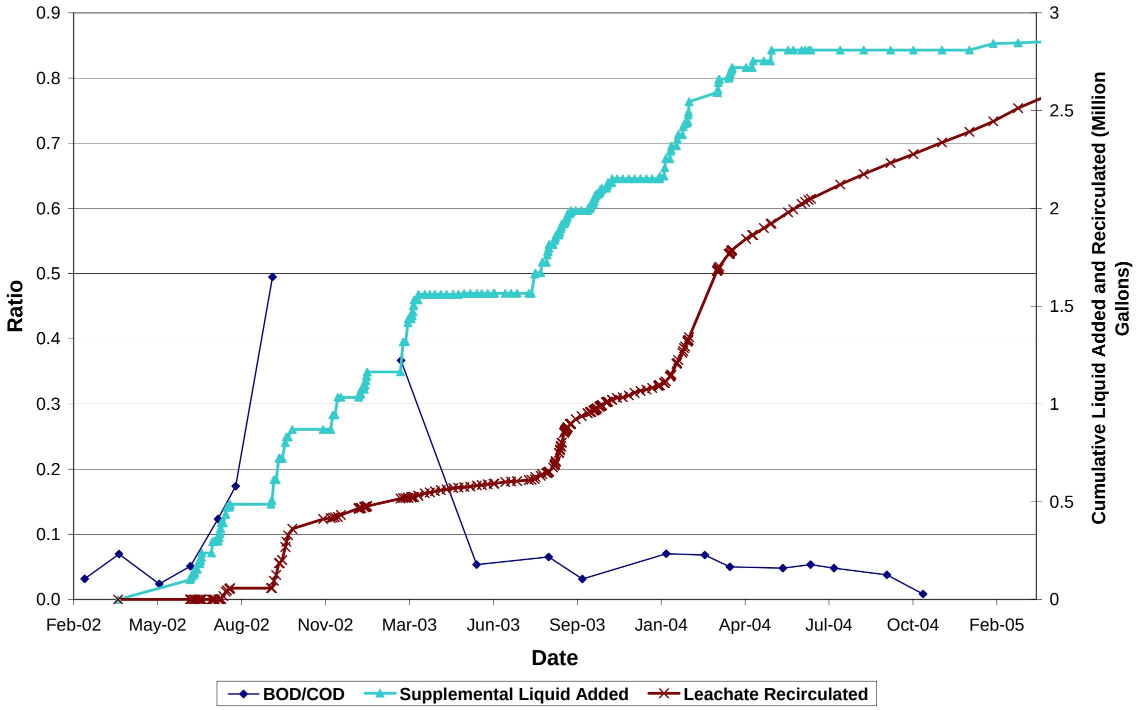


Figure 10. Northeast cell – BOD_5/COD over time

In Appendix A, Table 13, an anomaly existed for the October 17, 2002 sampling event wherein the BOD_5 value of 3,000 mg/L was higher than the COD value of 1,810 mg/L. BOD_5 values should not be higher than COD. This result was attributed to laboratory error and was excluded from our analysis.

The high biodegradability of the leachate from the northeast cell between September 2002 and March 2003 corresponds to what is a well-known process sequence that takes place in landfill, where initial high levels of organic acids are formed and consumed quickly for a period of several months. Following the initial spike, BOD_5 levels declined and stabilized between 100 and 150 mg/L, which were in the range of what was measured in the pilot-scale cell over the same time period. It is unclear the cause of the sudden increase in BOD_5 (770 mg/L) and decrease in COD (970 mg/L) in March 2005 sampling event.

To date, BOD_5 and COD levels in the west 6-acre cell have approached those recorded in the northeast 3.5-acre area. Unlike the northeast 3.5-acre area, the west 6-acre area has exhibited some large variations in BOD_5/COD ratio. In general, there typically occurs a fairly low base level of BOD_5 that is not biodegradable in leachate. In addition (as seen in Figure 11), there are transient increases in other anaerobically biodegradable components that are subsequently consumed. Typically organic acids are formed in the anaerobic decomposition process, particularly during early stages. These are variable over time in exiting leachate. Being readily degradable they will contribute to BOD_5. The net result of this can be quite variable BOD_5/COD that are not typical of long term operation. In alternate terms, amounts of fresh high-organic content leachate "breaking through" contribute to variations in BOD_5/COD. Still, the degree of variation is high. Given the still relatively early operation of the cell, we expect BOD_5/COD ratios to stabilize as waste decomposition progresses.

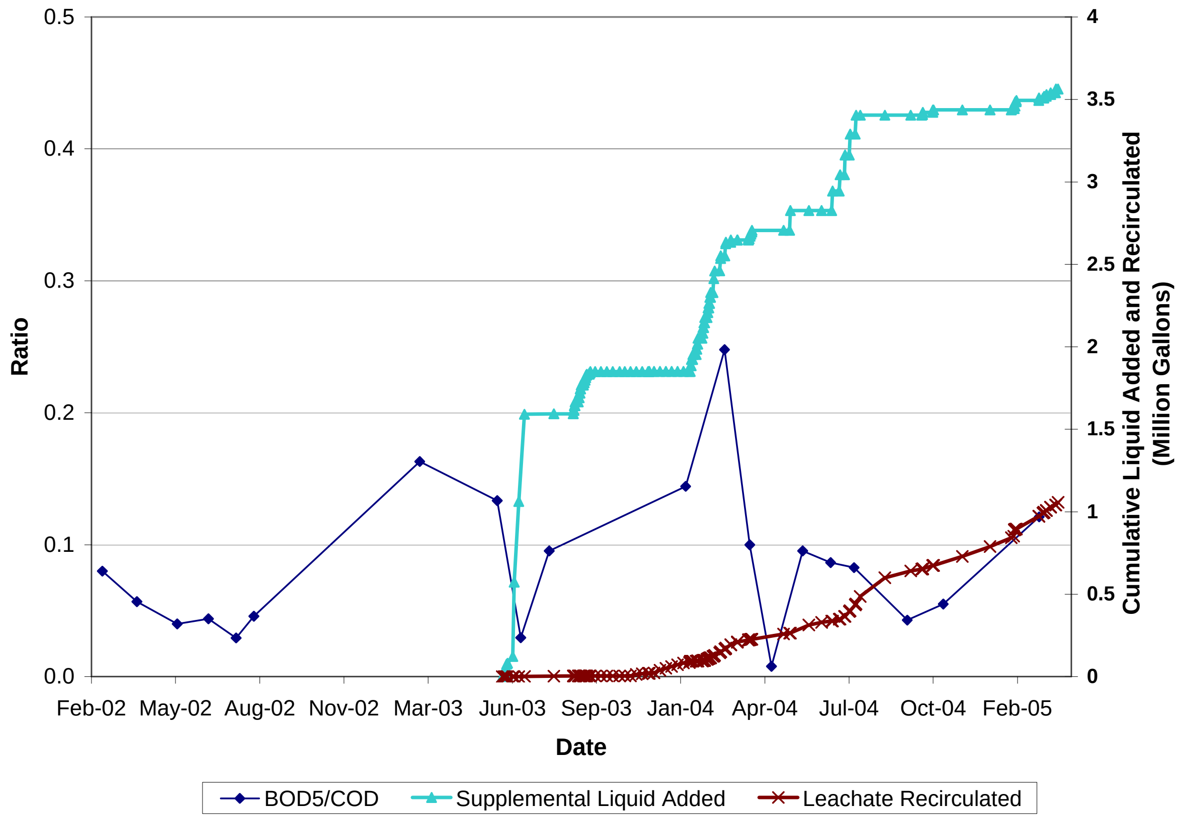


Figure 11. West-side cell – BOD_5/COD ratio

The BOD_5/COD ratio for the aerobic cell generally follows the pattern of the northeast cell showing an initial spike following the beginning of liquid addition followed by relatively low (less than 0.10) BOD_5/COD ratios during subsequent sampling.

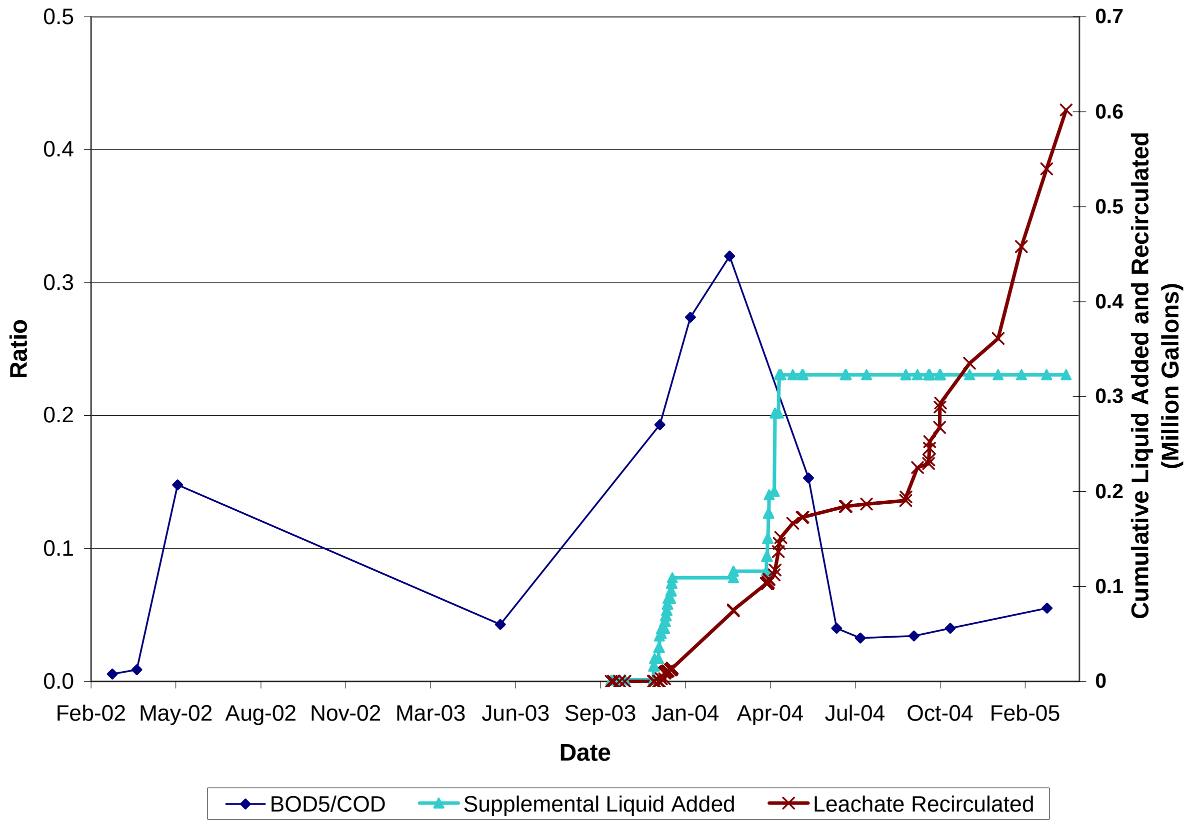


Figure 12. Southeast aerobic cell - BOD_5/COD ratio

3.5.3 Leachate Total Organic Carbon

In digestion processes, the conversion of certain degradable organic components, most notably cellulose, frees and solubilizes other organic materials that were bound to the cellulose. These organic materials, which is mostly derived from wood lignin or lignin like components, and such things as tannins, appears in solution. It is typically difficult for microorganisms to degrade it. (A rather similar mix of compounds appears in and darkens the liquid held within peat in peat bogs.) It is likely that newsprint, comprised of fibers of grounded wood/lignin, could be a major source of this material, but this is somewhat speculative. This unknown dissolved organic COD is evidently quite resistant to aerobic oxidation, as the leachate recycled from the leachate holding pond, which had been exposed to air for the better part of a year, still contained almost as much COD as the leachate exiting the cell.

Another component of refractory dissolved carbon that would appear as COD, but not BOD_5, is VOC compounds that are resistant to aerobic biodegradation. The main one of these that appeared transiently is methyl tertiary butyl ether (MTBE), which is a gasoline additive and can escape into the environment. Graphs of TOC over time for the bioreactor cells can be found in Appendix B, Figures 16 through 18.

3.5.4 Leachate Nitrogen

The rising nitrogen in the leachate is a consequence of degradation of nitrogenous waste, principally food wastes, although other materials (i.e. small amounts of sewage sludge, disposable diapers, and the like) also contribute. Nitrogen (principally from amine groups of amino acids) surplus needed to form the anaerobic organisms is freed as wastes break down and appears in solution. The behavior of nitrogen levels seen here are entirely typical of the nitrogen documented in landfill leachate elsewhere. However, it is to be noted that the rise in nitrogen is faster here because of the purposeful management of the landfill to speed biological activity.

Graphs of nitrogen content over time for the bioreactor cells can be found in Appendix B, Figures 19 through 21.

3.5.5 Leachate Phosphate and Other Nutrients

In contrast to ammonia nitrogen, the nitrate nitrogen drops to zero. It has been shown in work by Professor Morton Barlaz (NCSU) that this nitrate nitrogen is readily reduced as an electron acceptor. Thus, as the oxygen is used (and elemental nitrogen is formed), the free nitrite/nitrate levels are expected to be low.

The phosphorous levels represent the free phosphorus, which is likely from food wastes. The phosphorus in solution is released during waste breakdown, and is in excess of the amount needed by the anaerobic organisms. Graphs of leachate nutrients over time for both of the bioreactor cells can be found in Appendix B, Figures 22 through 24.

3.5.6 Leachate Semi-Volatile and Volatile Organic Compounds

Dissolved volatile organic compound (VOC) concentrations are presented in Appendix B, Figures 25 through 27. VOC (including the anaerobically biodegradable VOCs: acetone, 2-Butanone (MEK), and 4-Methyl-2-pentanone (MIBK)) levels in the northeast 3.5–acre cell leachate follow a similar trend to BOD_5 with initial levels being low, then rising to a peak in October 2002 and then falling again as leachate recirculation continued and as anaerobically degradable VOCs were consumed or otherwise removed. The anaerobic degradation of those VOCs that disappear by conversion to methane is typified by the example of acetone bioconversion to biogas,

$CH_3COCH_3 + H_2O \rightarrow 2CH_4 + CO_2$.

Similar reactions apply to MTBE. Another mechanism that applies to volatile compounds that cannot anaerobically biodegrade is the stripping of sparingly soluble compounds such as benzene. As VOCs, they have significant vapor pressures. They partition (evaporate) into the generated landfill gas and are collected with it. This is a very efficient method for collecting volatile organic compounds (like alkane hydrocarbons--propane, gasoline fractions) that are not biodegradable. The falling VOC levels in both the leachate and the collected landfill gas confirm that a combination of these mechanisms is at work. Altogether, this cleanup of the VOCs comprises an environmental benefit when the landfill gas is used for energy (or disposed by flaring) and the VOCs are destroyed.

3.5.7 Dissolved Metals

As bioreactor operation continues, the concentrations of dissolved metals in the leachate are expected to decline. Dissolved metals have a tendency to precipitate out as acids are then consumed and pH increases. Figure 29 in Appendix B presents the percentage change in dissolved metal concentration from the initial February 2002 samples for several important constituents for the northeast 3.5-acre cell. As presented in the graph, each of these metals showed a relative decrease in metal concentration over the first several sampling events, then as injected water percolated through the waste and reached the LCRS system, each of the constituents increased in concentration (although actual concentrations of the various dissolved metals are still relatively low, see Appendix A, Tables 13 through 15). In addition to the potential water quality impacts of high dissolved metals concentrations, dissolved metals can also be toxic to bacteria growth and retard landfill gas production. Further data will be required to demonstrate if dissolved metals reduce in concentration, continue to remain above baseline levels, or rise in concentration.

The analyzed metals concentrations were somewhat variable as seen in Appendix B, Figure 28. The pH in the range of 7 to 8 is close to the optimum for keeping all metals of concern to a minimum. Another thing to note is that there has been no evidence of metal toxicity in these or any known landfill experiments.

Appendix B, Figure 31 presents the percentage change in dissolved metals concentration from the initial February 2002 samples for the west 6-acre area for several important constituents (other constituents were omitted from the graph because of extremely low or non-detect levels). As presented in the graph, each of these metals showed an initial decrease in metal concentration over the first sampling events. This pattern is similar to that observed in the northeast 3.5-acre cell prior to significant leachate being generated by the cell. As the leachate generation increased, the organic acids also increased while the pH decreased, causing the levels of chromium and cobalt to increase as they were solubilized. This spike in dissolved metals was similar to that observed in the 3.5-acre cell.

In aerobic operation, organic acid constituents could be removed and pH would tend toward neutral more rapidly as the organic acids are oxidized. Thus, aerobic activity would be expected to neutralize acidity and reduce the dissolved metal levels more rapidly. Except for a spike in chromium between April 2003 and February 2004, metals levels remained much lower in the aerobic cell than in the anaerobic cells (Appendix B, Figures 32 and 33).

3.6 Landfill Gas Quantity and Composition Analysis

Background samples of landfill gas were collected from the northeast 3.5- acre area and west-side 6-acre area in March 2002 prior to liquid addition to the bioreactor cells. Since March 2002, landfill gas has been sampled from the northeast 3.5-acre area on a quarterly basis. Since March 2003, landfill gas has been sampled from the west 6-acre area on a quarterly basis. The southeast aerobic cell was sampled on a quarterly basis in 2003, but due to testing of the biofilter and blower station, no sampling was done from the cell in 2004 until December.

Analytical results are presented in Appendix A, Tables 16 through 18. As time progressed, the LFG methane content stabilized toward a range of 45-55% as expected.

3.6.1 Landfill Gas Flow Rate

Average landfill gas flow rate from each of the bioreactor cells is presented below in Figures 13 through 15. In each case, flow rate has dramatically increased following leachate injection and, following the initial increase, remained relatively stable.

As evident in the figures below, landfill gas recovery rate has fluctuated at times. These fluctuations, however, are not due to any intrinsic variation in generation, but rather can be attributed to several factors. The most important of which is the human factor in adjusting a gas extraction system. When adjusting a gas system, you are trying to match extraction exactly to generation, which, in practice, is extremely difficult to do. What more commonly happens is the system either slightly under or over extracts compared to the rate at which gas was generated. (Another way to state this is that the draw on gas can vary as engine gas use varies.) When this happens, the system is adjusted again to compensate, which in turn requires another compensation, and so forth. The other factor that is responsible for some of the most extreme variations is attributed to partial or complete shutdown of the gas-to-energy facility.

Under practical operating conditions at a landfill where multiple cells are producing landfill gas, the day-to-day variations in extraction from each of the cells (or individual wells) would have a tendency to cancel each other out such that the overall extraction would be much more consistent, which is the case at the YCCL.

