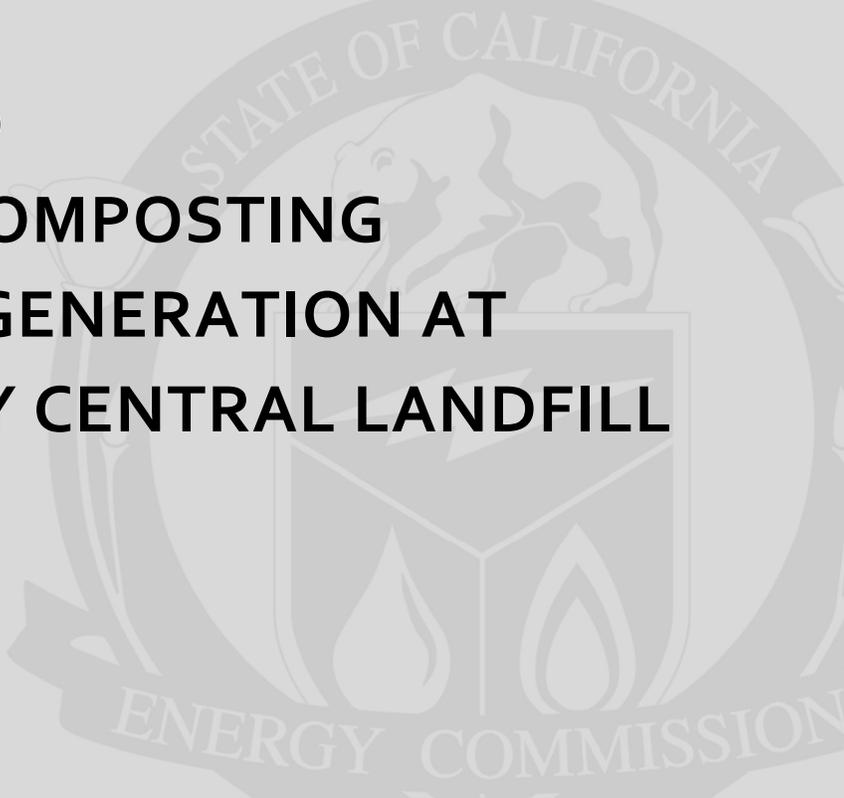


**Public Interest Energy Research (PIER) Program
FINAL PROJECT REPORT**

**ACCELERATED
ANAEROBIC COMPOSTING
FOR ENERGY GENERATION AT
YOLO COUNTY CENTRAL LANDFILL**



Prepared for: California Energy Commission

Prepared by: Yolo County Planning and Public Works Department

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
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- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Accelerated Anaerobic Composting for Energy Generation at Yolo County Central Landfill is the final report for the SMUD ReGen project (Contract Number 500-00-034), conducted by SMA America. The information from this report contributes to PIER's Renewable Energy Technologies program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916 327-1551.

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Abstract

This project involves the design, construction, and initial operation of a full-scale landfill at the Yolo County Central Landfill in Northern California to demonstrate the accelerated anaerobic composting technology. Landfills where biodegradation of waste is enhanced through liquid additions are generally called "bioreactor landfills." Two new 6-acre and 3.5-acre methane enhanced bioreactor cells were designed and constructed for this project. Extensive instrumentation and provisions for measurements allowed for the detailed study of waste decomposition and methane enhancement. Through this project, Yolo County has gained valuable knowledge about the design and operation of bioreactor landfills. It is likely that other landfills could construct and operate bioreactor cells with an acceptable factor of safety. This report outlines and recommends methods to site, line, fill, inject water, monitor, and collect landfill gas from bioreactor cells based on project experiences.