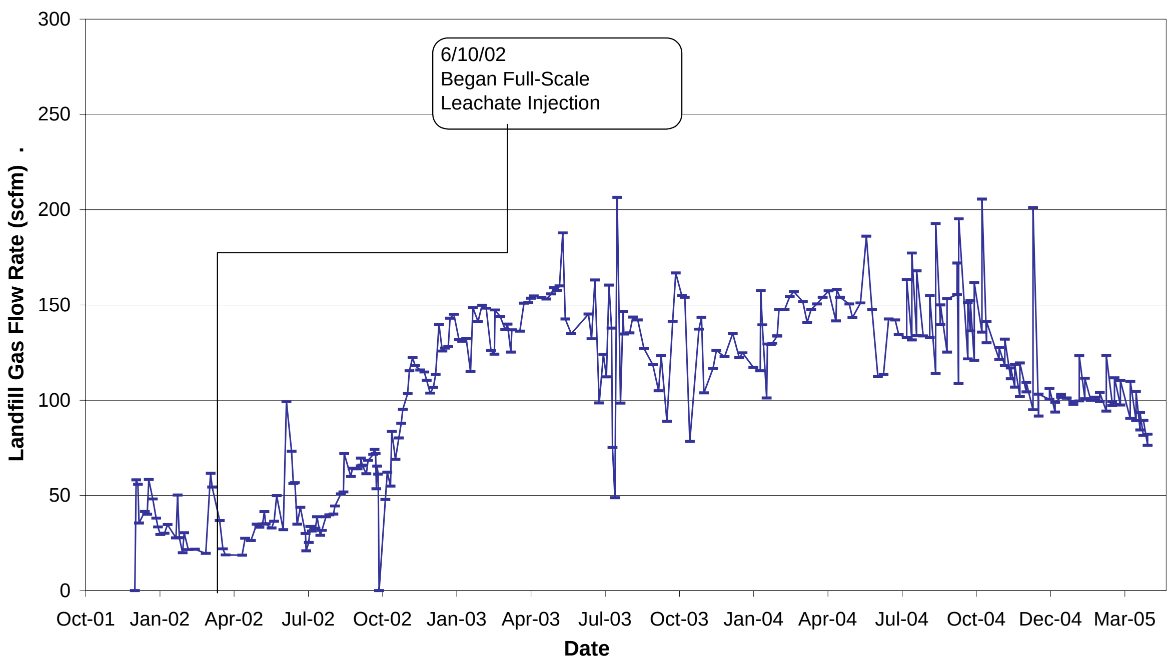


Figure 13. Northeast cell average daily flow rate

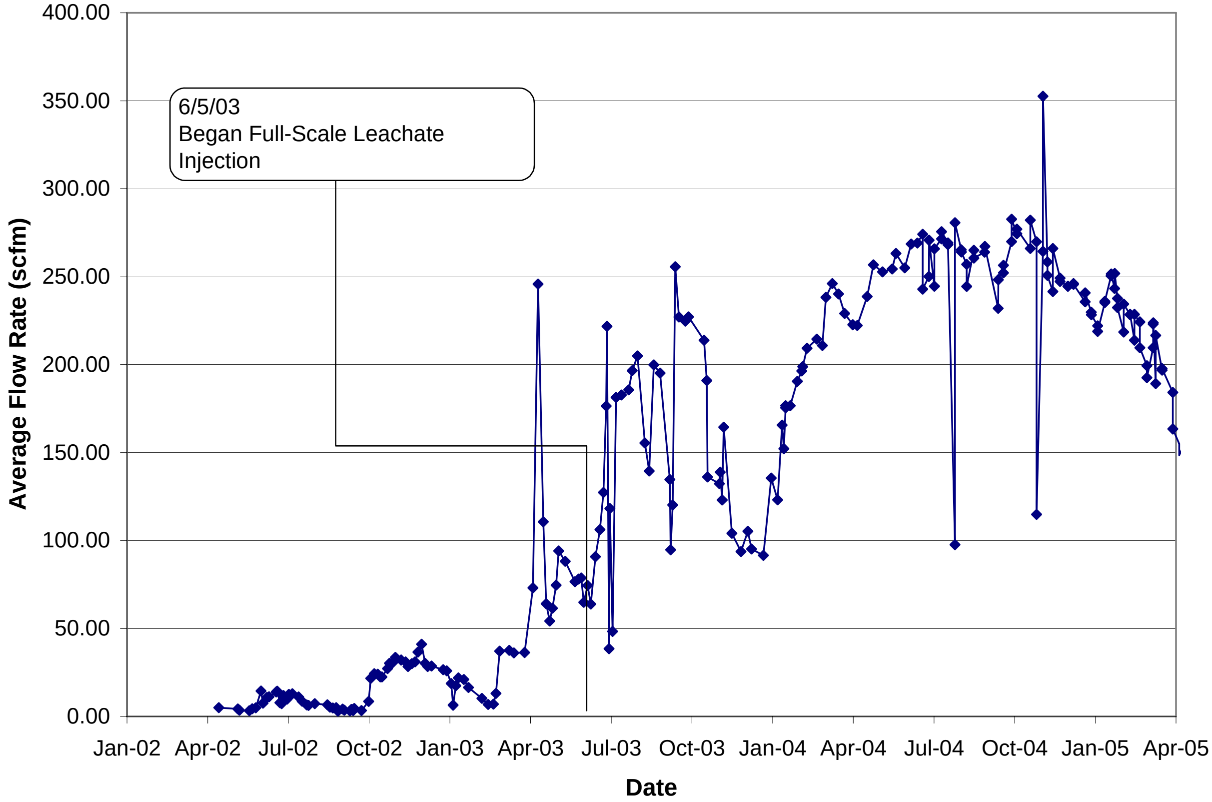


Figure 14. West-side cell average daily flow rate

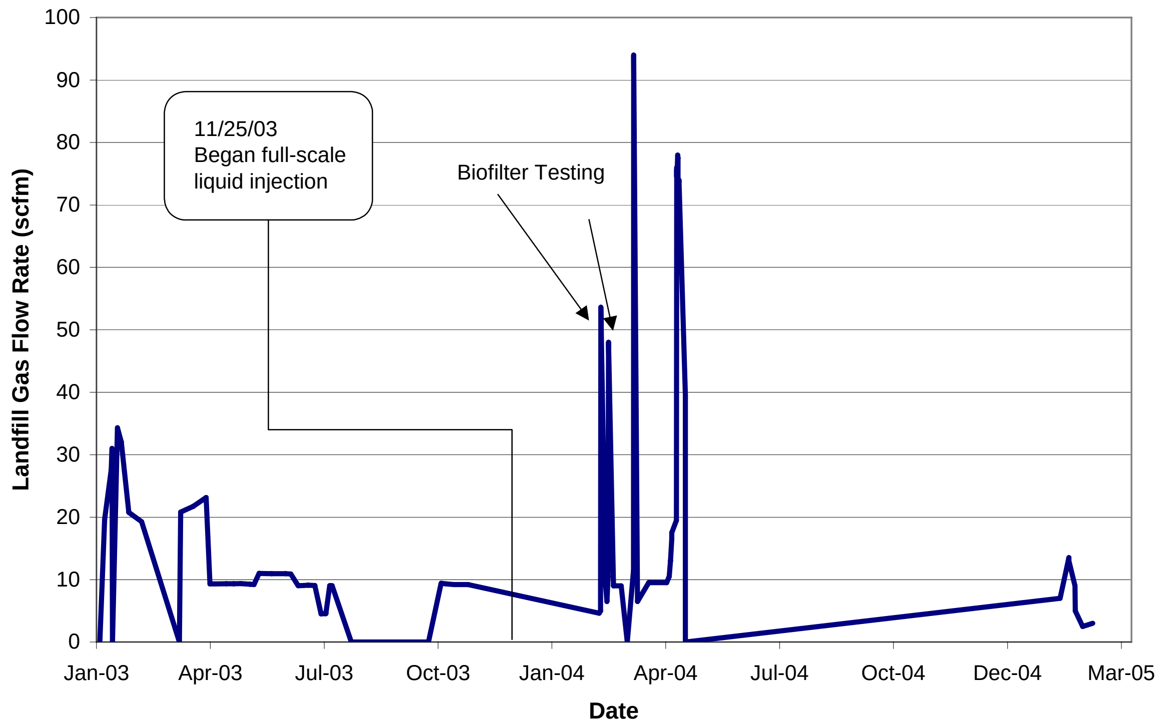


Figure 15. Southeast aerobic cell average daily flow rate

3.6.2 Landfill Gas Volume

Appendix B, Figure 34 presents the landfill gas flow rate and cumulative methane collected from the northeast 3.5-acre area. As presented in this figure, the volume of landfill gas collected from the northeast 3.5-acre area significantly increased following the beginning of full-scale liquid addition in June 2002. In conjunction with this increased flow rate, methane concentration in the landfill gas also increased from 40 ±5% to 50 ±5%.

Appendix B, Figure 35 presents the landfill gas flow rate and cumulative methane collected from the west 6-acre cell. Examination of the cumulative methane production curve indicates that gas production in this cell can be generally broken down into three phases: prior to surface liner installation (May 2002 to October 2002), following surface liner installation and shortly after leachate injection began (October 2002 to June 2003), and following leachate injection (June 2003 through the present).

Figure 16 presents the cumulative methane generated per pound of dry waste for both the northeast 3.5-acre and west 6-acre cell. This number is used as a gage to determine the progress of decomposition, and the values obtained can be utilized by other landfills to estimate landfill gas production. Through October 2004, the cumulative methane generated per dry ton of waste was approximately 0.685 ft^3/lb for the northeast 3.5-acre cell. Comparing this to the estimated maximum methane potential of municipal solid waste of 1.4 ft^3/lb, the northeast 3.5-acre cell has undergone 48.9% of its estimated potential decomposition. Based on the EPA Landfill Gas Generation model, a typical dry-tomb landfill would be expected to produce approximately 0.10

ft^3/lb of dry waste over the same time period. This translates to a nearly 7-fold increase over a typical dry-tomb cell. The total methane generation between December 2001 and October 2004 from the northeast 3.5-acre cell was approximately 78.3 million scf of methane, which is equivalent to approximately 12,426 barrels of oil or 6,525 MW-hr of electricity (at 12,000 ft^3 methane per MW-hr).

Also included in Figure 16 is the cumulative methane generated per pound of dry waste from the west 6-acre cell. Through October 2004, the cumulative methane generated per dry ton of waste was approximately 0.26 ft^3/lb. Comparing this to the estimated maximum methane potential of municipal solid waste of 1.4 ft^3/lb, the west 6-acre cell has undergone 18.6% of its decomposition. Based on the EPA Landfill Gas Generation model, a typical dry-tomb landfill would be expected to produce approximately 0.07 ft^3/lb of dry waste over the same time period. This translates to a nearly 4-fold increase over a typical dry-tomb cell. The total methane generation from the west 6-acre cell between May 2002 and October 2004 was approximately 77.5 million scf, which is equivalent to approximately 12,299 barrels of oil or 6,548 MW-hr of electricity.

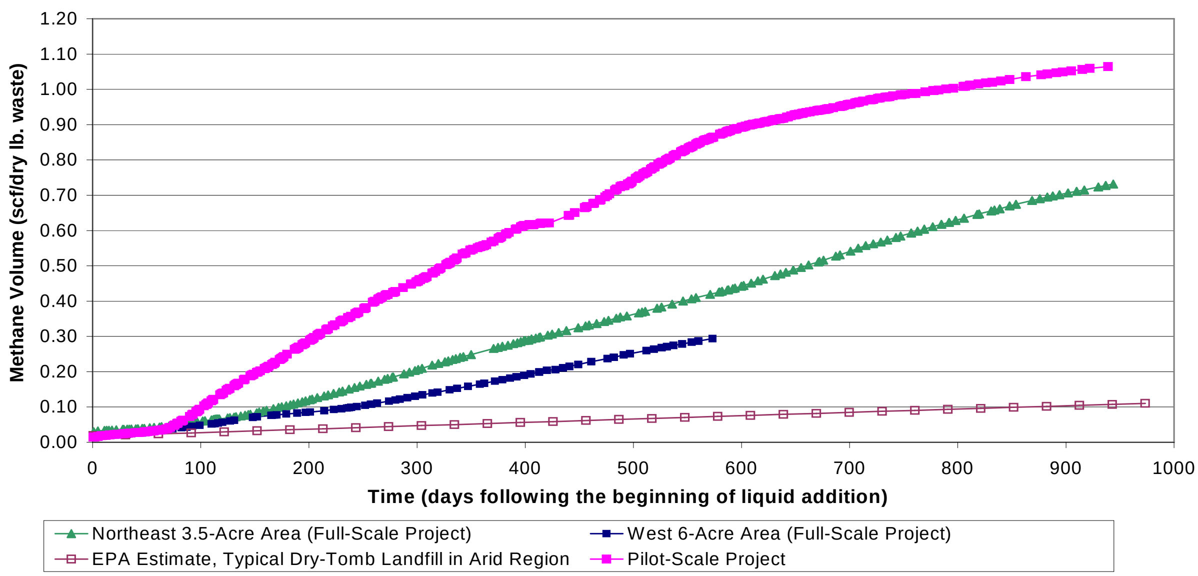


Figure 16. Cumulative methane per dry pound of waste from the northeast 3.5-acre, the west 6-acre cell, previous pilot-scale project, and what would typically be expected in a dry-tomb landfill

The normalized methane generation rates (or in alternate technical terms, rate constants) for the northeast and west 6-acre cells have thus been very encouraging, several-fold higher than would be expected for the same masses of waste if they were conventionally landfilled. Some slightly added methane might have come from decomposition of the "greenwaste" ADC, but this material (chipped twigs, leaves and the like) gives relatively low methane yields, under half that of waste, and small amounts of methane could not have materially altered the pronounced difference between the bioreactors' and conventional yields. The normalized methane productivities are lower than for the smaller demonstration cell, but this is considered in part due to type of waste and the slower infiltration of liquid into the waste mass. The project team believes that in future commercial operation, it should be possible to improve the methane rates seen for the northeast and west side cells even further. Improved leachate recirculation rates and more rapid infiltration should be attainable by substituting more permeable and readily available daily cover material for the cover soil that somewhat impeded liquid infiltration, and better cell geometry which may be possible at other landfills.

3.6.3 Landfill Gas Methane, Carbon Dioxide, and Oxygen Content

Landfill gas constituent composition over time is plotted in Figures 37 through 39 in Appendix B. The landfill gas composition at around 50% methane ±5% is acceptable for all landfill gas adapted equipment operation, including electricity generation that is of most interest. The variations in concentration are largely due to variations in extraction vacuum or draw.

3.6.4 Landfill Gas Collection System Pressure

Appendix B, Figures 40 through 42 illustrate the variations in the extraction system vacuum over time for each of the cells.

The gas extraction system for the west 6-acre cell has been operated at variable vacuum and on average at a lower system vacuum than the northeast cell. This is an unintended consequence of extraction system features and varying engine operations and fuel use at the landfill. This may, in part, be one of the reasons that the west 6-acre cell has had greater surface emissions than the northeast 3.5-acre cell (although still relatively low). For comparison purposes, the average emission (over all surface scans) for the 6-acre cell was 3.2ppm versus 0.8 ppm for the 3.5-acre cell.

3.6.5 Landfill Gas Collection System Temperature

Landfill gas temperature is monitored at each wellhead either with a temperature probe that is permanently installed in the wellhead or with an auxiliary probe to the GEM-500.

As material balances are made, the moisture loss can be determined from the content of water in the saturated gas at the temperature at which gas leaves the system. Because the extraction line condensate drains back into the cell and is not lost, this may require gas temperature measurements where the gas actually leaves away from the well, where the water vapor escapes.

Up to now, corrections for water vapor loss were minor, which is to say that adjusting for maximum conceivable loss would change calculated moisture content by under 0.2%. Gas temperatures fluctuated between 50 and 90°F, and waste temperatures averaged around 110°F.

3.6.6 Landfill Gas Condensate

The landfill gas collection system was designed and installed to eliminate the need to remove condensate from the system. Lateral piping ran uphill to a main collection header so any condensate that collected in that section would drain back into the waste. The header line then gravity drained to the landfill gas-to-energy facility where condensate was removed and discharged to the landfill's LCRS.

This, and any similar condensate return arrangement, has advantages at Yolo and for other commercial operations. First, it is expected under normal circumstances that all condensate in the header will drain back into the waste. This can limit liquid loss and maximize retention of liquid in the cell. Also, it eliminates any need to handle the condensate that is instead returned to the cell.

Solids converted to gas will, to a close approximation, be equal to the weight of landfill gas leaving the system. The design of the condensate system is such that much condensate returns to the cell. Later in the project, measurements and corrections for water loss as vapor in the gas will be carried out.

3.6.7 Results of Biofilter Fugitive Emissions Testing for Southeast Cell

3.6.7.1 Comments on biofiltration emissions test results

Attempts to determine biofilter effectiveness proved to be challenging. Plainly, there were measurement difficulties. Among the best evidence for these was the anomalous calculation of methane leaving the biofilter that was higher than methane entering the biofilter. Summarizing memoranda on the possible causes, there were several plausible reasons for these results, and several ways to improve testing in the future.

Some of the reasons for the biofiltration test results are as follows:

1. The biofilter matrix had permeability far higher than that to which the flux test was normally applied. In general, the flux box approach was applied to soils or waste with 100 to 100,000 times lower permeability. The Yolo County team estimated the permeability of the 1-cm particle bed to range from 1 to 5 million Darcys. This meant that gas could enter or escape around the buried edge of the chamber, or other flow related artifacts could occur. A thin polyethylene bag with porous material (10 mil would give 10 dynes/cm^2) placed over the exit of the flux chamber would actually provide enough backpressure to block gas exit and alter flow. The upshot was that this particular flux test, although endorsed as acceptable by regulators and workable under other conditions, was suspect under these conditions.

2. With such low flow resistance, it was also shown that wind pressure swept ambient air through the biofilter. This may have contributed to the decreased subsurface (1-ft down) methane concentration as seen later in the day of testing.

3.6.7.2 Improving measurements of biofiltration effectiveness

<u>Reliance on tracer</u>. One method to improve future assessment of methane reduction is to make use of a tracer. The methane concentration can be most accurately determined against any tracer gas within gas entering the biofilter, that is itself accurately measurable and that passes through the biofilter largely unchanged. Carbon dioxide happens to be one of the most convenient tracers since it will change very little on passage through the biofilter (and with a little algebraic work, the CO_2 resulting from methane destruction can be accounted for). This will be the measurement approach in future work.

<u>Appropriate parallel laboratory tests.</u> Appropriate laboratory tests are another avenue for more accurately determining methane removal rates. For the biofilter itself, the short residence time of exposure of methane containing gas to the biofilter results in uncertainty, when conversions are low. A more accurate determination of biofiltration can be taken by holding methane/air mixtures in the presence of biofilter matrix for much longer periods of an hour or day in laboratory conditions.

3.6.7.3 Other factors affecting and routes to improving biofilter effectiveness

The biofilter was designed with gas distribution, buffering, residence time, and matrix. Nonetheless effectiveness was low. Possible explanations for an apparent initially low biofilter effectiveness and ways for overcoming them are as follows:

1. Short term of operation and need for more acclimatization of biofilter to methane containing gas. The biofilter had been operated for only a period of two weeks when the tests were conducted. Significant time is normally required for the microbial population to grow and become maximally active, and this time requirement may lie anywhere between days to months, depending on the compound to be biofiltered. Thus, activity should improve by allowing sufficient time for outgrowth of the necessary methanotrophic bacterial activity, and initial results such as these to be regarded as preliminary only.

2. Nutrient deficiency and adding nutrients. The soil analysis indicated a carbon–to-nitrogen level that at between 45:1 to 50:1 ratio was lower than the recommended 35:1 ratio. Higher nitrogen levels would benefit the biofilter. Nitrogen was being added in the form of urea.

3.6.7.4 Aerobic cell operational schedule as a limitation

In operating the aerobic landfill cell, issues arose that have necessitated considerable shutdown time. The shutdowns were necessary for dealing with carbon monoxide (CO) and to carry out remedial measures. Upon aerobic bioreactor cell startup, March 2004 the aerobic cell was providing gas to the biofilter and enabling the biofiltration assessments described above. At the same time, exit gas from the aerobic bioreactor was being routinely analyzed for CO. In early November 2003, CO was detected in the exit gas from the aerobic bioreactor. To summarize the ensuing sequence of events:

1. The composition of gas from each extraction line was tested individually for CO. The interest was in finding whether the CO was fairly uniform among all exit lines, or whether it was more variable. Higher variability would increase the likelihood that the source of CO was a small fire or combustion zone starting in the aerobic cell. A zone of combustion would elevate the CO level in the vicinity of the nearest individual extraction line more than elsewhere. The concentration did in fact vary, suggesting that the source of CO was a small fire. If the source of CO was combustion, which is still not proven, then the amount of waste combusted was less than 100 lbs and may have been as low as 10 lbs. This estimate is based on the low level of CO in the exit gas and total CO seen.

2. Upon concluding that a fire was at least a possible cause of observed CO, the gas extraction from the aerobic biocell was turned off to limit oxygen to the fire.

3. It was decided to address the CO and presumed fire problem by injecting liquid nitrogen into the line with the highest CO, which would be closest to the fire. A nearby supplier of liquid nitrogen was located (name of company, Vacaville, CA). About 40,000 lbs of liquid nitrogen were pumped into the gas collection line nearest the presumed fire.

After liquid nitrogen injection into the aerobic biocell, exit CO was transiently reduced. But, the liquid nitrogen did not eliminate CO and it slowly increased to levels of over 60 ppm. Liquid nitrogen had reduced the level of CO reading by a factor of 10.

4. Over the next several months, it was decided to slowly and carefully add more water to the aerobic cell. Water addition was still ongoing with level of added moisture being tracked by sensors. Further aeration was deferred due to other project demands, but will be added soon.

3.6.7.5 Implications of biofilter results for methane abatement by landfill surface biocovers

Another application of biofiltration for methane abatement is as a biocover on landfills, where methane emissions are abated in the biocover matrix as described above. It needs to be noted here that Yolo County's biofilter was considerably different from those of proposed landfill biocovers. Most importantly, the retention time in the biofilter in this set of Yolo County tests was about 15 minutes. The typical residence time in surface biocover to reduce methane in gas exiting a landfill surface is 10-100 times as long. Thus, there is every likelihood that fugitive methane abatement in landfill biocover will exceed that of the biofilter as applied at Yolo County, because biocovers on landfills will have greater times to accomplish fractional methane abatement. This is verified based on the surface emissions test results from the surface of the aerobic cell that have shown no emissions to date.

3.7 Surface Liner Emissions Monitoring

3.7.1 Northeast anaerobic cell

Scans to detect methane surface emissions from the northeast 3.5-acre cell have been performed quarterly since April 2002. Figure 43 in Appendix B provides a three-dimensional representation of the surface emissions from the northeast 3.5-acre cell for each of the scanning events. Note that the graph has multiple pages, and also that a wide range of vertical calibrations exists across the range of graphs. No emissions were detected during surface scans performed in April 2002 and January 2003 or during a rescan in September 2003. Therefore, plots could not be created for those scanning events.

The detection of surface emissions in June and September 2002 may have been due to emissions from waste placement activities in the west 6-acre area or from construction activities in Module D Phase II construction, which involved exposing waste from an adjacent unit to facilitate base liner installation. Methane surface emissions detected in March and April 2003 can also be attributed to background emissions detected on the west 6-acre area. Note that the September 2003 and November 2004 use different scales than the other surface plots. This is due to emissions of over 200 ppm for September 2003 and 75 ppm for November 2004. Again, it was concluded that the emissions were probably a direct result of the active waste placement in the adjoining Module D Phase II. This was confirmed by performing a rescan for the September 2003 event, which resulted in no emissions detected.

Emissions throughout the 3.5-acre area appeared to have a high degree of randomness. One contributing factor was change in wind currents during the surface scan, which could have transported methane from adjacent areas, resulting in the detection of surface emissions (apparent hot spots) that were not detected in background measurements. The fact that the hot spots often appeared to move would confirm this explanation that methane was drifting in from outside the measured area. For various reasons, a true hot spot would tend to remain fixed in location. Otherwise, in general, though the scans are useful, they are only qualitative indicators of emissions.

Surface scan measurements can track down areas of higher emissions with reasonable accuracy. The high emissions from a given landfill surface area will result in elevated combustible gas readings at the locations of higher emissions. However, the surface scan readings are more qualitative than quantitative. Without good or easy alternatives, regulatory agencies (EPA and California) have chosen combustible gas measurements as the best and most practical indicators to give feedback on control effectiveness. (Emissions of LFG containing methane will be referred to here simply as methane.)

Reasons the surface scans tend to be qualitative indicators include:

- Methane surface readings will vary inversely with depth of the convective boundary layer over the landfill. This boundary layer depth easily varies several-fold, for example from 10 ft on a cool morning, to over 100 ft as, later in the day. Solar heating greatly increases mixed layer depth.
- Combustible gas readings vary inversely with wind (breeze) speed that sweeps away methane to greater or lesser extents. Wind speeds can vary ten-fold even while remaining within prescriptive limits of a 5 mph maximum. A realistic example is variation from 0.5 mph to 5 mph.
- As noted above, flow of methane from adjacent areas of the landfill can result in methane detections that are not representative of emissions coming from the area being monitored.
- Surface emissions can vary over short time periods of hours or days because of barometric fluctuations. Normal barometric fluctuations expand and contract void gas and this, in turn, results in short term variations in surface LFG flux.

All of these factors combined will result in the following:

- At constant emission rate per unit area, measured surface concentrations can vary by over an order of magnitude.
- At constant surface emission readings, (for example, 50 ppm) the underlying flux giving rise to the reading may vary by an order of magnitude.

All of these factors can lead to issues of spatial and temporal variations and repeatability that should be kept in mind when reviewing surface scan results.

Despite the inherent uncertainties in the surface scan in quantifying emissions, the surface scans are valuable. Much experience across the U.S. shows that data from emission scans as conducted in this project are extremely useful in such areas as tracking down cover leaks. (Yolo experience in successfully finding leaks is documented later.) To some extent, surface scans can also be made more quantitative. Taking readings while avoiding convection problems under well-defined conditions can lessen uncertainties in the emission data. This includes taking early morning measurements under stable and slow wind speeds, and in conditions of steady barometer readings. These precautions were also taken as much as practical when performing scans.

The average and maximum surface emissions from the northeast 3.5-acre area are presented below in Table 5. As presented in this table, the highest single emission detected from this cell was 209.8 ppm and the highest average emission detected was 5.2 ppm. Both of these occurred in November 2004 and are attributed to adjacent waste placement activities. The areas of significant emissions were rescanned with the highest emission being 80 ppm along the east perimeter of the cell, which is again adjacent to the active waste placement area. Average emissions were calculated by taking a weighted average of emissions detected along the entire scan. For example, if the entire traverse of the surface scan were 1000 m and surface emissions of 100 ppm were detected along 200 m of that traverse, the average surface emission would be,

$$\text{average emission} = (800\text{ m}*0\text{ ppm} + 200\text{ m}*100\text{ ppm})/1000\text{ m} = 20\text{ ppm} \quad (4).$$

Table 5. Summary of surface scans for the northeast cell

Date performed	Weighted average emissions (ppm)	Maximum emission (ppm)	Average vacuum applied by LFG extraction system (inches of water)
4/3/02	0	0	-0.10
06/06/02*	1.1	9	-0.54
9/19/02	0.25	8	-0.54
1/7/03	0	0	-7.5
3/19/03	0.18	10	-14.5
4/15/03	0.08	6.7	-7.5
9/25/03	3.7	209.8	-15.9
9/29/03	0	0	-15.9
12/17/03	0.24	7.0	-8.3
1/29/04	0.14	10.3	-6.4
4/21/04	0.10	25.3	-9.3
8/4/04	0.32	21.1	-6.3
11/18/04	5.2	79.8	-8.15
3/24/05	2.7	35.8	-11.5

* First date after liquid addition

3.7.2 West-side anaerobic cell

As presented in Table 6 below, higher emissions were detected on the west 6-acre area. This can also be seen in Appendix B, Figures 44, in which the emission scale is from 0 to 650 ppm. Note that the maximum value presented for the August 2004 scan was over 1000 ppm, but the figure shows a maximum peak of roughly 650 ppm. This discrepancy is due to the interpolation method used by the plotting program, which was used to produce the surface plots. Before a plot is produced, grid nodes are generated and data points closer to the grid nodes are given more weight than points farther from the nodes. The points in between the grid nodes are then obtained by interpolation to give a smooth surface.

Table 6. Summary of surface scans for the west-side cell

Date performed	Weighted average emissions (ppm)	Maximum emissions (ppm)	Average vacuum applied by LFG extraction system (inches of water)
4/3/02	0.84	50	No vacuum applied
6/6/02	6.5	37	-0.08
9/19/02	4.2	124	-0.36
1/8/03*	0.70	30	-3.2
3/19/03	5.8	85	-0.55
4/15/03	2.1	126	-1.05
9/29/03**	0.64	59.3	-1.98
12/17/03	10.4	404.50	-0.76
1/29/04	1.96	636.6	-1.2
4/21/04	0.96	84.7	-1.2
8/4/04	3.79	1052.9	-2.9
11/18/04	1.04	59.3	-1.34
3/24/05	3.97	67.5	-7.50

*Cover system installed, ** First date after liquid addition

In April 2002, higher emissions were detected because the west 6-acre cell was still under construction and a surface cover system had not been installed. In June 2002, the LCRS was connected on an interim basis to the header line that conveyed landfill gas to the onsite LFG-to-energy facility. Monitoring during the June 2002 scan indicated lower surface emissions than the previous scan, but still elevated compared to the northeast 3.5-acre area. This was most likely because waste placement activities were still underway and a cover system had not been installed. In December 2002, the cover system was completed and the average emissions detected during the January scan declined. By March 2003, the gas collection system had been completed and applied to the landfill gas collection system to increase the flow rate from 16 standard cubic feet per minute (scfm) to 44 scfm. In April 2003, the average emissions detected decreased, even though higher emissions were detected on the east face of the cell. The source of the high emissions was generally traced to unsealed areas on the cell (less than 1 in) where piping penetrated the surface liner. In response to these emissions, three additional wells were opened and placed under suction in the area where the surface emissions were detected (increasing the LFG flow rate from 38 scfm to 99 scfm). Prior to the surface scan in September 2003, the pipe penetrations were sealed with expanding foam. While the average of emissions detected in September 2003 was lower than previous surface scans, surface emissions were not completely eliminated because small leaks still existed at the junctions between the foam and the liner.

Similar conclusions (as presented for the northeast 3.5-acre area) regarding the status of the surface cover in relation to the amount of surface emission can be drawn for the west 6-acre area. Prior to September 2003, no significant ballooning was observed on the west 6-acre area while the LFG collection system was shutdown. This was most likely because any excess gas buildup was escaping out the small gaps between the liner and piping (which would result in higher surface emission measurements). Subsequently, the pipe penetrations were sealed with expansion foam. As a result, during a gas collection system shutdown in September 2003, positive pressure built up under the surface cover, causing the liner to slightly balloon. These observations in combination with the September 2003 surface scan indicated that the foam was effective at reducing emissions, however foam sealing was not completely effective at eliminating them. In December 2003, Yolo County permanently sealed the pipe penetrations on the west 6-acre area by extrusion welding permanent boots made of HDPE liner to the surface liner. This was done in hopes of eliminating any surface emissions coming from the pipe penetrations, however this again proved not completely effective at eliminating surface emissions.

In general, when there is no highly conductive layer beneath the cover, gas flow analysis indicates that increased vacuum in some cases could partially, but not completely, eliminate local areas of positive pressure under the cover. The sealing of the cover openings in one area can result in increased emissions in other areas. (These emissions are estimated as small, probably 1-3% of generation). For the west 6-acre cell, excess gas production under particular areas will tend to find an exit somehow. The exit is often through other interstices or small perforations, often nearby, in the surface cover. One solution is to provide additional wells under the emitting area, or using a highly conductive layer, such as loose waste or shredded tires under the cover to even out pressure, so that a slightly negative pressure can be maintained beneath the entirety of the cover footprint.

In September 2004, the County installed two additional gas collection wells under the surface liner along the east edge of the cell in the continued effort to reduce surface emissions. The subsequent November 2004 surface scan indicated reduced peak and average emissions relative to the August 2004 scan.

Because small gaps existed between the surface liner and piping exiting the cell, the surface emissions detected from the west 6-acre cell were more dependant on the suction applied by the landfill gas extraction system. Appendix B, Figure 46 compares the average surface emissions to the average suction applied to the landfill gas system. With the exception of the August 2004 scan, surface emissions were reduced when higher levels of suction were applied to the system.

3.7.3 Southeast aerobic cell

In the case of the southeast aerobic cell, the air emissions were, on the whole, rather similar in nature to the anaerobic cells. However, it must be noted that there was a high degree of scatter in emissions measured from all cells, and the aerobic cell, in contrast to the aneaerobic cells was not covered, which may have acted to increase emissions despite lower methane productivity.

Table 7. Summary of surface scans for the southeast aerobic cell

Date performed	Weighted average emissions (ppm)	Maximum emissions (ppm)	Average vacuum applied by LFG extraction system (inches of water)
04/03/02	0	0	0.0
06/06/02	2.17	8	0.0
09/20/02	0.13	3	0.0
04/30/03	0.64	3.6	-0.1
09/29/03	0.43	48.9	0.0
12/17/03*	1.12	38.4	0.0
01/23/04	4.3	209.7	0.0
4/27/04	2.6	176	Gas collection system not operating
8/23/04	0.79	18.4	Gas collection system not operating
11/18/04	7.88	146.9	Gas collection system not operating

***** First date after liquid addition

3.8 Waste Solids Sampling

3.8.1 Testing and results

Waste samples have been collected prior to liquid addition and following each year of liquid addition. These samples were then sent to North Carolina State University where they were analyzed for moisture, cellulose, lignin, and BMP. The laboratory BMP test is a standard measure of the amount of decomposition that is possible for a particular waste sample under anaerobic conditions. The other measurements are also standard for assessing biochemical conditions and status of decomposition of wastes. Full analytical results are located in Appendix A, Table 19 and are plotted in Figures 47 through 52 in Appendix B.

The first sampling event occurred on June 4 and 5, 2002, the second event on July 15 and 16, 2003, and the third on June 3 and 4, 2004. Samples of refuse were excavated to evaluate the extent of water addition and solids decomposition in the bioreactor cell. A 0.61-m (2-ft) diameter solid stem auger was used to core through the waste and collect samples. Samples were collected roughly at every 1.5-m (5-ft) vertical interval. Images of the sampling events are shown in Appendix C.

As presented below in Figure 17, the waste samples have indicated an increase in moisture content in the northeast 3.5-acre cell over the last 3 years. During the first sampling event, the average moisture content of the waste was 18.4%. Based on samples collected during the third event, the moisture content of the waste averaged 40.8%. This measured moisture content was substantially greater than the calculated moisture content of 29.3% calculated under Section 3.3.1. Figure 18 presents the moisture content of the waste from the west 6-acre cell. Trends are not distinct, although results do indicate an increase in moisture over the pre-liquid addition sampling event. The differences are attributed to only a limited number of samples being collected, which were likely not representative. The substantial point-to-point heterogeneity of landfilled MSW is well recognized and very much evident in this case. The heterogeneity of samples is discussed more below. Figure 19 presents the moisture content of the waste from the aerobic cell. Moisture content has increased in the aerobic cell from an initial average of 18.8 % in the first sampling event to an average of 25.7% in the third sampling event.

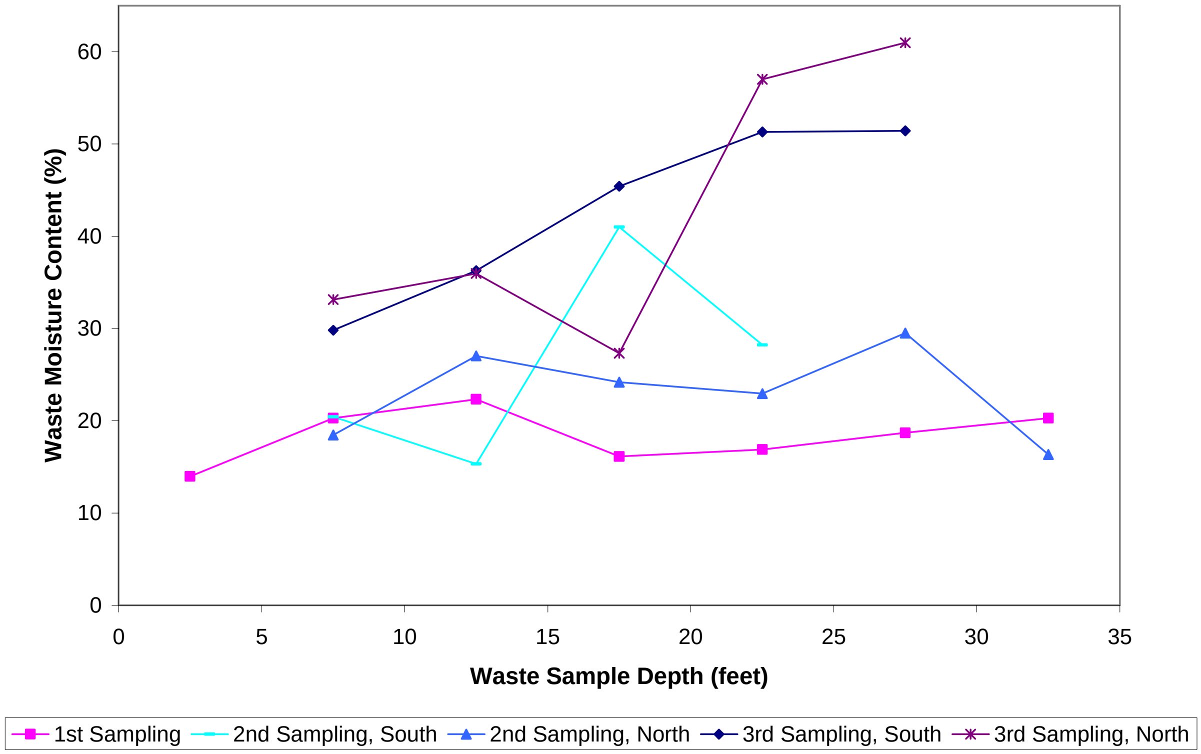


Figure 17. Waste moisture content for the northeast cell

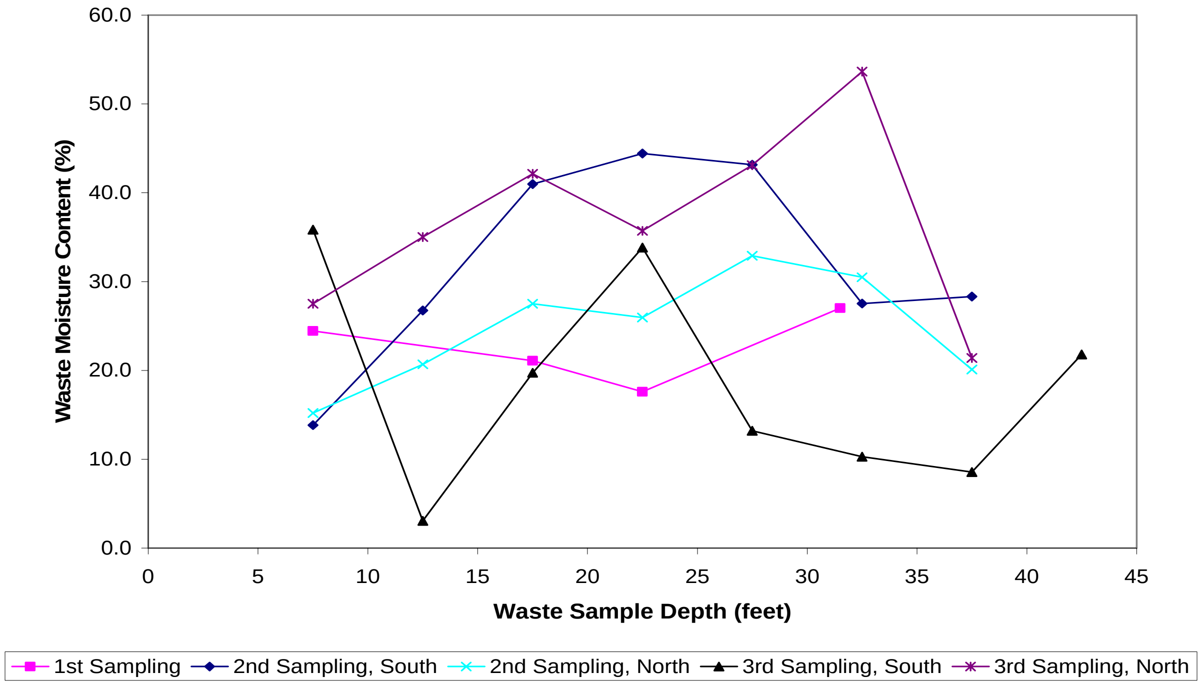


Figure 18. Waste moisture content for the west-side cell

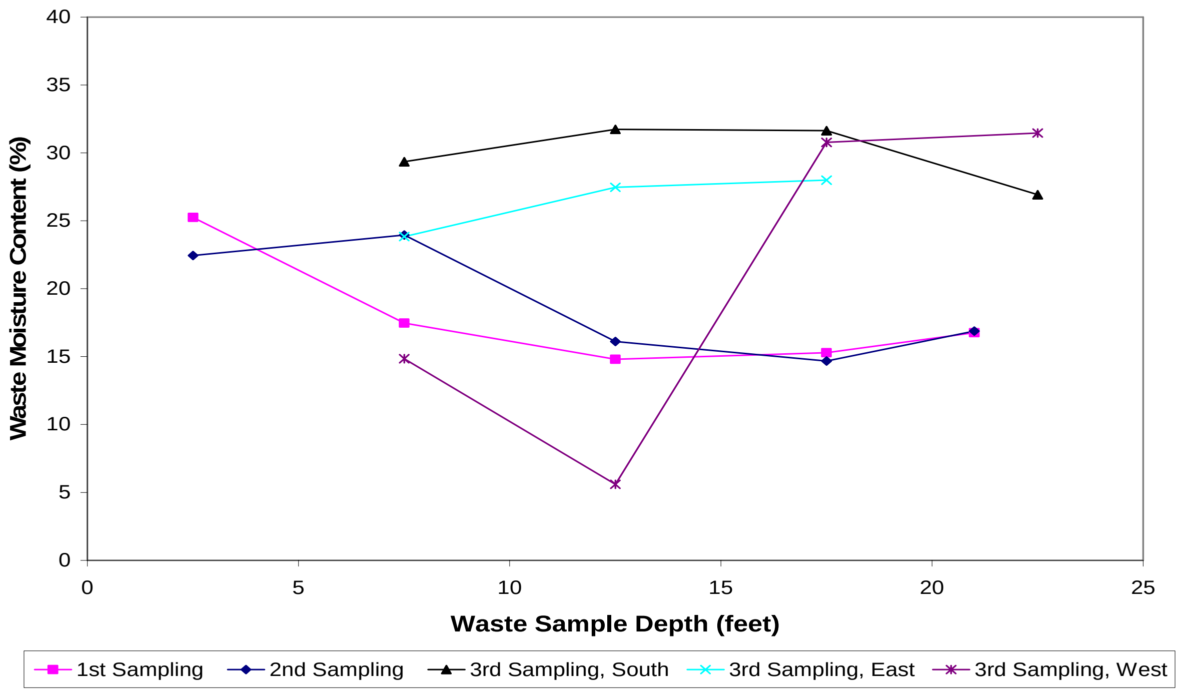


Figure 19. Waste moisture content for the southeast aerobic cell

3.8.2 Discussion of test results on samples

The obvious feature of the sampling results is high variability, i.e. major scatter. The variability is due in part to the heterogeneous nature of the waste itself, likely magnified further by other factors like remnant cover soil as discussed below. The variability in waste has been observed and commented on in other work. For example, large-scale tests were carried out on the <10% fraction of mechanically separated organic residue (MSOR) fraction of European Union Waste not expected to be combusted. Oonk et al. (2000) stated in a presentation summary at a Swedish Landfill Conference that "the measured in situ water content could not be related to areas of leachate injection and it was not possible to determine flow paths of or flow characteristics of the waste." The observed scatter with these samplings was greater than, i.e. drowns out any trends that might exist.