Keywords: Landfill gas, biogas, biodegradation, bioreactor landfills, methane, bioreactor cells

Executive Summary

Introduction

Organic materials in municipal solid waste landfills decompose to a gaseous mixture of methane and carbon dioxide via microbial activity. This mixture, known as landfill gas, is already widely used for electric power generation; with about 1000 megawatts (MW) installed capacity in the United States. However, landfill gas remains an underutilized renewable energy resource, with only about half of the United States' generated landfill gas being captured and less than 25 percent actually used for electric power generation (with the balance of collected gas flared). The main factors limiting landfill gas utilization are the very long, slow rates of waste decomposition and landfill gas generation in landfills, combined with inefficient recovery of the gas that is generated.

Project Objectives

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 moisture levels. Rapid, complete, and permanent landfill stabilization requires liquid addition to allow the anaerobic microbial processes to complete, producing an inert, stabilized residue. This process is called *accelerated anaerobic composting*. This project involves the design, construction, and initial operations of a full-scale landfill at the Yolo County Central Landfill in Northern California to demonstrate the accelerated anaerobic composting technology. Landfills where biodegradation of waste is enhanced through liquid additions are generally called *bioreactor landfills*. Two new 6-acre and 3.5-acre methane enhanced 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.

The objectives of the project are to:

- Demonstrate full-scale bioreactor landfill operation to accelerate methane generation through liquid addition without impact to the bioreactor or the groundwater.
- Collect data for analysis by instrumenting a full-scale bioreactor landfill.
- Improve generated methane gas efficiency capture by withdrawing it at a slight vacuum using a layer of shredded tires and low-permeability cover that will not impact air quality.
- Document the environmental and energy benefits, and provide project technical data to regulatory agencies for permitting and acceptance of bioreactor landfill operation.
- Document the capital and operations cost to determine the cost benefit ratio for full-scale bioreactor landfill operation for the economic viability of commercialization.

Project Outcomes

The results of the project were:

- Bioreactors can provide greater energy benefits than conventional landfill operations. Methane enhancement continues to be manageable and controllable.
- Collected data shows, at a minimum, a four-fold increase in the methane recovery rate, with increases up to seven-fold, compared with conventional operation.
- Efficient capture of the generated methane was documented. Tests showed methane average surface emissions concentration to be less than 10 ppm. In many cases surface emissions were undetectable.
- Project documents technical data needed to establish environmental and renewable energy benefits to help facilitate regulatory acceptance.
- Capital and operating costs have been documented. From a purely economic standpoint, commercialization is very attractive. Public acceptance is developing and long-term performance remains to be established.

A summary of the operational results are included in Appendix A, and complete details of these results can be found in the Project Outcomes section of the report.

Conclusions

A 9.5-acre bioreactor landfill cell was designed, constructed, and filled with 270,000 tons of waste. Yolo County has gained valuable knowledge about the design and operation of bioreactor landfills as a result of this construction.

It is likely that other landfills could construct and operate bioreactor cells with an acceptable factor of safety. This report outlines and recommends methods to site, line, fill, inject water, monitor, and collect landfill gas from bioreactor cells.

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

The energy balance of a full-scale bioreactor showed that the extra energy required to operate the bioreactor amounted to less than 1 percent of the incremental added methane energy obtained.

The controlled landfill or accelerated anaerobic composting, as conducted at Yolo, should have excellent commercialization potential.

Recommendations

The following are recommendations considered important by the project team:

- Continue monitoring full-scale operations to obtain information on reliability, long-term management requirements, and key performance parameters.

- Gain experience in dealing with problems such as leachate seeps (liquid that contains contaminating substances), better control of gas recovery, and maintenance of containment.
- Continue to demonstrate the reliability and predictability necessary to provide confidence in benefits to future users of the controlled landfill energy technology.
- Explore alternative gas collection methods that do not require an expensive geomembrane (geosynthetic lining) cover.
- Explore the use of a more permeable alternative daily cover that would allow easier liquid infiltration and lessen side seeps.
- Explore variable-rate gas collection, thereby testing opportunities to match power output (“peaking power”) to diurnal variations in power demand.
- Test the excavation of stabilized “old” waste to provide alternative daily cover for new cells, thereby extending landfill life.

Benefits to California

A large number of benefits are possible from bioreactors. The potential renewable energy benefits to California are quite significant. With an assumption of controlled landfilling applied to 70 percent of the waste in California, the additional power made available by bioreactors is about 300 MW. Although this is only around 1 percent of California’s electricity generation, it is enough power for 250,000 to 300,000 Californian homes. Further, assuming the control of California generated methane from 22.5 million tons of waste increases from 70 percent to 95 percent, the decreased carbon dioxide (CO₂) equivalent emission would be 7 million tons per year.

More greenhouse benefit comes from the CO₂ equivalent emission reduction (also termed the fossil CO₂ offset) of the methane fueled electricity. Assuming the 300 MW time average above for a year, another 2 million tons of fossil CO₂ emission could be prevented.

The benefit in air pollution emissions abatement is also significant. Landfill gas contains roughly 1000 parts per million of volatile organic compounds in addition to CO₂ and methane. If burned in electricity generation from a bioreactor, the abatement for California would be slightly in excess of 10,000 tons. Reduction of volatile organic compounds (chemicals emitted as gas from certain solids and liquids) by this amount would provide a significant improvement in local air quality in the vicinity of landfills.

The potential employment and economic benefits from bioreactors are also noteworthy. The realization of 300 MW of extra power, annually, at 10,000 Btu saved per renewably fueled kilowatt-hour (kWh), would reduce the need for about 30 trillion Btus. At a rather conservative cost for the swing fuel energy of \$5 per million Btus, this 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 for out of state for energy, is that each \$1 in income/savings translates into \$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. In the most basic terms, bioreactor operation in California can help promote economic activity in California.

An additional benefit is that landfill life extension is possible by assuming that about 15 percent more waste can be filled because of the now well-established waste "shrinkage" from a bioreactor. This means that landfills can operate 15 percent longer, a significant benefit in California and elsewhere.

1.0 Introduction

Sanitary landfilling (where municipal solid waste (MSW) is deposited in a lined open pit, then covered with an earth/clay cap) 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 (the liquid that percolates from the base of the waste) is then re-circulated, 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 (CH_4), a potent greenhouse gas, carbon dioxide (CO_2), and small amounts of volatile organic compounds (VOC). This byproduct of anaerobic landfill waste composting can be a substantial renewable energy source when recovered. 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.

Landfilling of MSW is considered by many environmentalists and regulatory agencies as a less desirable solid waste disposal technology, to be avoided and limited as much as possible. However, landfills can be used for a much greater 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. 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 *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 can be overcome with recent conventional landfill practice. 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 situ* moisture levels. Landfills where 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. This process is called *accelerated anaerobic composting*.

The advantage of accelerated anaerobic composting technology (also termed 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 biogas production and collection over a relatively short period of time. This allows for more economical biogas power generation. It also eliminates the great bulk of fugitive biogas emissions that are normally experienced because of inefficient biogas collection. This fugitive biogas 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 initial 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 through 2002. The California Energy Commission supported the present project, in addition to cost-sharing by Yolo County and other state and federal agencies.

1.1 Project 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 the United States Environmental Protection Agency (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 United States, but worldwide. Results from Yolo County's pilot-scale project have already been shared among many other jurisdictions as well as the private sector throughout the nation and world.

The Energy Commission has also played an extremely helpful role in supporting the Yolo program since its inception (first planning in 1989). The initial pilot program startup support was through a contract with the Commission's Energy Technologies Advancement Program (ETAP). Later, severe shortfalls in California electricity generation, U.S. EPA's facilitation, and California Integrated Waste Management Board support of the program, in conjunction with early pilot program successes, all combined to enable further support through the Energy Commission. This support was provided under the PIER program contract administered by the Sacramento Municipal Utility District (SMUD), which is the subject of this report.