Visual observations confirmed the highly variable analytical results. At Yolo, very pronounced variations in moisture content and decomposition were obvious on inspection during even the most recent sampling. The appearance of waste samples taken from different locations in the same cell differed widely. With given cells, some waste samples appeared dry and printed-paper was entirely legible. In other cases in samples from other areas and other depths of the same cell, the decomposition was far advanced, and waste was blackened and steaming to the point where print was not legible at all. In a modest fraction of cases, "perched" liquid (or liquid trapped and unable to drain quickly through the waste) was indicated as liquid appeared in the bottom of the test sampling borehole on drilling

The main conclusion is that moisture distribution and waste properties have, to date, been heterogeneous in the cells and in waste samples from the cells. It may be possible to reach better conclusions as waste decomposition progress, and more analysis of additional waste samples provides more information. The methane recovery data and moisture balance presented earlier in this report stands as, by far, the best indicators of the decomposition progress.

Regarding these results, some further comment can be offered that might be useful in explaining the results for the Yolo cells, and for future operation of controlled landfill cells.

1. Although results are scattered, the effects of decomposition should become clearer, and scatter less important, over longer terms. At most, the decomposition is under 50% complete. A sampling analysis 5 years from now (for example) should show BMP trends more definitively.

2. Although BMP results are helpful as indicators, they do not, even for the same waste lot and sample, correspond to decomposability and methane yield of the same waste in the landfill. This is because (a) BMP samples are finely ground and (b) their decomposition is carried out for a shorter time in the North Carolina State University lab, a few months. These will have opposing effects: finer particle size will increase decomposition but the shorter retention time will tend to decrease it. Thus, the BMP tests are best regarded as somewhat qualitative indicators.

3. The presently uneven liquid distribution is considered very likely due to remnant daily cover soil. This soil at Yolo is clayey and low permeability. Although diligent attempts were made to remove it, enough evidently remained so that it impeded liquid percolation. Evidence for better

liquid distribution with more permeable cover is found in results from the 9000-ton pilot-scale cell where more liquid permeable greenwaste cover was used rather than soil.

3.9 Waste Settlement and Volume Reduction

3.9.1 Northeast and west-side anaerobic cells

Settlement in the waste cells was monitored on an annual basis through a complete topographic map comparison. In addition to the complete topographic mapping, intermediate surveys were conducted on specific monument points established along the surface of the cells.

The following tables provide a summary of the complete topographic survey events along with the associated volume reduction.

Table 8. Summary of topographic information for the northeast cell

Survey date	Survey description	Total volume, yd^3	Change in volume from initial survey, yd^3	Change in volume from first survey, %
11/15/2002	Initial	132,295	NA	NA
01/16/2003	1st Year	128,613	3,682	2.78
01/28/2004	2nd Year	123,760	8,535	6.45

Table 9. Summary of topographic information for the west-side cell

Survey date	Survey description	Total volume, yd^3	Change in volume from initial survey, yd^3	Change in volume from first survey, %
01/16/2003	Initial	324,209	NA	NA
01/28/2004	1st Year	315,290	8,919	2.75

Settlement was also calculated utilizing a number of benchmarks established on the geomembrane liner. Initial elevations of the survey monuments were conducted during the initial topographic survey of each of the cells. The total depth of waste was then calculated based on the known elevation of the module liner. Subsequent surveys then established the new benchmark elevation, and the percent settlement was calculated relative to the waste depth at each benchmark location. The volume reduction presented in Tables 8 and 9 were consistent with the calculated settlement from the benchmarks (the 2.75% settlement from the 1/28/04 survey of the 6-acre cell compared to 2.57% calculated from the benchmarks). Results from the 3.5-acre cell were similar.

The following graph presents the settlement over time for the northeast 3.5-acre and west 6-acre cells along with the previous pilot-scale enhanced and control cells (Figure 19).

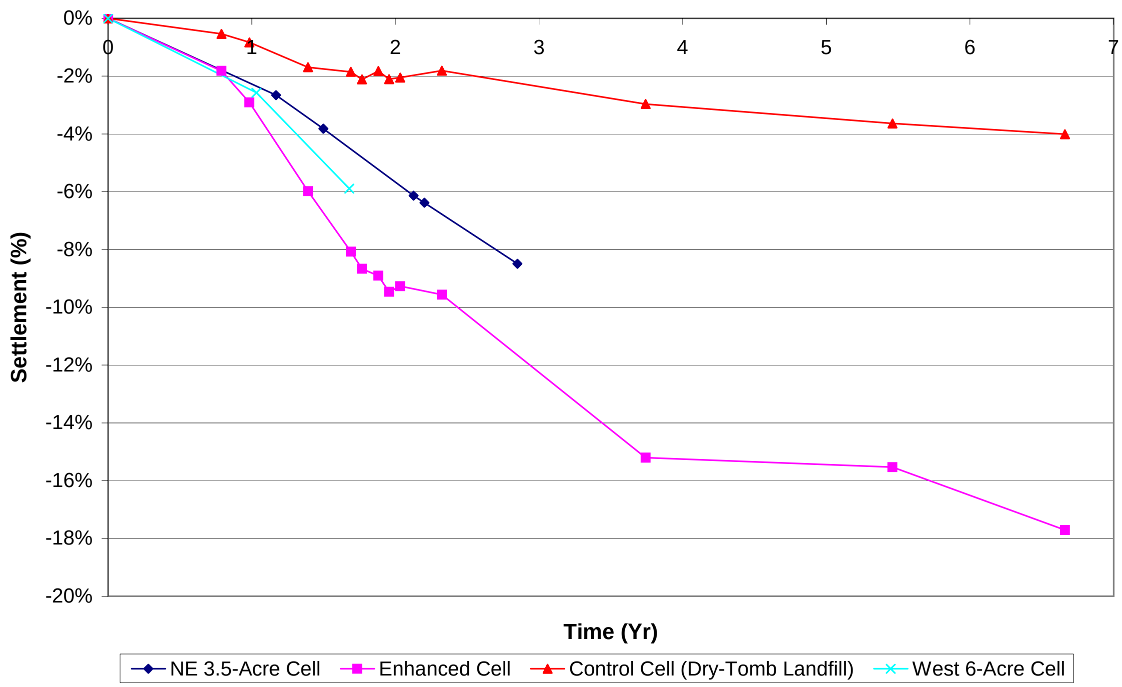


Figure 19. Settlement over time for the northeast and west-side anaerobic cell, along with the previous pilot-scale enhanced and control cells.

To rate the progress of each of the cells, the settlement measured from the cells were compared to the settlement measured from the pilot-scale project. During the first year, settlement in the pilot-scale project was approximately 2.9%, which strongly agrees with the first year results from both the 3.5-acre and 6-acre cells. During the second year of operation of the pilot-scale cell (May 1997 to May 1998) the rate of settlement increased significantly to approximately 1% every 2 months, reaching 9.47% at the end of the second year. In contrast, the northeast 3.5-acre cell has only reached 6.45%. The lesser amount of settlement observed in the northeast 3.5-acre cell is most likely due to the slow rate of liquid addition compared to the pilot-scale cell.

At this point in time, still early in the large-scale cells, it is noted that settlement in both large-scale cells is accelerated by 2 to 3-fold to date, compared to the dry-tomb pilot-scale control cell at the same point in time. As leachate addition and recirculation continues, we expect the overall settlement of each of the two cells to approach that observed in the pilot-scale project.

3.9.2 Southeast aerobic cell

The aerobic cell settlement is shown in Table 10. The measured settlement of 8.24% measured over 2 years appears to translate into an annual rate that is as great as the fastest settling northeast anaerobic cell. Though the aerobic cell certainly experienced oxidative waste breakdown, the cell was much less compacted at the outset than the anaerobic cells. Thus settlement of the aerobic cell could reflect the lesser initial compaction as well.

Table 10. Summary of topographic information for the southeast aerobic cell

Survey date	Survey description	Total volume, yd^3	Change in volume from initial survey, yd^3	Change in volume from first survey, %
11/15/2002	Initial	35,524	NA	NA
01/16/2003	1st Year	33,174	2,350	6.62
01/28/2004	2nd Year	32,597	2,927	8.24

3.10 Methane Production Modeling

A landfill methane generation model is a tool to estimate methane generation over time from a waste mass in landfill. Such a model is used to project or estimate methane generation from a batch of waste that is landfilled at a given point in time. The total methane production at given times, and over the landfill lifetime is obtained by summing the methane from all waste that is placed. Models can assist designers in sizing pipes for the gas collection systems installed for energy recovery, and for purposes including control of migration, odor problems, landfill gas emissions, and connecting the collection system to the energy production facilities.

Other than models, alternative means of estimating landfill methane generation is using landfill gas test wells. Such tests are performed in the field using a series of pump-tests. This is a very costly method and can take weeks or months to yield meaningful results. Another drawback is that pump tests only represent a point in time for the test locations in the landfill rather than a long-term result for the entire landfill. Landfill methane generation models have an advantage of being much less expensive and provide comparable accuracy to extrapolations of pump test results for the entire landfill.

3.10.1 Modeling

Landfill methane generation models are only accurate if sufficient field data are available for calibration. The accuracy of models can only be established over time by calibration against real recovery data measurements. Since numerous variables affect waste decomposition in landfills, the methane production is difficult to predict using the analytical and microbial kinetic models such as the Monod equation that predict the performance and activity of microbial processes for biological conditions that are known. The biological conditions are very difficult to determine for landfills. Another difficulty in modeling methane generation from landfills is that methane recovered from landfill is aggregated from many years of waste placement rather than from an individual batch of waste. The methane generation rate in a landfill is also a function of many site-specific variables such as waste type, waste composition, local climate, available nutrients, moisture content of waste, and waste temperature.

A number of models have been developed to predict landfill methane generation and recovery. The most commonly applied model is the first-order or Scholl Canyon model (EMCON 1981). In this first-order model, a constant fraction of remaining decomposable waste degrades each year. Methane generation is proportional to decomposable waste remaining in the landfill. The result is that methane generation decreases exponentially. This model uses a moderate margin to give the most successful projections (Vogt and Augenstein 1996). In 1996, the U.S. EPA made freely available its version of the first order landfill gas emission model (LandGEM) as a tool for estimating air pollutant emissions from landfills. This first-order model, often referred to now as the EPA model, uses a first-order decomposition rate equation. The methane generation is a function of two values: k, the methane generation rate constant, and L_0, the methane generation potential. The methane generation rate constant determines the rate of generation of methane of refuse in the landfill. The higher the value of k, the faster the methane recovery occurs and approaches completion over time. The value of k is a function of waste moisture, availability of the nutrients for methanogens, pH, and waste temperature. The k values reported by EPA vary over a wide range, from 0.003 to 0.21. However, the industry generally observes a narrower range of k values from 0.03 to 0.10. The value for the methane generation potential L_0 depends on the type of waste in the landfill. Waste with higher cellulose content would have a higher L_0. EPA has specified the values of theoretical L_0 to be in the range from 6.2 to 270 m^3/Mg waste (0.1 to 4.3 ft^3/lb). However, field observations showed a much smaller range for yield. The typical U.S. MSW compositions result in methane potentials normally ranging from 1.0 to 1.5 ft^3/lb of waste as received.

Despite the numerous variables that could potentially greatly affect generation, and the variance in k values reported by EPA, field data bear out models' utility when models are properly "calibrated". It was found in a major 19-landfill study (Vogt and Augenstein 1997) that most landfill gas generation from typical or conventional landfills can be projected to within –30% to +50% of a median projection using the EPA first-order model. In other words, waste composition and other conditions are such that conventional landfill methane generation can be projected with precision that is very useful for many purposes. Despite remaining uncertainty, modeling is helpful in sizing recovery systems, and also in estimating energy that might be recoverable. Furthermore, the model calibration can be improved by using the data from the landfill being modeled. It should also be remarked that the uncertainty of -30 to + 50% cited above is much better than results of some earlier models (including early versions from EPA) where modeling often gave results that were off by a factor of two or more. However, bioreactor landfills are "atypical" in that decomposition is much faster than conventional, so the question of how to model these is just now being answered by studies at Yolo County as described next.

3.10.2 Methodology

The objective of this report is to estimate the first-order gas generation rate constant for the northeast and west bioreactor cells under test in this project by applying the first-order EPA gas generation model. The methane generation rate constant, k, will be calculated for the northeast 3.5-acre and west 6.0-acres bioreactor cells according to the following methods:

Data for methane generation for the northeast 3.5-acre and west 6.0-acre anaerobic bioreactor cells were plotted as shown in Appendix B, Figures 34 and 35. Methane generation over the first long-term interval of increased methane production was taken from these figures to develop a preliminary model. The first interval of increasing cumulated methane recovery plots for each cell was extrapolated back to an adjusted "zero generation" and also taken up to the most recent time that data was available. A straight-line regression was performed on each curve as shown in Figure 19. This regression line was superimposed on the cumulated methane curve for northeast and west cells in Appendix B, Figures 34 and 35. Using the actual tonnage and initial moisture content of the waste, the data was normalized for calculation of methane generation rate constant as shown in Figure 19.

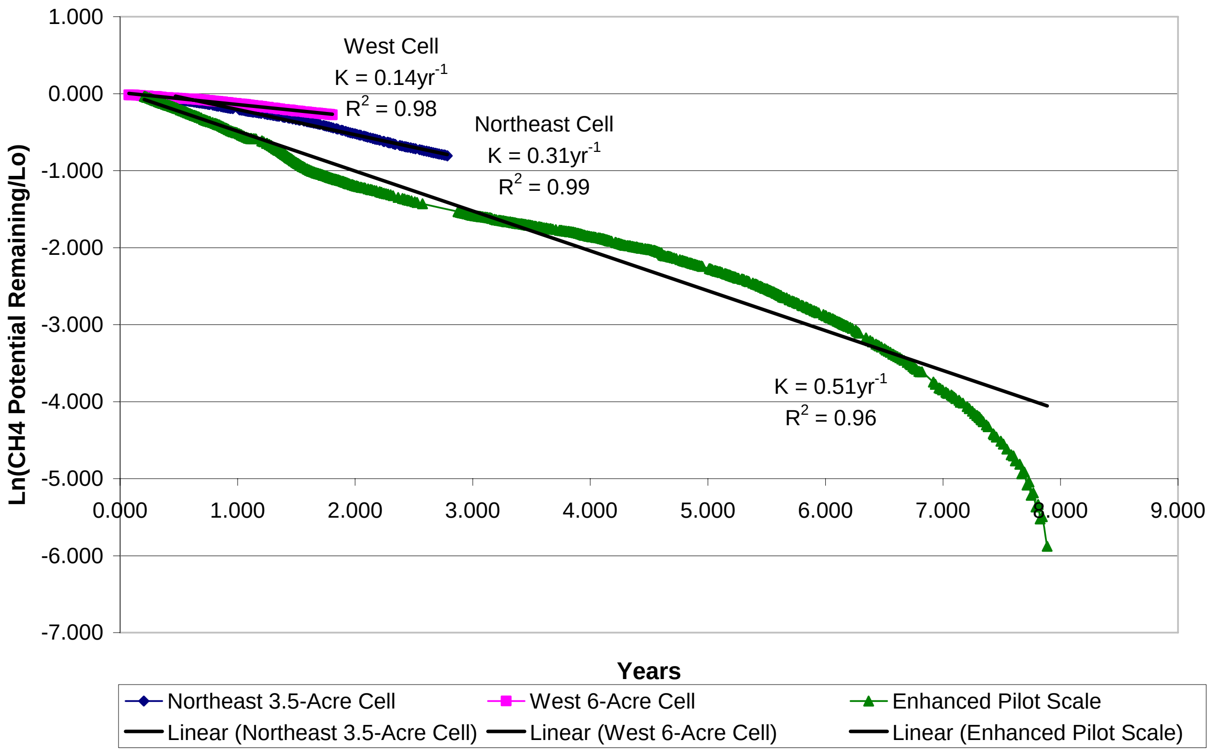


Figure 19. Calculation of k value for all cells, including previous enhanced cell

The best estimate of ultimate methane potential was assumed to be 1.4 ft^3 methane/lb dry waste, or 1.12 ft^3/lb wet waste. This was the best-fit yield result for the previous pilot-scale cells constructed in 1994 and the best information available. The fraction of ultimate methane potential recovered at each time was calculated over time for the northeast and west cells from the normalized methane yield (assuming this ultimate methane potential at L_0 = 1.4 ft^3 methane/lb dry waste). From this, the fraction of remaining methane potential was estimated using standard modeling methods.

Applying this model to the pilot-scale enhanced cell from the previous study at Yolo County Central Landfill resulted in a k value of 0.51 yr^{-1} (Figure 19 Also shown in Figure 11 are the data for the northeast 3.5-acre and west 6-acre cells for comparison. From these data, the preliminary values for k are:

- West 6.0-acre cell - 0.14 yr^{-1}
- Northeast 3.5-acre cell - 0.31 yr^{-1}

Although the scaled up cell k values are below the 0.51 yr^{-1} of the previous pilot-scale cell, the k of 0.31 yr^{-1} for the northeast cell is still very encouraging and over twice the usual dry landfill.

The lower 0.14 yr^{-1} for the west side cell may be due to the fact that only 1/3 of the planned liquid has been added.

These calculated values for the first-order rate constant k, have been determined relatively early in the methane generation cycle of the northeast and west side cells. It is important to note that the first-order model is not perfect, only that it best approximates methane generation. Many factors can affect k, including the further distribution of nutrients and bacteria that occurs within the waste with time as liquid percolates, and self generated temperature. Some degree of change in the best-fit k values are likely and best long-term k values will become known more accurately with time.

3.11 Energy Balance and Parasitic Use

An energy balance, though preliminary at this point, can be projected assuming,

- The gas will be recovered at a yield of 1.4 ft^3/lb dry waste (1.12 ft^3/lb wet waste) as seen in the pilot-scale cell, methane is recovered at 95% efficiency (it could actually be closer to 100%), and moisture content of the waste is about 20%.
- The pumping work on the gas is expended at 1 psi. Measured vacuum in the cell was actually well under 1 psi-- at a maximum of 3 in H_2O, about 0.15 psi. See Figure 31 where surface emissions are plotted as a function of vacuum.
- The liquid is percolated twice through the waste during the term of digestion.
- The head through which the liquid is pumped is 100 ft (it is less, but flow restrictions and inefficiencies make this a reasonable and still conservative assumption.
- The energy for all mechanical work can be accounted for by combustion of methane at 30% thermal (HHV) to mechanical efficiency. At this efficiency, the production of 1 kWh requires 11.4 ft^3 of methane.

It is important to note that the incremental energy associated with all other aspects of bioreactor operation will be (as closely as can be estimated) negligible. This is because all other operations would be required for waste landfilling in any event.

With these stated assumptions, calculations are as follows:

Methane out per ton = 2,240 x 0.95 = 2,128 ft^3 methane

Energy, methane equivalents per ton for gas pumping = 2,128 ft^3/ton x 1/(0.5 = fraction methane in gas) x 144 ft•lb/ft^3 x (1/ 2.6552 x 106 ft•lb/kWh) x 11.4 ft^3 CH4/kWh = 2.63 ft^3 methane equivalent

Energy, methane equivalents for liquid pumping = 30 (estimated) gal/ton x 8.32 lb/gal x 100 ft elevation x 2 cycles percolating through waste x (1/ 2.6552 x 106 ft•lb/kWh) = 0.21 ft^3 methane equivalent

So in summary, an energy balance, stated as cubic feet of methane recovered per ton, is as follows:

Gross methane energy out of bioreactor = + 2,128 ft^3 methane equivalent

Minus energy for gas pumping= - 2.63 ft^3 methane equivalent

Minus energy for liquid pumping = - 0.40 ft^3 methane equivalent

Net energy output = + 2,125 ft^3/ton methane equivalents

In any case, it now seems clear that with a range of energetic accounting approaches and assumptions, that the incremental parasitic energy requirement will be well under 1%. Such low parasitic energy consumption for the controlled landfill bioreactor is obviously desirable.

We would like to note as an aside, another important aspect of municipal waste to methane conversions in bioreactor landfills. A recent review of the compiled waste-to-methane literature (Verma and Shefali 2002) has compiled yields per unit waste fed to the European vessel processes. The Yolo pilot-scale bioreactor has actually produced significantly more methane per unit waste fed, by 20 to 50%, than the methane per unit weight of waste with European approach of carrying out conversion in vessels. This is because only about 60-75% of organics' methane potential can be realized in economically allowable vessel detention times (2 weeks to 2 months), and extended residence times of a year or more appear required for full conversion. The bioreactors greater energy yield is also obtained despite use of landfilled waste that was not ground or reduced in size (this is also a very important finding because size reduction at $10-$30/ton would translate to prohibitive expense, adding over $5/mmBtu to gas cost). The vessel-based process also consumes about 35% of the produced energy in the best of cases (De Baere 2004) and up to all energy in the worst of cases that have been compiled by Dr. Wellinger (1995) and others in Europe. Thus, the bioreactor is estimated to produce about twice the net energy of the vessel based digestion processes. The better net energy performance comprises yet another argument for the bioreactor landfills.

3.12 Carbon Monoxide and Suspected Thermal Decomposition in Aerobic Cell

Aerobic bioreactors, or alternatively aerobically composting landfills are relatively new. One of the possible dangers of operating an aerobic bioreactor, supported by anecdotal reports, is that of fire or thermal decomposition within the landfilled waste mass. If fires are encountered frequently, they could be a serious impediment. In any case, the detection and suppression of thermal decomposition in aerobic landfills is of high interest. Thermal decomposition detection and suppression was part of the Yolo County contingency planning before CO was detected.

The best indicator of fire or thermal decomposition is considered to be elevated concentrations of CO, which would result from oxygen-limited fire within the waste. The limits are not well established, since small amounts of CO (a few ppm) can be naturally present in gas from landfills. However, a sudden rise from less than 5 ppm to 50 ppm or more would be a cause for investigation. The gas from the total exiting the header can be routinely checked for CO. If elevated concentration of CO is seen, individual gas exit lines serving portions of the landfill can be investigated. An elevated CO level in one or a few individual headers, well above that in the mixed exit gas, would indicate thermal decomposition. So would elevated temperatures, if measurable in zones of concern. Conversely, a uniform CO concentration across all headers would tend to suggest that CO could conceivably be arising naturally from non-combustion causes.

Testing of total gas in the main header from the aerobic bioreactor by Draeger carbon monoxide detection tubes began in November 2003. Potential problems were suggested by the detection of CO levels at 40 ppm in the main header and 600 ppm in a well on November 4, 2003. This was in contrast to negligible levels of CO seen earlier. (The CO levels were less than 5 ppm, or Not Detectable in earlier laboratory gas analyses.) To trace down the source, the exit gas from each individual header was analyzed. A CO level test of the well designated 1-A4 -SE (see Appendix D) showed a reading of 600 ppm, and 45 ppm CO in the lines to either side (west and east) of the line giving 600 ppm. A test of the same line on November 6, 2003 again showed 450 ppm CO (field log).

When these elevated readings were found, a traverse of the headers was carried out to detect any hot spots (i.e. elevated temperature). Although the thermocouple did not traverse the entire gas collection line, temperatures approaching 70°C were seen in the header showing the highest CO concentration. All available information, taken together, suggested that a small area of thermal decomposition had started within the waste. Despite elevated CO, there was no odor of smoke that often accompanies thermal decomposition. However, thermal decomposition was possible even without the characteristic burned or smoky odor.

3.12.1.1 Response to Suspected Thermal Decomposition

Two possible strategies for dealing with thermal decomposition are (a) water addition and (b) use of liquid nitrogen (LN2), a very cold (-300°F) liquefied gas that quenches combustion. LN2 is an industrial product available in bulk at relatively low cost. It was considered superior because nitrogen added as liquid vaporizes quickly and the resultant nitrogen gas would expand to infiltrate to the suspected fire zone faster than water. Discussions among the Yolo County project team suggested LN2 was worth trying. A tanker truckload of 42,000 lb of LN2 was arranged from MG Industrial Gases (Vacaville, CA). The tanker load was injected on November 14, 2003, into the header showing the highest CO concentration in the outlet gas. Appendix C shows steps in the nitrogen injection into the lateral that had the highest CO reading.

3.12.1.2 Results of Liquid Nitrogen Injection

After injection, the gas sampling tubes emplaced in the landfill showed nitrogen to have expanded into a wide zone. Also, temperature, as expected, was considerably depressed in the zone around the line receiving the injection.

Unfortunately, indications of thermal decomposition reappeared after the nitrogen injection. The CO content in the lateral initially showing the highest reading returned to a reading of 280 ppm in the well and 450 ppm in tube 1-12-SE on November 19, 2003. CO was also detected at 40 ppm in the mixed gas in the main header on November 20, 2003.

3.12.1.3 Additional Measures – Water Addition

A second approach was adding water to the suspected area. Water additions to the waste began on November 25, 2003. Additions were to the lateral in layer 1 showing the highest CO concentrations and nearest the suspected thermal decomposition, and those laterals on either side. The total amount of water added from the start of addition on November 25, 2003, to December 17, 2003 was 115,532 gal. Once the water addition was completed, CO levels were less than 5 ppm. Summary of the water additions are shown in Table 11.

Additions were to the lateral 1-L7-SE, which initially showed the highest CO reading Additions were also made to adjacent laterals 1-L9-SE and 1-L5-SE (See Appendix D for details and locations of laterals). Some additions were to the lateral 2-L5-SE, the one above lateral 1-L7-SE. Only the total daily additions are shown below.

Table 11. Summary of liquid addition to the southeast aerobic cell

Date	*Water added, gal*
11/25/2003	13,913
11/26/2003	7,502
12/10/2003	11,332
12/02/2003	11,670
12/03/2003	2,705
12/04/2003	4,578
12/08/2003	14,777
12/09/2003	6,775
12/10/2003	5,875
12/11/2003	6,532
12/12/2003	6,111
12/15/2003	8,587
12/16/2003	9176
12/17/2003	5,859
TOTAL	115,232

Calculated waste decomposition. If it is assumed that CO indicates slow thermal decomposition or fire, the amount of waste involved in the decomposition can be roughly estimated based on collected CO. It is assumed that 20% of the decomposed waste may go to CO based on experience with gasification and pyrolysis (this estimated value is likely only accurate to within a factor of perhaps 3, but it is interesting to know the magnitude, even if not approximate, of the waste involved in any problem). At an extraction rate of 10 CFM and average CO concentration in the exit gas stream of 50 ppm for a month, it can be calculated that 36 lb of waste were consumed over the month. This may actually mean that an amount of waste likely between 10 to 100 lb of waste was consumed. The fire or thermal decomposition was likely limited by oxygen access. However, this would not always be the case if air were drawn through the waste mass at projected rates in the future. The principal value of this experience was to show the value of early CO detection and suppression of undesired reactions or fire, especially before water addition has started.

4 PROJECT OPERATIONS, CONTROL AND PREVENTATIVE MAINTENANCE

The following section is divided into 3 subsections associated with the major systems for the bioreactor cells. Each subsection discusses the operation and maintenance activities for each of the cells.

4.1 Leachate Pumping and Injection System

The leachate pumping and injection system includes the main injection header and laterals for each of the cells. Also included are the leachate recirculation pumps located in the leachate collection sumps of each cell and the liquid addition pumps located in the adjacent leachate ponds.

Initially, a fully automated liquid addition and recirculation system was envisioned for this project. In practice though, a predominantly manual system has evolved. Injection is controlled to each lateral by a manual valve and injection is cycled through banks of valves periodically. Liquid addition from the leachate ponds was controlled manually and typically involved pumping for a 24-hour cycle, and with a down period to allow the liquid to infiltrate. Leachate recirculation, on the other hand, was automated. When leachate levels reached a certain level in the sumps, pumps were automatically cycled and the liquid was removed from the sump and recirculated to the cell (to whichever bank of laterals was open).

4.1.1 Maintenance

Prior to beginning injection in the northeast 3.5-acre cell, each injection lateral was tested and calibrated to determine the flow potential of each lateral. During this testing, several leaks in the system were discovered and repaired. The leaks discovered during testing were the result of an incorrect gasket installed for the saddle and injection header pipe during initial construction of the system. To repair the leaks, each saddle was removed and reinstalled with the correct gasket.

In June 2002, minor leaks in the threaded fittings located at the leachate injection lateral valve assembly were discovered, thus each fitting was tightened.

In August 2002 a major leak was discovered in the leachate injection header line. The leak developed at a butt fusion weld joint and was the result of a faulty fusion weld at the time of initial construction. The construction contractor was notified and performed the repair under warrantee. To ensure no contamination occurred in the area of the leak, all of the standing water was removed and any wet soil was excavated and buried at the active face of the landfill.

Over the course of several months, the flow rate for each injection lateral was observed to be decreasing slowly over time. An investigation revealed that calcium precipitate was forming on the inside of the injection piping. The source of this precipitation was the leachate that was being injected into the cell, which chemical analysis revealed to have extremely high amounts of dissolved solids and a pH of over 9. On September 11, 2002, approximately 3000 gallons of citric acid (pH approximately 4) was added to the injection laterals on the northeast 3.5-acre cell to dissolve scale buildup. The citric acid was added to the injection laterals and allowed to set for approximately 14 hours. Groundwater was then flushed through the injection lines to remove the citric acid and scaling residue. Once the scale buildup was removed from the injection laterals, the flow rates for each lateral returned to its pre-clogged condition. To prevent future clogging, only groundwater (with lower total dissolved solids and pH) has been added to the bioreactor since.

During the month of May 2003, a valve was installed on the main leachate injection header line that fed both cells, allowing the majority of the header line to be drained back into the cells leachate collection and removal system in the event maintenance to the line was necessary.

A pressure relief valve was installed on the main leachate injection header line at the on-site leachate storage pond to prevent over pressurization of the leachate injection systems. In the event an over pressurization occurred (if for instance a main valve was accidentally closed while a pump was running), the pressure relief valve would open and allow liquid to flow back into the on-site storage pond.

Prior to beginning injection in the west 6-acre area, each injection lateral was flushed with clean water to remove any debris that may have deposited during construction activities. Each lateral was then pressure tested to ensure that there were no leaks in the system.

In July 2003, leachate addition in the west 6-acre area was temporarily halted due to liquid buildup under the surface liner at the toe of the slope on the west side of the cell. An investigation determined that liquid most likely injected into layer 4 had migrated laterally until it reached the surface liner, where it then traveled down between the surface liner and soil cover until it accumulated at the toe of the slope. To mitigate this situation, County personnel cut a small hole in the surface liner and pumped approximately 110 gallons of accumulated liquid. To prevent this situation from reoccurring, a portion of the surface liner was temporarily removed so that a subsurface drainage layer could be installed to allow any future liquid to drain into the Module 6D leachate collection and removal system. The liner was then replaced and repaired. Liquid addition in the west 6-acre cell resumed in August 2003.

In September 2003, a volumetric analog flow meter was installed on the main leachate injection line for the northeast 3.5-acre cell. This flow meter was used as a backup meter and for verifying readings from the previously installed digital flow meter.

In March 2004, leachate was again found to have built up under the toe of the west-side surface liner. In this instance, the liquid build up occurred near the southwest side of the module. In response, the County installed additional tire and gravel drainage trenches in the areas of liquid buildup. As a preventative measure, the County also completed a drainage trench along the remaining portions of the west side of the cell. In total, approximately 600 ft of drainage trench was installed along the west side of the cell. It appears that the cause of this problem was a layer of soil that was placed during the filling phase of the cell (6 inches of daily cover is regulatory), but was not completely removed prior to the next lift of waste being placed. These problems that Yolo County have encountered underscores the need to tightly control the amount of soil placed in bioreactor cells, because it can severely impede downward percolation of liquid.

During the installation of these drainage trenches, 3 moisture sensors were installed to monitor the performance of the trenches. If moisture readings were to increase, it would be an indication that the trench may not be draining as intended. To date, 2 of the moisture sensors are reading dry conditions and one is indicating liquid buildup.

The sensors will continue to be monitored to assess the effectiveness of the trenches. Elevated sensor readings might indicate limited liquid intrusion that could be of minor importance. But if any additional sensor registers increased liquid additional steps may be taken. The nature of these steps would be decided by the project team.

4.2 Gas Collection System

The gas collection system for the northeast and west-side anaerobic cells and the southeast aerobic cell consists of the main collection header, the horizontal collection lines connected to a main collection header. The main headers on the anaerobic cells were connected to an on-site LFG-to-energy facility, and the header on the southeast aerobic cell was connected to a biofilter and on-site blower station.

The gas collection systems were operated manually. The main collection header valve was opened such that enough suction was available for collection of gas across the entire cell. Adjustments to the wellheads at each LFG collection line were performed manually during the weekly field readings, and were based on the gas composition. High methane contents above 50% meant an increase in flow was desired for that particular collection line, whereas concentrations below 45% meant a reduction in flow.

4.2.1 Maintenance

In order for a landfill gas extraction system to maintain operation, it is necessary for the piping to be graded such that condensate cannot collect in low spots and block the flow of landfill gas. In the fall of 2004, it was necessary to adjust the grade of the header lines for both cells due to waste settlement. As the waste continues to decompose and settle, re-leveling of the header to eliminate any low points will continue to be necessary.

Though PVC pipes had the advantage of being inexpensive and easy to assemble, they also had the disadvantage of being susceptible to damage by UV radiation. To prevent this, all of the exposed piping were painted with exterior grade latex paint, and repainted as needed. In addition, flexible couplings also needed replacement due to UV degradation.

A gas collection lateral carrying sensor lines was found to be leaking gas condensate where the sensor lines exited the piping. Previously, the sensor lines exited the pipe through a hole that was sealed with silicone, however this proved ineffective. To correct the leaks, special watertight fittings were installed on each sensor line.

Prior to completion of the biofilter and blower station, the southeast aerobic collection header was connected to the gas-to-energy facility. This was done to prevent surface emissions. On July 31, 2003, the gas collection header line was disconnected from the gas-to-energy facility and connected to the biofilter system in preparation for operation. Due to delays in construction, operation did not commence in the following months and the piping was reconnected to the gas-to-energy facility on September 30, 2003.

On August 25, 2003, the landfill gas flow meter for the west 6-acre cell was found not operating. The flow meter was sent for servicing and a back-up flow meter was temporarily installed. On September 26, 2003, the permanent landfill gas flow meter for the west 6-acre cell was received from servicing and reinstalled.

During September 2003, the LFG-to-energy facility partially shut down for several weeks due to a mechanical failure of a compressor unit used to feed landfill gas to the engines. The shut down resulted in low landfill gas flow rates and consequently a build-up of positive pressure under the surface liners. To reduce pressure and increase gas flow rates, perforated piping was installed directly under the surface liner at one location on both the northeast 3.5-acre cell and the west 6-acre cell. The piping was then connected to an existing gas well. The installation of the piping reduced the pressure under the surface liner and enabled landfill gas flow rates to increase by approximately 30 scfm from each 2-inch well.

Over the course of the project, numerous landfill gas collection lines have become temporarily blocked with liquid as a result of leachate injection activities in both the northeast and west cell. As leachate is injected into the cells, liquid levels build up to such a level inside the shredded tires layer (that comprises the gas collection line) that the gas collection piping becomes blocked. This phenomenon was expected during the design phase of the project, and as a result, significantly more landfill gas collection lines were installed (so that several could be blocked at any one time) than would typically be required. As a way of compensating for the reduced horizontal collection lines in the west 6-acre cell, four vertical collection lines were installed in the bores used for waste sampling.

With so many horizontal collection lines being blocked, the County wanted to try to better understand the gas permeability of the waste. Pressure sensing tubes were installed in each of the west 6-acre cell gas lines. The County will continue to monitor the clogging and unclogging of the gas collection lines to better understand the relationship with leachate injection in hopes of reducing the duration and frequency of this phenomenon. During the installation of the pressure sensing tubes in the gas collection lines, significant leachate buildup was discovered in 4 gas collection lines (2-G3, 2-G4, 2-G6, and 2-G7). Previously, leachate buildup had been suspected but not confirmed, because it had not been possible to collect landfill gas out of these lines. By utilizing the recently installed pressure sensing tubes, it was possible to drain leachate out of these lines with 2-G2, 2-G4, and 2-G6 draining for approximately 10 days and 2-G7 draining for nearly 7 weeks. Even though significant leachate was drained out of these lines, they remained blocked, most likely due to liquid buildup deeper in the cell.

On February 13, 2004, the aerobic cell off-gas was temporarily sent to the biofilter for treatment. This was the first of several tests that lasted a few hours and were intended to test the operation of the blower station and biofilter. Full-scale operation was anticipated to begin in August 2004, but was further postponed due to unresolved problems discussed in Section 3.12, however collection of landfill gas was reinitialized in December 2004. Once operation of the aerobic cell commences, all the off-gas will be collected and sent to the biofilter for treatment.

4.3 SCADA and Instrumentation System

The SCADA system is responsible for most of the data collection associated with the bioreactor project. The various sensors hooked up to the system include temperature sensors, moisture sensors, pressure transducers, and flow meters.

The SCADA system incorporates two main components. An Allen-Bradley small logic controller (SLC), which is essentially a small computer, controls the data collection from all the various sensors. A personnel computer is linked to the SLC and makes up the second half of the SCADA system. A program called Wonderware InTouch® is then used to display the data graphically.

4.3.1 Maintenance

To-date, essentially no maintenance of the SCADA system has been necessary. During the initial development stage of the system, it was necessary to perform program revisions to correct several bugs, but over the course of the last year, the system has performed extremely well.

Pressure transducers used to measure head over the liner have been removed several times to test their operation and recalibrate as necessary. During the most recent removal process, the cable that is used to remove pressure transducers 4 through 6 (which are under the northeast 3.5-acre cell) broke and we were unable to remove them. The inability to remove these sensors was compounded by the fact that pressure transducers 4 and 5 were reading significant leachate levels, but these readings were not supported by the pressure sensing tubes. The County plans to perform a video inspection of the pipe that the transducers are installed in the spring in hopes of determining the cause of the cable break (we suspect a crushed pipe) and confirm the lack of liquid buildup on the liner.

A number of temperature sensors have failed and were removed from the SCADA system. Moisture was speculated as the cause for failure of the sensors, but has not been confirmed. To date, the number of failed sensors in the northeast, west-side, and southeast aerobic cells are 13, 18, and 6, respectively. A total of 9 temperature sensors in the baseliner have failed. Attempts to revive the failed sensors by inducing a current through the wire proved unsuccessful.

4.4 Surface Liner Cover System

A geomembrane cover was installed over both of the bioreactor cells. A 36-mil RPP was used on the northeast 3.5-acre cell and a 40-mil LLDPE was used on the west 6-acre cell.

4.4.1 Maintenance

As part of a preventative measure for excess uplifting or ballooning of the geomembrane cover, a rope and sandbag ballast system was installed on the northeast 3.5-acre cell. Special UV resistant sandbags that have a life expectancy between 3 and 5 years were used, however, almost immediately following installation of the sandbags, damage began to occur. This damage was not the result of UV radiation, but the result of seagulls pecking holes in the bags. To prevent further damage, each sandbag was covered by a tire and piece of geomembrane. To prevent water being trapped in the tire and a subsequent mosquito problem, the bottom sidewall on each of the tires was removed.

In contrast to the sandbags used to secure the surface liner of the northeast 3.5-acre cell, tires were utilized on the west 6-acre cell because of their durability. Rather than place a complete rope and tire grid over the entire surface cover, the County opted to only place tires in areas that were susceptible to wind uplift. Throughout the course of the project, tires were placed in areas of localized wind uplift. The result of this change was positive in that the surface liner remained intact and the County saved significant time and money as compared to the northeast 3.5-acre cell, without sacrificing liner performance.

At the end of 2003, the surface liner ballast system (either tires or sandbags) required further maintenance. For the west 6-acre cell, additional tires were placed on the liner in areas where they had not previously been installed. During this phase, the County experimented with the use of solid "forklift" tires rather than the previously used passenger car tires with rims. The advantage of the forklift tires was two-fold. First, they were significantly heavier than the passenger car tires, and second, because they were solid, it was not possible for them to trap rainwater in the tire. To reduce the costs associated with this work, labor from the County probation department was utilized. In the northeast 3.5-acre cell, some of the sandbags had become damaged and were replaced with forklift tires.

During the original installation of the surface liner over the west 6-acre cell, the County elected to not install geomembrane boots at each of the liner pipe penetrations. This was done as an experiment to see if surface emissions could be controlled and with the benefit being significantly reduced cost for liner installation. Unfortunately, surface emissions were detected. The initial effort to reduce surface emissions involved using waterproof and airtight expansion foam to seal the surface liner at the pipe penetrations. Surface emissions persisted so permanent geomembrane boots were installed in January 2004. Even following the permanent boot installation, some moderate emissions were still detected. As a result, additional gas extraction wells were installed under the surface liner, which we believe will eliminate any residual emissions.

5 PROJECTS ECONOMICS

In this chapter, sections 5.1 and 5.2 first present costs actually experienced at the YCCL for the scaled up northeast and west anaerobic bioreactor cells. Following these, in sections 6.3 and 6.4 are the projections for a commercial operation.

5.1 Capital Costs

The total capital costs for the Full-Scale Bioreactor Landfill at YCCL during the contract interval are shown in Table 12 below. An explanation of the derivation of each capital cost item is presented in this section.

Table 12. Summary of capital costs for Yolo County Central Landfill's Full-Scale Bioreactor Project during the contract interval

Item	Description	Capital cost
5.1.1	Base Liner Costs	$ 3,364.67
5.1.2	Surface liner Costs	$ 454,923.72
5.1.3	Liquid Addition and Pumping	$ 193,606.85
5.1.4	Landfill Gas Recovery	$ 102,855.39
5.1.5	Instrumentation	$ 126,203.14
5.1.6	SCADA	$ 137,429.80
5.1.7	Total "other" design, administrative	$ 82,843.30
	Total capital costs	$ 1,101,226.87

5.1.1 Base Liner Costs

The marginal cost of the base liner attributable to the bioreactor has been minimal, at $3,364.67. This is because the base liner and its experienced costs would be required in any event.

5.1.2 Surface Liner Costs

The surface liner cost is high, at $454,923.72 for 9.5 acres, or over 400,000 ft^2 with effect of side slopes. Note here that similarly high cost for surface liner is unlikely to be experienced again if total capture of gas is not desired. Because of the nature of this research project, Yolo County wanted to install a cover system to control and measure all of the gases produced.

If a surface liner is used, the cost per acre would be comparable to other such liner installations, estimated at under $1/ft^2$, and possibly much lower. This reflects the fact that the purchased cost of the liner material (without installation) generally runs under $0.25/ft^2$. And given the welding requirements and accessibility of surface liner, if used, certain components such as Construction Quality Assurance (CQA) would be less demanding than with base lining.

5.1.3 Liquid Addition and Pumping Costs

Liquid addition and pumping costs were $193,606.85. This included the cost of design and construction for liquid injection and pumping capital cost.

5.1.4 Landfill Gas Recovery and Utilization Costs

Landfill gas recovery capital costs were $102,855.39, covering the horizontal gas collectors placed in trenches in the waste as landfilling proceeded, and the associated piping system.

5.1.5 Instrumentation Capital Costs

Instrumentation capital costs were $126,203.14. This includes the design and material costs for installation of instruments.

5.1.6 Supervisory Control and Data Acquisition System (SCADA)

The Supervisory Collection and Data Acquisition System capital cost totaled $137,429.80.

5.1.7 Other Capital Costs

Other capital costs include other more general components. These are allocable among several categories, partly to capital. In detail, these costs are assumed at 100% of Project Startup at $926.38, half of Project Management and Data Analysis, $57,202.02 and $24,714.90 for a total "other" of $82,843.30.

5.2 Operation and Maintenance Costs

Costs in the section below were in some cases aggregated rather than broken down in detail for the project. For example, maintenance of the cover (repairing leaks) and of the landfill gas and leachate collection systems is all contained (aggregated) in other categories, such as instrumentation and equipment maintenance. However, costs listed give a good overall picture of the maintenance cost.

Note that the testing costs have major experimental components and purposes. It is estimated by the project team that most of the costs below would be at least considerably reduced in a commercial operation.

The total operating costs are summarized as follows in Table 13.

Table 13. Summary of total operating costs for Yolo Field Experiment

Item	Description	Capital cost
5.2.1	Waste sampling and analysis	$ 41,354.05
5.2.2	Field testing and monitoring of Landfill gas	$ 127,208.40
5.2.3	Leachate Sampling and Testing	$ 61,694.96
5.2.4	Methane emission monitoring	$ 34,516.90
5.2.5	Landfill Settlement Surveys	$ 35,629.09
5.2.6	Methane Production Modeling	$ 7,770.59
5.2.7	Instrumentation and Equipment Maintenance	$ 62,938.29
5.2.8	Project Management and Data Analysis	$ 114,404.13
	Total Operating Cost	$485,516.41

5.2.1 Waste, Leachate, and Gas Sampling and Testing

The waste sampling and analysis costs were incurred during sampling and characterizing of waste from the landfill. Moisture content indicates the degree to which moisture has distributed in the landfill and the biochemical methane potential tests give a check of the methane potential of the waste. The total costs were $41,354.05.

Leachate sampling and testing costs were for the purpose of determining leachate pollutant loads. This in turn, is related to the reduction of risk for groundwater contamination as discussed elsewhere in this report. Total cost was $61,694.96.

Costs experienced for field testing and monitoring of landfill gas totaled $127,208.40. These were for purposes of characterizing landfill gas methane content, VOC content, and generally assessing the quality of gas recovered from the Full-Scale Bioreactor project.

The amount of testing and monitoring was largely for experimental objectives specific to the project, and less testing would normally be required in a large landfill running at steady state.

5.2.2 Instrumentation and Equipment Maintenance

Instrumentation and equipment maintenance include a number of necessary items not broken down or appearing elsewhere. Examples of these include gas flow meter repairs, repairs of cover leaks, and a wide variety of operational activities. The total cost for these in the contract interval has been $ 62,938.29.

5.2.3 Methane emission monitoring

Methane emission monitoring is a standard requirement to determine landfill emission compliance under EPA and California rules. As an experimental program, frequent emission testing was, among other things, a condition of Full-Scale Bioreactor project under EPA's Project XL. In the Project XL circumstances, emission monitoring was several fold (about 3 times) more frequent than would be required in a commercial operation. The total cost was $34,516.90.

5.2.4 Landfill Settlement Surveys

Landfill settlement, item 5.2.5 in Table 13, is an important measurement parameter, indicating how much additional space may be made available as placed waste decomposes and loses volume. The total cost for landfill settlement surveys was $35,629.09.

5.2.5 Methane Production Modeling

Methane production modeling was conducted to determine the kinetic coefficients for waste decomposition. Decomposition rates and kinetic parameters are extremely important as indicators of the efficacy of bioreactor operation. The total charge for modeling work during the contract interval was $7,770.59.

5.2.6 Project Management and Data Analysis

Project management and data analysis costs were $ 114,404.13. This project management and data analysis category is self-explanatory and includes the management activities and data interpretation needed for the project activities in the contract interval.

5.3 Cost for a Full-Scale Commercial System

5.3.1 Summary of Costs for a Commercial System

5.3.1.1 Electricity-only case

The costing in the simplest electricity-only case for a commercial system reduces to a very straightforward situation. The basic assumption is that a waste stream must be managed through landfilling. Governing factors in the "simplest" case are,

- The benefits of bioreactor operation, independently of energy recovery, justify implementing a bioreactor by themselves.
- For most landfills where a bioreactor would be implemented, gas must be recovered using best available control technology.
- Availability of recovered gas at effectively very low or no marginal cost is a "given".
- The cost of electric power is that of the genset running on "free" fuel.

In contrast to previous reports in earlier years on the Yolo project, we do not attempt to cost out in detail the operational costs of engine-generator sets. The project team's expertise is less than other organizations more experienced in landfill gas conversion to energy. We use the costs reported by Waste Management, Incorporated (WMI). WMI generates over 600 MWe of its own electricity from solid waste sites and fuels in including over 200 MWe powered by internal combustion (spark-ignited) engines on landfill gas. The presentation we cite here is that of Paul Pabor, vice president, renewable energy, Waste Management, Inc., "The Energy Value of Landfill Gas". This talk was presented at various symposia including the RecycleMinnesota Symposium in October 2002 and can be found at:

http://www.recycleminnesota.org/2002_conference.htm

For discussion purposes, Mr. Pabor of Waste Management, Inc. notes the following parameters for the average landfill gas to energy (LFGTE) Project:

- 1,600 CFM of landfill gas,
- 400,000 mmBTU/yr,
- 4000 kWe,
- About 32,000,000 kWh/yr.

For this size plant the capital cost is $3.2 to $5 million ($800 to $1250/kWe) and would be comprised of:

- Site Work,
- Building,
- Gas conditioning,
- Equipment (electricity generation) price,

- Interconnect and other miscellaneous.

With this cost picture, the total cost to generate power is generally in the range of 2.5 to 3.5 cents/kWh consisting of these general elements:

- Capital costs,
- Financing costs,
- Depreciation period,
- O&M contract
- Taxes, administration, permitting.

The sole adjustment to power costs would be the application of fairly standard scale factors to account for larger or smaller scales. Otherwise, although the cost picture could be broken out in more detail, the summary of cost by Waste Management is based on the largest experience base in the world, and estimates of more cost detail by us would not, in our view, add significantly to precision.

5.3.1.2 Landfill Gas Price

Electricity cost in following sections does not include any LFG purchase price. Although the landfill gas is a necessary byproduct of bioreactor operation, thus at no net cost to produce, it is often necessary to assign a transaction value, essentially a purchase price for tax purposes (usually only a few percent of the energy worth), because of the intricate IRS tax code section 29. However, this is a minor internal transaction and mostly "out of one pocket and into the other". An energy system must simply be self-justifying on its own merits, i.e. the cost is that of an engine or turbine that is supplied with fuel in the form of landfill gas at what is effectively no marginal cost. As will be seen later, the long-term economic picture is good but there are non-technical barriers of other sorts, permitting requirements, and risks that remain as barriers so the picture is not nearly so simple as this might imply.

The electricity generation cost has been calculated for a 500 TPD and 1000 TPD (365 day/year time average) landfill operation as follows in Table 14.

Table 14. Summary of example electrical generation scenarios

Waste inflow, TPD (time average 365 day/yr)	Power output time average, MWe	Power output, MWh/ yr	Approx. capital Cost, $/kW capacity	Total Plant capital cost, Million $	Cost of generation, Cents/kWh ($/MWh)	Net revenue or profit with sale at 50/MWh, $/yr
500	4.65	40,548	$1200	$5.6	3.5 (35)	$608,000
1000	9.30	81,096	$900	$8.4	3.0 (50)	$1,621,000

This summary represents only two examples distilled or culled from the wide range of power generation scenarios that are actually very complex. The detailed calculations and determinations of performance and power revenue/cost data are presented in subsequent sections 5.3.2 to 5.3.5. The bioreactor can potentially be self-financing based on benefits that are independent of power generation. The benefit/cost ratio calculations for a bioreactor are discussed later in section 6.4.

5.3.1.3 Comment on costs: Incremental costing

The costs presented in this section, whether for power generation or bioreactor operation, are only those incremental costs that would be incurred as the result of operating the landfill as a bioreactor. For example, (a) leachate, the liquid that percolates from the base of the waste, will be present in any case. It must be addressed by an adequate leachate handling/recovery system needed and in fact mandated in all landfills to prevent groundwater contamination. (b) Waste surface coverage will be required in any event to standards that assure continuing coverage with time, as well as assuring rodent, bird exclusion, etc. (c) All normal maintenance and operation work will be required in any case. Cost assumptions are based on the professional judgment of the project team, and experience, and the assumptions used are listed with each cost component developed. Note that in this simplified analysis, the stated installed costs incorporate engineering and design.

5.3.2 Kinetics of gas generation and capture

It is necessary for calculations to follow to assume methane generation kinetics and yield coefficients.

A methane generation yield of 3000 ft^3 (3 million Btu's or mmBtu hereafter) per ton is assumed. Before enhancement, gas is generated with a first-order kinetic rate constant of 0.04 yr^{-1}. Gas generation is assumed to occur with a rate constant of 0.20 yr^{-1} after enhancement begins. These yields and coefficients are from sources including results with the Yolo County Demonstration cell, and the report. This parameter is important, not so much as a cost factor, but in extrapolating the time course of gas recovery and electricity production.

5.3.3 Assumptions about modules

A number of design features must be assumed in order to conduct an economic and performance analysis, and the design must be one that can be straightforwardly implemented at typical U.S. sites.

The landfilling occurs in modules, (also commonly referred to interchangeably with cells, although a module can contain more than one cell or "subcell"). Assumptions about module size are important in the analysis, as they refer to filling time and fugitive emissions during filling. A module can be any size, from 5 to 30 acres but for bioreactor operation a module should be of a size that can be filled quickly, in three years or less to limit early emissions during filling. Subunits of the module, about 10 acre cells, can be completed relatively quickly. Another assumption is that filling results in net density of placed gate waste of 50 lb/ft^3 or 1,350 lb/yd^3 for the total landfill volume. At this density, an acre-foot of waste weighs 1,089 tons. An acre of waste 50 ft deep will contain 54,450 tons, and 100 ft, 108,900 tons. These assumptions will be used below.

5.3.4 Startup And Management Of Landfilling And Gas Recovery Operation

5.3.4.1 Time To Fill Module

At a module size of 10 acres, depth 50 ft and a waste inflow of 500 tons/day, the time requirement to fill a 10-acre module is 3 (actually 2.98) years. Some details of the rather intricate startup sequence are shown for reference in the next subsection. These startup and management parameters will be generally applicable to bioreactors, and independent of whether power is generated or not.

5.3.4.2 Startup Sequence And Timing

The time from initiation of filling to completion of coverage and initiation of full enhancement is assumed to be 3.5 years. During the time to full enhancement, the waste stream entering up to year 3.5 generates about 7% of the methane potential of a year's entering waste (average of 1.75 years' waste x kinetic coefficient of 0.04 yr^{-1}). This gas is captured with 80% efficiency but may be flared as the most convenient early option. After start of enhancement, starting at year 3.5 once the gas capturing cover is in place, the modeled generation rises to 70% of full potential in 5 years and 90% of full potential within 10 years. It is assumed that infrastructure for the electrical generating equipment, such as lines, site preparation and interconnects, can be installed initially at year 3.5 in one operation to achieve economies of scale. The necessary generation equipment can be brought up to full capacity as justified by gas availability, in stages in years thereafter. A heat rate of 12,000 Btu/kWh is assumed, based on higher heating value (HHV) of the methane. At a 500 tons per day time average fill rate, the full capacity, at 95% recovery of the steady state recovery of 1,500 mmBtu/day, is 1,425 mmBtu/day. Accounting for a 95% gas capture, and 1% gas loss at the beginning and end of the landfill methane generation cycle, the recovered gas will also fuel 4.30 MWe. At 1,000 tons/day, recoveries double.

5.3.5 Scenarios For Calculating Methane Recovery And Power Generation

A 25-yr continuous filling operation is considered. From assumptions above, and using estimates based on accepted kinetic models (parameters given above), about 7% of one year's LFG generation is lost to energy use at the start of filling. To use remaining LFG recovered after closure, it is also assumed that the generating equipment will keep operating (part load of some engines as necessary) down to the point where the "last engine" or 17% of a 6-engine combination becomes fuel limited. At the assumed kinetic rate constant of 0.2 yr^{-1}, this occurs 9 years after closure. In this "optimistic" scenario, the total LFG energy forfeit because of unusable gas at the beginning and end of filling is small, amounting to less than 25% of the methane potential (gas) that could be generated from one years' waste, or 1% of the total gas over the landfill's gas generation cycle. An assumed loss of 5% of gas due to inefficient recovery adds to this 1% for a total loss of methane potential of 6%--perhaps optimistic, but appearing attainable. In other words it is assumed that a 94% fraction of generated gas is recovered.

The calculation of both methane and its cost will assume the following two scenarios. These are:

Scenario 1:

"Small" landfill, time averaged (365 days/year) inflow of 500 tons MSW/day.

Waste per acre=	54,450 tons
Methane Generation per acre=	163,350 mmBtu
Methane recovery efficiency=	94%
Methane recovery per acre over life of landfill=	153,549 mmBtu HHV
Engine online factor=	95%
Engine heat rate=	12,000 Btu/kWh
Calculated total MWh per acre=	12,795
Time averaged power production=	4.65 MWe (365 days/year)
Power production per year=	40,734 MWh

Scenario 2:

Same as scenario 1 except time averaged inflow of 1000 tons MSW/day.

Waste per acre=	108,900 tons
Methane generated per acre =	326,700 mmBtu
Fractional methane recovery=	94%
Calculated total MWh per acre =	25,590 MWh
Time averaged power production=	9.30 MWe
Power production per year =	81,468 MWh

In assigning costs to power generation later, the time between expenditures and revenue deriving from these expenditures is under 4 years and averaging 2 (given a 3-yr module life). In all financial calculations, particularly the low discount rate of 4% used in previous reports to California Energy Commission (June 1997) on this project, the time value of money is "in the noise" making a limited difference to cost estimates as will be seen below. The time value of money also largely cancels if discount rates will be close to the rate of escalation in costs and electricity or energy value. Within the precision of this type of analysis, the application of any discount factor or required interest can be easily treated in other ways. For example, it can be embedded in installed capital cost or in the capital recovery factor. On this basis, elaborate accounting that breaks out discount factors, etc., has been omitted.

5.3.6 Engine Economics Alternative

When engine economics or capital costs are necessary for purposes of incorporating more detail on engine or prime mover costs in cost evaluations such as this, it can be assumed that the landfill gas fueled engines have a capital cost component of 1.8 to 2.5 cents/kWh (capital recovery factor of 14% to 18% per annum on $1,000/kWe and 8,000 hrs/yr as reported in industry experience) and 1.0 to 1.2 cents/kWh variable costs that occur per unit power generation.

Summarizing, the genset related cost of landfill gas fueled generation is taken from this and Waste Management data as 2.5 to 3.5 cents/kWh. To be conservative, we use 3 to 3.5 cents/kWh at various points below.

5.3.7 Caution on regulatory issues and risks "outside the box"

Both risks and regulatory issues remain for the power generation that may occur from bioreactors. Although the picture developing is positive, large-scale performance must be confirmed. An example of risks and barriers is the imposition of extra lining requirements on bioreactors. However, such lining system may also be required for all landfills constructed in California, regardless of the operation as a bioreactor. This issue is currently under discussion at the California State Water Resources control Board and Central Valley Regional Water Quality Control Board. The issue is not yet resolved, but parties intending to implement bioreactors may need to play it safe and spend considerable (to them) "up front" money to install base lining.

One other issue of extreme importance that remains to be resolved for electricity generation is that of exhaust emissions. Present lean-burn engine emissions are falling as engines improve, but are still above allowable limits. As increasingly large sections of California come under increasingly tight emission constraints, NOx offsets must be available, which they are often not. And when available, they must be purchased. These emissions issues are considered solvable by the project team, but their solution would entail more development work. There are two avenues recommended by authors to abate emissions:

- Biofiltration of engine exhaust in large masses of solid waste, already showing practicality in a research project at UC Davis.
- Chemical and mechanical treatment of engine and turbine exhaust followed by standard catalytic removal of contaminants. This is a moderate extension of standard technology.

5.3.8 California Regulations

State regulations, until recently, adversely affected the prospects and costs for bioreactors. However, the Federal regulatory situation has become more favorable. And the regulatory situation in California is resolving in large part favorably as California is moving toward adopting the new federal standards. More discussion is presented in the discussions of cost to benefit ratios risks, and regulatory factors affecting bioreactor implementation at the end of this chapter.

5.4 Estimated Benefits

5.4.1 Airspace Recovery

The results from the Yolo County enhanced cells thus far suggest that airspace of at least 20% of the originally placed waste volume can be gained back within a reasonable time (under 10 years) from the time of placement of waste. All other things being equal, this airspace can be used over time to allow greater waste acceptance, and extend life of the landfill. The value to the landfill over time is judged to be equivalent to adding 20% to existing gate revenue. After adjusting for added (variable) operating expenses, the additional value to the landfill of additional air space created can be about 15% more. The revenue can be seen in alternative terms, as added net revenue per ton of waste received with bioreactor operation compared to no bioreactor operation. This value for the Yolo situation is calculated at about $4.80 more per ton of waste. Although the value will depend on the site, it will be similar for other landfills.

This valuation may be on the low side. Several aspects of it can be noted: (a) The Yolo volume reduction is by no means complete. Furthermore, (b) additional steps—particularly slow aerobic treatment of the bioreactor remnant after methane production is essentially complete—can give further volume reduction to destroy at least 5-10% more of the original gate waste. Aerobic landfill operation is already permitted and encouraged at some sites. (c) The cost of additional landfill sites has been increased, if anything, at greater than the cost of inflation, as landfills become progressively more difficult to site near populated areas in California and in the U.S. For these reasons, a volume reduction of 25% seems quite likely and with landfill cost escalation equaling the compound interest rate, a "high end" valuation for volume reduction calculated on the same basis as above would be $9/ton waste. Thus, value of volume reduction for this analysis is between $ 4.80 and $9/ton of waste.

Table 15. Summary of the benefits

Fill Rate	Low end benefit at $4.80/ton	High end benefit at $9.00/ton
500 TPD	$ 876,000	$1,642,500
1,000 TPD	$1,752,000	$3,285,000

5.4.2 Leachate Treatment

The experience with projects that use permeable layers beneath conventional clay cap for gas recovery suggests that for new projects using this approach, leachate production would not be much altered. In essence, rain will enter and leachate will drain through a conventional cover with conventional practice at rates and costs rather similar to the bioreactor. This in turn would imply little savings in terms of leachate disposal. However, leachate will be cleaner with somewhat lower BOD. Also, in intermediate stages, any leachate from earlier operations can be directed to fulfill liquid needs of later stages. Given all factors for now, there will be no credit or debit assumed in the economic evaluation for leachate associated costs, compared to conventional practice.

The benefit-to-cost ratio of cover membrane is affected by many factors and a multitude of associated design options. Newer cover approaches could easily have net cost close to zero compared to a conventional design. In fact, recent modeling has suggested that gas capture can be extremely high without cover membrane, providing that there is judicious use of near-surface high permeability layers (such as shredded tires) and low permeability cover. This is being found in modeling work by both D. Augenstein (unpublished) and the University of Delaware working in cooperation with Yolo County. And, when surface geomembrane cover is used, its cost can be offset by further benefits such as prevention of precipitation infiltration, reduction in leachate generation and volume through post-closure. The value of this leachate prevention is very roughly estimated here at $50,000/acre (for example, avoiding the cost of treating 20 to 40 gal/ton of waste of leachate at 2.5 to 5 cents/gal and about 50,000 to 100,000 tons MSW/acre). This value for leachate abatement justifies surface liner, and once waste is stabilized, surface membrane can ensure reduction of long-term risk.

Thus, in the simplest case, geomembrane cover may not be needed and if cover should be used, the leachate reduction noted above lower or “zero out” net cost of surface geomembrane cover. This is a complex situation that needs more study than is possible here. Given the possibilities for limiting leachate management cost, and likely positive benefit-to-cost ratio of surface lining if used, neither surface lining nor leachate credits or benefits’ costing are attempted in the analyses below.

5.4.3 Gas Recovery

In this analysis, any gas value is normally embedded in the electricity output, whose value is already counted. When there is electrical generation, there will normally be no other sale of gas energy. This ignores the internal transaction valuations that may exist. Internal transactions may occur when the energy developer finances some gas collection for the bioreactor, and values this gas, but this is associated with tax credits to the developer so that the net result is very small or negligible addition to the gas cost that fuels generation.

Thermal uses. A moderate but significant fraction of LFG projects, about 20%, sell the LFG for thermal energy. The fraction of 20% results from the percentage of nearby thermal use opportunities at particular sites. When gas is sold, the value will be tied to the avoided cost of fossil fuel otherwise necessary. With existing prices of fossil fuel around $6/million Btu under long-term contracts, but depending on the situation, sellers have to now netted about 50% of the raw energy’s market price. The lower revenue than pipeline gas comes from cleanup needs and needs for equipment adjustment, for example to run on gases with widely varying energy content. The value of gas derived above multiplied by a presumed value of $3/million Btu would result in revenue of $8/ton of waste. These revenues can clearly vary and are becoming more variable and nearly always higher in the rapidly changing U.S. energy situation.

Thus, revenue from landfill gas, other than the electric revenue, may range all the way from zero to $8.00+ per ton of waste. Realization of $8/ton has been a high end that is relatively uncommon because of the need to clean contaminants, and cost to modify energy equipment. The purpose of the Yolo bioreactor program is, however, to generate electricity. Thermal energy sales are presently not possible at Yolo and thermal uses will not be discussed further.

5.4.4 Greenhouse Gas Emissions

The present status of greenhouse gas abatement credits is not only uncertain but also poor.

The party desiring credits must demonstrate that it can sell a greenhouse emission that can be abated. Greenhouse credits were discussed at symposia sponsored by LMOP in the talk by Michael Carolan and can be found at:

http://www.epa.gov/lmop/conf/01_greenpower/carolan.pdf.

A greenhouse gas (GHG) reduction program involves various constraints: (a) the emission cannot be one that would have been reduced anyhow, by regulations; (b) the emission reduction must be rigorously quantifiable and verifiable; (c) no other entity than the seller of credits (in this case the party collecting landfill gas) is likely to sell the same credit; (d) there must be a willing buyer.

The constraints reduce the projects eligible for credits to a small fraction of landfill gas energy sites and prospects. And without U.S. participation in the Kyoto accord, the market valuation for U.S. sale of "carbon credits" is very poor. Therefore, few landfill gas energy projects seek, let alone, have revenue from greenhouse credits, although some projects are "banking" them. Those that do quantify GHG credits find that the market price is very variable, but in the best of cases where there is a willing buyer of credits, the sale of credits can gain over $1/ton of waste. One such case, documented by Michael Carolan in the reference above, involved a sale of credits to Ontario Hydro Corporation of Canada. However, the anecdotal information available now is that the credits are rare as well as minor.

A carbon credit of even $1/ton of CO_2 and acceptance of abatement of methane with a global warming potential (GWP) weight ratio of 21-to-1 over CO_2, as accepted by the Intergovernmental Panel on Climate Change (IPCC), would lead to a credit for capture of methane of 1.6 cents/kWh, or about $5/ton of MSW landfilled. (This is using the above per ton methane yield calculations as a basis.) Since the CO_2 abatement credits of several dollars per ton have been under consideration in the past, the greenhouse credit could be extremely high, over $10/ton. However, the political situation and other constraints are such that such a credit is not near-term.

Likely range of still-speculative greenhouse credit in the next few years: Zero to about $1/ton of MSW landfilled. This amounts to:

- 500 TPD = zero to $182,500 per year
- 1000 TPD = zero to $ 365,000 per year

5.4.5 Closure and Post-Closure Maintenance

The effort now required under state and federal rules for necessary landfill maintenance after landfill cells are closed, is considerable. Among other reasons, major effort is necessary to maintain gas and liquid emission control once the landfill is closed. A major uncertainty is what post-closure care may be required, in terms of components of, and length of, post-closure care. This uncertainty and the possibility of more than 30-yr ongoing care causes concern, even if projected post-closure costs may appear reasonable at some discount factor.

After closure, conventional landfills' gas control requirements continue, depending on gas generation. Typical gas systems require continuing adjustments of gas extraction so that gas is captured with reasonable efficiency while air entrainment is avoided. Gas system adjustment is labor-intensive, and maintenance of the gas system (which may involve maintaining pipes and blowers) is likewise costly. Pipes and blowers must be repaired. Costs can be estimated to be between $ 0.01 and $0.10 per annum per ton of waste in place, but are quite site specific. The cost for other waste decomposition related maintenance—such as cover subsidence—is about equal to this. All of the costs associated with the gas system monitoring and maintenance would be expected to cease if gas production were to end (i.e. be 95 + % complete) earlier than the mandated 30 years post-closure. In a simplified (long-term steady state) analysis of a bioreactor the assumption that gas generation and recovery effort could end in 15 years rather than 30 years leads to an estimated savings, at $ 0.10/ton/year of about $1.50/ton. The value of minimizing post-closure care may be at least as high from a liability standpoint for "responsible parties" as it is from a monetary standpoint. Large mandatory "up-front" financial assurance deposits to assure post-closure care are required under law and these could potentially be reduced.

Considering everything, including the industry's strong weighting of and concerns about post-closure liabilities even at long-term, this analysis assumes that bioreactor benefits to post-closure care is $1.50/ton, and at 500 TPD, $274,000/yr and at 1,000 TPD, $ 548,000/yr. It is emphasized that these values though used below, could vary substantially.

5.4.6 Tax Credits

Tax credits, or other regulated incentives may also be possible. Presently applicable IRS (Section 29) code relating to tax credits has been changing with many constraints and valuations on credits, but tax credits of over $1.00 per million Btu (mmBtu) of landfill gas can accrue to qualifying recipients of recent IRS "Section 29" tax credits. The landfill operator typically arranges by one mechanism or another to receive all or a portion of the credit value. Where the gas recovered from one ton of waste is 2.6 mmBtu, the tax credit would also be $2.60/ton MSW (about) or 1 cent/kWh. Purely hypothetical tax credits (based on $2/ton waste) are as follows:

- 500 TPD = zero to $ 336,000,
- 1000 TPD = zero to $ 672,000.

5.5 Economic Analysis of Full-Scale Project with Energy Generation

5.5.1 Benefit to Cost Comparison for Bioreactor Operation

In this section, costs were calculated for the bioreactor independently of electricity generation for fill rates of 500 TPD and 1,000 TPD (time average). The resulting costs and resulting benefits are expressed on an annual basis.

5.5.1.1 Assumptions

See the previous section 5.3 for the assumed filling sequence and kinetics assumptions. Other assumptions are outlined below. However, the site-specific and design aspects of bioreactors can range very widely.

In projecting results of bioreactor cells to a commercial operation, adjusting benefits to later commercial operations from both a learning curve and economies of scale, it was assumed that savings would be between 25% and 50% less for similar installations of similar equipment.

The initial cost projections below are for the bioreactor operation, which is the critical unknown area, and the area where the project team has greatest experience.

The incremental costs for all power-related and bioreactor related items below are assumed over the 25-yr period of filling. Items that might plausibly be included as capital costs such as various lining, instrumentation, gas conveyance pipe, and other items are treated as operating costs because of their recurring nature.

Another basic assumption for projections below is that landfill cell filling and operation follows approaches that are largely conventional, unless otherwise specified. The key assumptions and differences from conventional landfill practice were described in the above sections 6.4.3 to 6.4.5.

The landfill is filled using conventional operations. The specifications of a conventional LCRS, highly permeable and requiring accommodation for a 100-yr rain event, with associated pumping are also more than sufficient. This allows a large safety factor to accommodate the leachate expected from a bioreactor.

Note that infiltration rates, shown highly effective, are equivalent to below 1 in/day precipitation. The recirculation rate in the pilot experiment at Yolo County was equivalent to below 30 in/yr of liquid infiltration, far under the drainage capacity of a large-pore drainage layer. All required liquid management is well within the capacities of present drainage layer design. Note that the possibility of precipitation clogging must be forestalled by use of large pore drainage material such as shredded tires or gravel.

These same constraints exist for conventional landfills, and no incremental cost was assumed for the LCRS.

Waste is filled as with conventional practice. However, alternative daily cover is used, that will allow later liquid infiltration, rather than conventional cover soil. This porous daily cover may be greenwaste, tarp, or alternately, fully decomposed waste from a cell filled earlier, or water based foam of some type that collapses within a few days. Such porous daily cover actually offers considerable savings and has regulatory acceptance. Thus, no incremental cost is assumed.

Instrumentation is required, as moisture and temperature sensors and hydraulic transducers are embedded in the waste as the filling proceeds. However, the sensors' spacing will be much lower than that of earlier demonstrations. It is assumed that 50 moisture and 50 temperature sensors per 10 acre module will be adequate to indicate temperature profiles and the degree of moisture penetration. Projecting from the large-scale demonstration program a cost of $2,000 per temperature/moisture sensor, or $ 10,000/acre is assumed. This cost is incurred for bioreactor operation, regardless of power generation.

From fill rate and other statistics, the time to fill a 10-acre module is the same for 500 tons/day (50-ft depth) and 1,000 tons/day (100-ft depth). This time is 2.98 years. Correspondingly, 3.36 acres are filled per year. The annual cost for instrumentation at the $10,000/acre cost is $ 33,600/yr.

Provision for liquid addition is made by installing piping with appropriate perforation in layers. For the 50-ft deep cell, the layers are midway up and at the top of the cell. Liquid addition occurs at 25, 50, and 75 ft up and at the top of the 100-ft deep cell. The cost of liquid lines for the demonstration cells was $160,000 per 9.5 acres, or about $4,000/acre per level of 25-ft spaced injection lines. The cost is assumed to be $2500/acre per level of injection lines for a commercial operation. This cost is incurred for bioreactor operation, regardless of power generation. For the 500-ton/day fill rate, annual cost experienced for the liquid addition system is estimated at $16,800/annum and for the 1,000 tons/day operation, $33,600/annum.

A surface membrane cover is not used but instead the default assumption is that a near-surface conductive layer is used, beneath final and conventional clay or other low permeability cover. As noted above, flow modeling of gas recovery with this design is expected to be over 95% of the generated gas. As what is basically a modest variation of permeable daily cover, the extra cost for compost, wood chips, or tires layer would be expected to be minimal. A minimal incremental (added) cost of $3,000/acre is assumed for this cover.

On this basis, annual cost experienced for gas capture is $10,000/annum (rounded from $10,080). At a roughly $1/ft^2 cost, a surface geomembrane, if needed, would add a further $146,000/yr in incremental cost. The cost components, if surface geomembrane are used, are listed in Table 13 at $3.58/MWh for 500 tons/day, or 0.36 cents/kWh. At the 1000 ton/day fill rate, the cost would be 0.18 cents/kWh.

Costs associated with conveyance of landfill gas from the bioreactor will increase. Compared to conventional gas recovery from the same mass of waste, the bioreactor's flow of gas may easily reach four times as much at peak generation as with a conventional landfill design.

This does not, however, translate to proportional increase in piping cost. A 4-fold increase in flow leads to a 65% increase in required diameter. And much of the piping cost is installation, which is not flow dependent. The landfill gas conveyance cost will increase by not more than 50%. This is based on industry figures of $8,000 to $20,000/acre (Waste Management, Inc.) and a 50% increase would result in added incremental cost of landfill gas conveyance due to bioreactor operation between about $5,000 (500 TPD) and $10,000 (1000 TPD).

On this basis, the cost of piping is conservatively estimated by the authors' professional judgment at $20,000 for the 500 tons/day and $ 35,000/annum for the 1000-tons/day cases. This value, used as a "proxy" cost in Table 16 below should be recognized as potentially quite variable by landfill site.

Because of potentially differing stability of wastes in bioreactors, initial geotechnical analyses of stability are likely to be required. However, once the first few generalized analyses are completed, it is expected that the stability issues will be satisfactorily resolved and guidelines developed. The long-term incremental cost is assumed to be zero. Permitting is also likely to be more intricate and costly. The extra cost is again a difficult call, but we estimate a cost of $3,000/acre for the other costs. This cost is incurred for bioreactor operation, regardless of power generation.

Permitting and geotechnical analyses as needed for 500 tons/day and 1,000 tons/day is $10,000/annum.

All of the cost calculations above assumed that the costs of base lining would be the same whether a landfill is conventional or a bioreactor. However, extra base lining costs may be incurred if the landfill must, for example, have double membrane base lining as opposed to a conventional landfill's single liner. In California, the double membrane requirement may become the standard design for all landfills in the future. This awaits resolution by regional water boards.

The base per-acre cost of base layers for a single lined landfill is shown in Table 16 below and will be approximately $100,000. (This cost, required in any event, is presented for reference.) Though the first liner cost is not attributable to the bioreactor, the costs of the single liner serve as a good guide to the costs of the second liner if a double liner is required. If a double liner is required, the incremental cost attributable to a bioreactor is the cost of the second liner.

Table 16. Typical costs of landfill base layers

Base Layers (listed from the bottom up)	Cost per acre
Purchase soil	$ 19,000
Compacted clay liner	$ 12,000
60 mil HDPE liner	$ 15,000
HDPE geonet (drainage layer)	$ 8,000
Geotextile	$ 8,000
Operations layer	$ 6,000
HDPE pipes, 4-in diameter	$4,000
Subtotal liner cost	$ 72,000
Other associated costs:	
Engineering and Design	$ 5,800
Quality assurance & quality control	$ 12,000
Contingencies @ 10%	$ 7,200
Subtotal other costs	$ 25,000
TOTAL COSTS	**$ 97,000**

Cell depths of 50 ft and 100 ft are again assumed and, other assumptions and particularly gas recovery are identical to that derived above.

Although need for a surface liner appears uncertain, the surface liner could turn out to be a valuable adjunct to (possibly) maximize gas recovery efficiency. The type of liner integrity required of a base liner is not necessary and imperfect coverage could still substantially limit fugitive emissions. The surface liner would have obvious value when installed at closure (after 25 years) to prevent precipitation infiltration and bring the stabilized waste to a "drier", i.e. more leachate drainage-free condition. The estimated cost of surface lining, estimated at roughly $1/ft^2 earlier or 43,560/acre) would work out to $ 146,000/yr and could be another cost factor. However, long term the surface lining value is probably offset by the value of leachate mitigation that would otherwise occur without it. Because of this, and as noted earlier, surface lining is not included as a net cost.

The most significant additional operating cost for a bioreactor, versus conventional operation, is labor. Extra labor requirement is another factor that is difficult to estimate precisely, but it might be judged that the extra monitoring and other operations of a bioreactor would require the presence of one additional employee. At a fully burdened operating cost of $60,000/yr, the assignment of this employee cost to the recovered electricity adds $60,000/yr to both the 500 and 1,000 TPD case.

The accounting of the bioreactor cost components is inherently complex with several options. For example, expenses might be assigned against: (a) the electricity, or (b) waste management benefits like volume reduction and the other landfill benefits. Although much uncertainty remains about exact magnitudes of costs and benefits, the benefit-to-cost ratio is positive even with all likely uncertainties, and however the accounting is done. Next is a list of some estimated annual expense and benefit components for the 500 and 1000 ton/day fill rate.

Table 17. Annual dollar expense of cost items specific to bioreactor

(Representative but approximate values, vary by site. See text for discussions.)

Cost Factor	500 TPD		1,000 TPD	
	High End	Low End	High End	Low End
Sensors	29,800	29,800	29,800	29,800
Leachate Injection Lines	16,800	16,800	33,400	33,400
Surface Membrane	146,000	0	146,000	0
Extra Cost for Gas Conveyance	20,000	20,000	35,000	35,000
Permitting	10,000	10,000	10,000	10,000
Extra Base Lining	289,000	0	289,000	0
Totals	511,660	76,600	542,300	108,200
Cost/MWh (see below)	12.56	1.88	6.66	1.33

Table 18. Annual Value Of Bioreactor Waste Management Economic Credits
(Exclusive of electricity: All figures approximate. See text for discussions.)

Credit Valued	500 TPD		1,000 TPD	
	High End	Low End	High End	Low End
Landfill Gas Gain	$1,642,000	$876,000	$3,284,000	$1,752,000
Greenhouse Credit	$182,000	$0	$365,000	$0
Post-closure Care at $1.50/ton	$274,000	$274,000	$548,000	$548,000
Tax and Similar Incentives	$336,000	$0	$672,000	$0
Total Benefits Estimated	$2,434,000	$1,150,000	$4,869,000	$2,300,000

The MWh per year estimated for the 500 and 1000-ton cases are as follows (repeated from 5.3.5 Scenarios 1 and 2):

- 40,734 MWh/yr for 500 TPD cost factor.
- 81,468 MWh/yr for 1,000 TPD cost factor.

Even if all costs were assigned to the gas used to fuel power generation, the estimated costs would clearly be acceptably low, ranging from $1.33 to $12.56/MWh (0.132 to 1.26 cents/kWh). These costs appear quite tolerable despite attendant uncertainties. It is also clear from the above that the value of prospective benefits exclusive of energy outweighs the costs by several-fold. This basically justifies the assumptions of "free" gas as was used in the cost analysis for electricity generation above.

This benefit-to-cost ratio is, however, a preliminary estimate. Operational experience is as yet limited. What must also be considered is public perception of bioreactors, and perceived or real environmental impact. Any serious environmental mishap would set back bioreactors' implementation, and it must be shown that bioreactors can be operated with confidence by typical landfill operators without creating environmental problems. In a heavily regulated situation such as waste landfilling where control is as tight as it is, the benefits must be well-established with extensive operating experience. All RD&D operations must be cautious and carefully thought out and run

5.6 Effect of New Regulations

The recently implemented U.S. EPA Bioreactor Landfill Research, Development and Demonstration (RD & D) rule allows and facilitates large-scale landfill testing of bioreactors for energy production and their other benefits noted above. This testing will occur under auspices and regulations of individual U.S. states. U.S. EPA rules permitting bioreactors are in the process of adoption by California (after nearly a decade of bioreactor related discussions by Yolo Staff with the California Integrated Waste Management Board, CIWMB, and the help to the Yolo team of Waste Board staff). The Yolo County findings and the long trail of ongoing negotiations and discussions by Yolo team members with waste board members are proving extremely valuable to the advancement of bioreactors in California.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

With the initial construction phase of the project completed for the northeast and west side anaerobic cells, Yolo County has gained valuable knowledge about the design and operation of bioreactor landfills. The following sections provide major conclusions and a summary of recommendations for future bioreactor operation and areas that require additional research.

The 9,000-ton pilot-scale cell continues to show that bioreactors can provide projected energy, environmental (greenhouse gas reduction) benefits, and waste management benefits. Methane enhancement has proven to be manageable and highly controllable in the demonstration. The full-scale cells are confirming the same benefits on larger scale.

The objectives were stated on pages 20 and 21 of this report as:

1. Acceleration of waste decomposition and leachate treatment, via liquid amendments and recirculation of leachate via a pipe network serving the waste mass. This was to be done while showing that recirculation could be accomplished without excessive leachate head build-up over the base liner. The ultimate objective was to accomplish rapid completion of composting, stabilization and generation of methane to the maximum practical yield.

2. Efficient capture of nearly all generated methane, by withdrawing at slight vacuum from a freely gas-permeable shredded tires collection layer beneath low-permeability cover. The withdrawal was to be accomplished with negligible impact to the local air quality.

3. Document the capital and operations cost of a full-scale bioreactor and determine the economic viability of its commercialization.

4. Establish these environmental and renewable energy benefits to facilitate regulatory acceptance.

The results of the objectives were:

1. The acceleration of decomposition was shown in Figure 16 in Section 3.6.2. There has been, at minimum, a 4-fold increase in the methane recovery rate, with increases up to 7-fold, depending on the time from filling/startup at which recovery was compared with conventional operation.

2. The efficient capture was documented by surface scanning as seen in Table 5, Section 3.7.1, Table 6, Section 3.7.2 and Table 7, Section 3.7.3. The data of these tables are supported by Figures 43 through 45 of Appendix B. This showed averaged surface emissions to be under 1/50 of the allowable standard of 500 ppm. In many cases, surface emissions were undetectable.

3. The capital and operating costs were documented in section 6 above. From a purely economic standpoint, commercialization is attractive. Public acceptance is developing and long-term performance remains to be established.

6.2 Conclusions on Other Issues

6.2.1 Stability Analysis

Based on the stability analysis performed for the YCCL, it is likely that other landfills could construct and operate a bioreactor module with an acceptable factor of safety. We would recommend any landfill operator perform a site-specific slope stability analysis prior to considering bioreactor operation.

Early recovery of the landfill gas being generated by the northeast cell was possible because the landfill gas collection system (horizontal gas collection lines) were installed during waste placement and subsequently connected to the site gas collection system shortly after completion of waste placement. In addition, the placement of the synthetic surface liner has ensured near complete capture of the landfill gas that was being generated.

6.2.2 Staging And Sequencing Of Controlled Landfill Operations

Early installation of a landfill gas collection system and subsequent gas collection could significantly reduce fugitive emissions in addition to increasing the opportunity for power generation.

6.2.3 Exploration Of Alternative Cover And Surface Biofilter

Because the early installation of a membrane cover represented a significant capital outlay, an area for future research should involve the trial operation of a bioreactor module that is without a synthetic cover. The purpose of this research would be to determine if surface emissions could be controlled with an active gas collection system without the presence of a synthetic cover. A possible alternative that would require demonstration would be the inclusion of a relatively thick layer of greenwaste or compost over the entire module that could act as a natural biofilter for possible fugitive emissions.

Based on the findings of this project, it is recommended that research on both of these areas, alternate covers that allow high control of gas emissions, and use of a biocover to further mitigate emissions be continued.

6.2.4 Further Options: Landfill Mining

One option that requires further study would be mining and sorting of the waste following aerobic and/or anaerobic decomposition. One attractive option for appropriately reclaimed waste that adds no net volume to the landfill would be used in place of other cover that does occupy volume. Such use of reclaimed waste can further reduce use and extend life of landfills. The further benefit from use of reclaimed waste is in facilitating moisture addition. The moisture addition necessary to enhance methane generation can be relatively slow. Care and slow addition are required to avoid seeps, and in general moisture addition to enhance methane remains incompletely understood. The full-scale test results so far suggest that deeper, better compacted cells may require less liquid per ton of filled waste, because of lower void (i.e. pore volume) fraction and other factors. It appears likely that standard, low permeability daily cover soils should be avoided because they may impede liquid addition and cause side seeps. Instead, if possible, porous greenwaste, removable tarps, or the mined and separated residual waste fines from old cells could be used for daily cover instead.

6.2.5 Moisture Addition

Moisture addition is manageable with a degree of care that should be possible at most landfills. Work associated with moisture addition was fairly straightforward whether moisture was added to the top of landfilled waste or at multiple levels in the full-scale cells.

6.2.6 Energy Balance

Energy balance of a full-scale bioreactor showed that the extra energy required to operate the bioreactor amounted to less than 1% of the incremental added methane energy obtained. The bioreactor was better than any alternative waste-to-energy technology in terms of minimal parasitic energy.

6.2.7 Sensors and SCADA

Yolo's network of moisture, temperature, pressure and other key sensors were linked to commercially available data acquisition and logging equipment and software. This linkage has been highly successful. Yolo's unique and advanced system was custom constructed, but Yolo's experience showed that this type of sensor and datalogging arrangement can be set up where bioreactors are implemented elsewhere. Such a system greatly eases the tasks of both tracking and controlling the bioreactor's operation.

6.3 Commercialization Potential

The controlled landfill or accelerated anaerobic composting, as conducted at Yolo, should have excellent commercialization potential. At the same time it needs to be appreciated that there are several necessary steps along the way. The following is a general overview of factors affecting commercialization, and activities to date on behalf of commercialization.

6.3.1 Yolo Team Efforts Toward Commercialization

Over the past decade, Yolo County project team members have had central roles, carrying out several activities aside from the experimental work to help advance and realize the potential of the bioreactor. These activities include:

1. Working through SWANA to develop a white paper on bioreactor benefits.

2. Cooperating with regulatory agencies to modify rules to allow bioreactors. Ramin Yazdani, Don Augenstein and John Pacey and other Yolo staff have all promoted the cause of bioreactors via U.S. EPA's Project XL and other avenues. This has resulted via an involved, and several steps process, in the issuance of EPA draft and final rules (RD&D rules) in the United States' Federal Register allowing bioreactor implementation across the U.S. Similar rules have been issued for California and will be finalized this year.

3. Presenting papers at major conferences, particularly the Solid Waste Association of North America (SWANA) and also worldwide (U.S. EPA and Department of Energy climate and renewable conferences in China and Russia) for the recent years. It should be of interest

that these international conferences were cosponsored by the U.S. Department of Energy and U.S. EPA, with Russia and Chinese counterparts. These have increased appreciation of the bioreactor's possible benefits.

4. Sharing project data and providing information on environmental benefits, and on how environmental risks may be mitigated by approaches that are being demonstrated.

5. Assisting California Energy Commission in the review of other projects in California.

6.3.2 Yolo Team Collaborations

In short, the project team members have been doing a range of necessary things, although not direct marketing. In some ways the bioreactor is self-selling to most landfill operators provided volume reduction can be realized. The use of membrane cover for gas capture, and the minimization of greenhouse emissions is self-selling based on value added from energy capture. The use of cover for better gas capture becomes increasingly attractive as energy prices rise. The fact that Waste Management is pursuing bioreactor technology is other evidence of this. Yet other evidence is provided by the support of bioreactor advancement by the Solid Waste Association of North America, the U.S.'s largest professional association dealing with solid waste issues. Provided a reasonable design basis is available, the expertise is available do design and construct bioreactors.

In terms of coalitions to advance commercialization, IEM and other team members have proposed liaisons with other active entities such as Hydro Geo Chem. These and other entities can move the technology forward. However, realizing maximum energy potential from bioreactors involves intricacies that may not be obvious to outside observers. Aside from the scientific advancement, facilitation requires that regulatory and political hurdles continue to be addressed and the bioreactor merits be emphasized in terms of environmental and energy benefits to California. Such benefits must continue to be emphasized. Bioreactor technology needs help from all involved stakeholders, and not just landfill operators.

6.3.3 Facilitating Interagency Collaboration On Bioreactors

Interagency cooperation can help advance bioreactor energy technology. It would be helpful to use an "environmental balance sheet" to weigh benefits and debts across different agencies' jurisdictions, globally as well as locally, and over the full life cycle of landfilled waste. A particular concern and present barrier appears to be fear of groundwater contamination if liquid is added to landfills. Where liquid and wastewater additions may be desirable, base lining systems may be mandated whose incremental costs to operators may preclude controlled landfilling and its benefits. This will depend on the location of the landfill and the State Water Control Board and Regional Water Quality Control Boards requirement for liner system for all Class III landfills in California. In the recent years there has been discussion about requiring double liner system for all Class III landfills in California. Yet, reduced pollutant loads in conjunction with hydraulic analyses show risks might well be reduced with bioreactors. It seems likely that conventional dry tomb landfills could pose greater threats, particularly over the longer term.

6.3.4 Facilitating Intercomparison Of Waste Management And Waste To Electricity/ Fuels Options For Waste Management Jurisdictions

Another issue is comparison of the controlled landfill with other waste management to energy alternatives that might ultimately be permitted in California. For example other MSW to methane conversion approaches are often claimed to be superior to variants of the bioreactor landfill. However careful analysis of the dominant alternative, MSW to methane in vessels, shows a host of barriers, including kinetic limitations to conversion in the allowable vessel retention times, high parasitic energy use, economics, and (even) very serious but little recognized environmental impacts that are not present with bioreactors. The same kinds of limitations also occur with other waste-to-energy conversion processes including (for examples) MSW to alcohol conversions and gasification. Aerobic composting is widely favored by a number of entities in California. Yet aerobic composting lacks necessary markets and incentives for the compost, particularly compost from dirty mixed wastes, and has much less renewable energy and greenhouse benefit. The only realistic alternative that is widely proven is MSW combustion. The near term prospects for implementation of combustion technology in California are non-existent.

6.3.5 Describing Advantages Of Waste To Electricity/Fuels Options For Waste Management Jurisdictions And Advantages In Light Of California's Needs

Aerobic composting is widely favored by a number of entities and environmental groups in California. Yet, aerobic composting lacks necessary markets and incentives for the compost, particularly compost from "dirty" mixed wastes, and has much less renewable energy and greenhouse benefits. The only realistic alternative that is widely proven is MSW combustion. The near term prospects for implementation of combustion technology in California are non-existent. Thus, the advantages to the controlled landfill or accelerated anaerobic composting bioreactor must continue to be pointed out to the range of stakeholders.

6.3.6 Addressing Remaining Barriers--Emissions Associated With Electric Generation

Other barriers exist for electric fueling uses of landfill gas. Various prime movers that might be fueled by landfill gas encounter somewhat differing barriers. For many otherwise attractive prime movers, particularly internal combustion engines, the barriers are posed by nitrogen oxide emissions that may be above statutory limits. At least so far, catalytic converters do not have sufficient life in the presence of exhaust from engines run on LFG. This is because of attack by hydrogen chloride from halocarbons. Though very low in quantity, any hydrogen chloride in exhaust gas attacks the catalysts that are satisfactory with most stationary or vehicle piston engines. For gas turbines and microturbines, silica from combustion of siloxanes also plates out on catalysts, and fouls turbines. Solutions can be identified in principle, and these barriers can be overcome. In fact aside from the emission problems, the history of LFG fueled piston engines has been excellent at landfills. The emissions issues are considered by the project team to be solvable, and university work has been progressing on exhaust gas remediation, but the necessary research, though underway, is incomplete.

6.3.7 Emphasizing Bioreactor's Other Benefits

Some other drivers strongly favoring bioreactors are California's newly active climate change mitigation initiative that favors Yolo's approach that maximizes mitigation of landfills' greenhouse gases. There are also looming long-term limitations that may constrain California's natural gas supply that fuels the majority of its "swing" electricity (the "swing" electricity is the extra over "must run" nuclear, hydro wind, and geothermal, etc.) that is all natural gas fueled. It includes a high fraction of peaking electricity.

Fortunately, the State of California is now recognizing greenhouse benefits, both from abating methane emission, and also the landfill gas use offsets of fossil fuel combustion that would otherwise occur. Further information on California's climate change advisory committee can be found at http://www.energy.ca.gov/global_climate_change/.

Given that about 70% of California's electricity is fueled by natural gas, the derivation of an estimated 1% or more added power from landfill gas would be welcome. Thus, the critical engineering, technical and reliability issues are being addressed by Yolo's work. It is felt by the project team that the engineering of bioreactors is part of a bigger picture containing the ancillary issues such as regulatory facilitation and defining what is adequate emissions compliance.

These are but a few of the considerations aside from technical feasibility and economics that will determine progress toward future wide commercialization. The sorts of regulatory issues mentioned cannot be addressed from narrow perspectives. Rather, they must be addressed by carefully evaluating and summing the widest possible range of impacts from environmental and other standpoints, over the full and post-closure "life cycle" of landfills.

6.4 Benefits to California

A large number of benefits are possible from bioreactors, for the State of California. The benefits lie in such areas as the betterment of waste management and landfilling, reduction of environmental impacts, economics, and yet other areas. The following summarizes some of the energy, environmental benefits and benefits to the state's economy.

6.4.1 Energy Benefits

The potential added renewable energy benefits to California depend on assumptions but are in any case, quite significant. We can make some estimates based on the following assumptions:

California waste pro-rated on population = 22.5 million tons/year (based on CIWMB statistics, 45 million tons, less 50% diversion).

Controlled landfilling applied to 70% of waste in California or to 15.75 million tons/year.

Methane yield = 3000 ft^3/ton of waste (Vogt and Augenstein, 19-landfill survey, 1997 as well as Yolo results). With predictable availability, 90% of methane converted to electricity at 11 ft^3 CH_4/kWh to give time-average power generation of about 500 MWe. Present California Generation is about 75% of a nameplate 240 MWe, or 180 MWe.

Thus, the additional power made available is about 300 MWe. Although this is only around 1% of California electricity generation, this is enough power for 250,000-300,000 Californians.

6.4.2 Greeenhouse Emission Abatement

We assume that the control of California generated methane from 22.5 million tons of waste increases from 70% to 95%. At the accepted Intergovernmental Panel on Climate Change (IPCC), 20-fold equivalence of methane to carbon dioxide, reduction of methane emissions by

2400 ft^3 equates to a reduction of CO_2 emissions by 1 ton. The decreased CO_2 equivalent emission by this example would be 7 million tons/year.

More greenhouse benefit comes from the CO_2 equivalent emission reduction; in other terms the fossil CO_2 offset of the methane fueled electricity. Here we note an aspect of energy that does not seem well recognized. In electricity generation, certain power sources including hydro, wind, and nuclear are must run, fixed at the maximum level afforded by the source. Consequently, the "swing fuel" for extra power generated "at the margin" is all fossil. Depending on the mix of displaced fossil oil or gas, the CO_2 abated by renewable methane is about 0.75 tons/MWh generated. Assuming the 300 MWe time-average above for a year, another 2 million tons of fossil CO_2 emission would be prevented.

6.4.3 Air Pollution Emission Abatement

Landfill gas contains roughly 1000 ppm of volatile organic compounds (using the EPA convention of expression as hexane) in addition to CO_2 and CH_4. This is about 0.7 grams of local air pollutant or volatile organic compounds (VOCs) per cubic foot. It is assumed, as above, that there is the abatement of an additional 1.68 x 1010 ft^3 of methane, or 3.36 x 1010 ft^3 of 50% methane landfill gas. At this loading of VOCs, the VOC (local air pollutant) abatement for California would be slightly in excess of 10,000 tons. Reduction of VOCs by this amount would provide a significant improvement in local air quality in the vicinity of landfills.

6.4.4 Employment and Economic Benefits

Just as do nations, states including California run a "balance of payments". The balance of payment is important in various ways to the state economy. The realization of 300 MWe time average of extra power, annually, at 10,000 Btu saved per renewably fueled kWh, would reduce the need for about 30 trillion Btu's or 30 million million Btu's (in common U.S. energy usage). At a rather conservative cost these days for the swing fuel energy of $5/million Btu's, this amount of extra power and associated fuel savings would keep an extra $150 million a year in the state's economy. Still more benefit not quantified here, comes from the fact that associated payroll and employment for the power generation is kept within the state.

An accepted economic correlation for money brought into an economy in the form of payrolls, or kept in the economy via savings on payment out of state for energy, is that each $1 in income/savings translates to $3 in personal income. Thus, the retention of energy dollars in the state's economy should mean the addition of over $400 million in personal income annually in California. Though this analysis is rather simplified, bioreactors can help increase personal income in the state by several hundred million dollars annually. In the most basic terms, bioreactor operation in California can help promote economic activity in California.

6.4.5 Landfill Life Extension

A rough estimate of landfill life extension is possible by assuming that about 15% more waste can be filled because of the now well-established waste "shrinkage". This means that given landfills can operate 15% longer. An alternative way of looking at the benefit is that five landfills of a particular size would be needed, whereas six such landfills would be needed with conventional operation.

6.5 Recommendations

The following are some recommendations considered important by the project team:

1. Continue monitoring full-scale operations to give the type of long-term performance information that is desirable to advance the technology. Bioreactor landfill operational assessments require extremely long times, beyond the typical time span of contracts issued by sponsoring agencies. A typical contract period is of the order of 3 years. Several promising projects elsewhere have been halted when funding ran out. However, information of great value will come at long terms, and continues to come from the initial Yolo pilot-scale cell as its operation continues in its eighth year.

2. Full-scale bioreactor operation and monitoring for long terms will give necessary information on reliability, long-term management requirements and key performance parameters that are not obtainable in any other way. Performance parameters include (but are not limited to) normalized methane energy recovery, emissions reductions (as determined by surface scans and other means) volume reduction, moisture management parameters and head over liner, the ultimate time required and other performance parameters as amply documented above. One very important long-term determination will be finding out the long-term stabilization performance-what to expect once the landfilled waste has produced most of its methane.

3. Gain experience in dealing with problems. To date, the problems (which are considered solvable) relate to leachate seeps, better controlling gas recovery, and maintenance of containment. Other problems relate to equipment fouling by precipitates.

4. Continue to demonstrate the reliability and predictability necessary to provide confidence in benefits to future users of the controlled landfill energy technology.

5. In future projects, explore alternative gas collection methods that do not require expensive geomembrane.

6. In future projects explore the use of more permeable alternative daily cover (ADC) that would allow easier liquid infiltration and lessen events such as side seeps.

7. Conduct additional gas tracer tests to determine the moisture content of the waste over time.

8. In combination of computer modeling and field tests determine the best strategy for air and leachate injection in the aerobic landfill.

9. Operate the aerobic landfill and conduct additional emissions testing on the biofilter to determine the best operational strategies for reduction of methane emissions.

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