This project's main objectives were:

- Acceleration of waste decomposition and leachate treatment, via liquid amendments and re-circulation of leachate through 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.

- Efficient capture of nearly all generated methane by withdrawing at slight vacuum from a freely gas-permeable shredded tire collection layer beneath a low-permeability cover. The withdrawal was to be accomplished with negligible impact to the local air quality. Near-complete extraction with this approach was demonstrated in the 9000-ton pilot-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.
- Establishment of the environmental and renewable energy benefits to facilitate regulatory acceptance.

1.2 Report Organization

This report is organized into the main sections of introduction, project approach, outcome, and conclusions. The approach section covers design and construction of the full-scale bioreactor. The outcome section discusses monitoring and data analysis, project operation and maintenance (O&M), economics, and benefits. 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 two bioreactor cells were separated into different sections.

2.0 Project Approach

Two new 6- and 3.5-acre methane enhanced 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.

In addition to these sensors, instrumentation, and monitoring capabilities, the main design modifications relative to conventional landfill practice in the United States 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 a gas collection system. Another construction aspect important to the controlled landfill included precautions taken in placing cell elements that would undergo strain during decomposition and settlement.

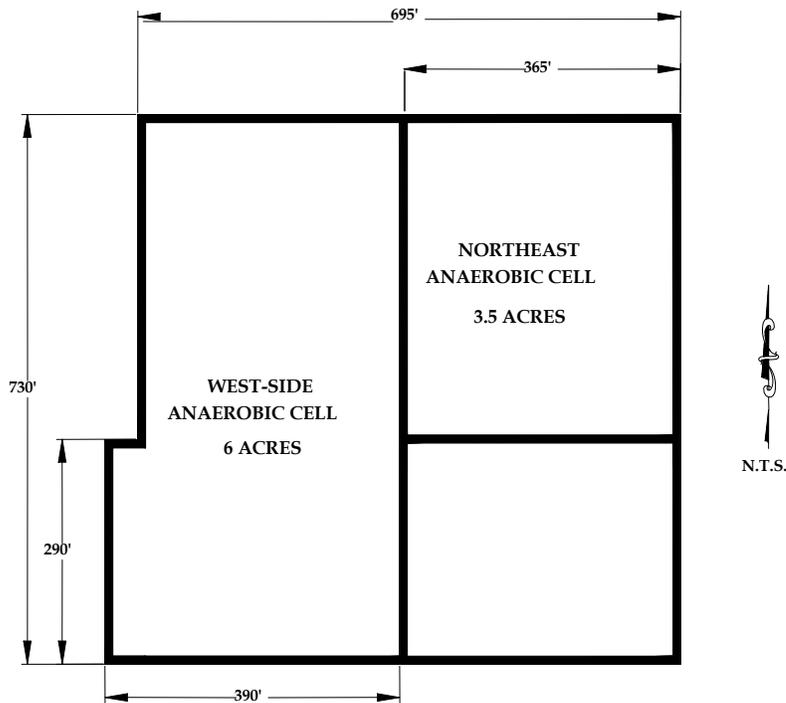


Figure 1. Overview of Module D bioreactor cells

Photo Credit: Yolo County Planning & Public Works Department

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 the 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 holding stakeholders meetings.

2.1 Project Design

2.1.1 Design of Base Liner System

The northeast 3.5-acre and west 6-acre 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-acre cell. The base layer slopes 2% inward to two central collection v-notch trenches located on the southeast and southwest side of Module 6D (Figure 2). 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-foot (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 has, from top to bottom, a minimum of:

- Two 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.
- Two ft of compacted clay ($k < 6 \times 10^{-9}$ cm/sec).
- A 1/2-foot of compacted earth fill ($k < 1 \times 10^{-8}$ cm/sec).
- A 40-mil HDPE vapor barrier layer (Figure 2).

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 6D leachate collection and recirculation system (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.

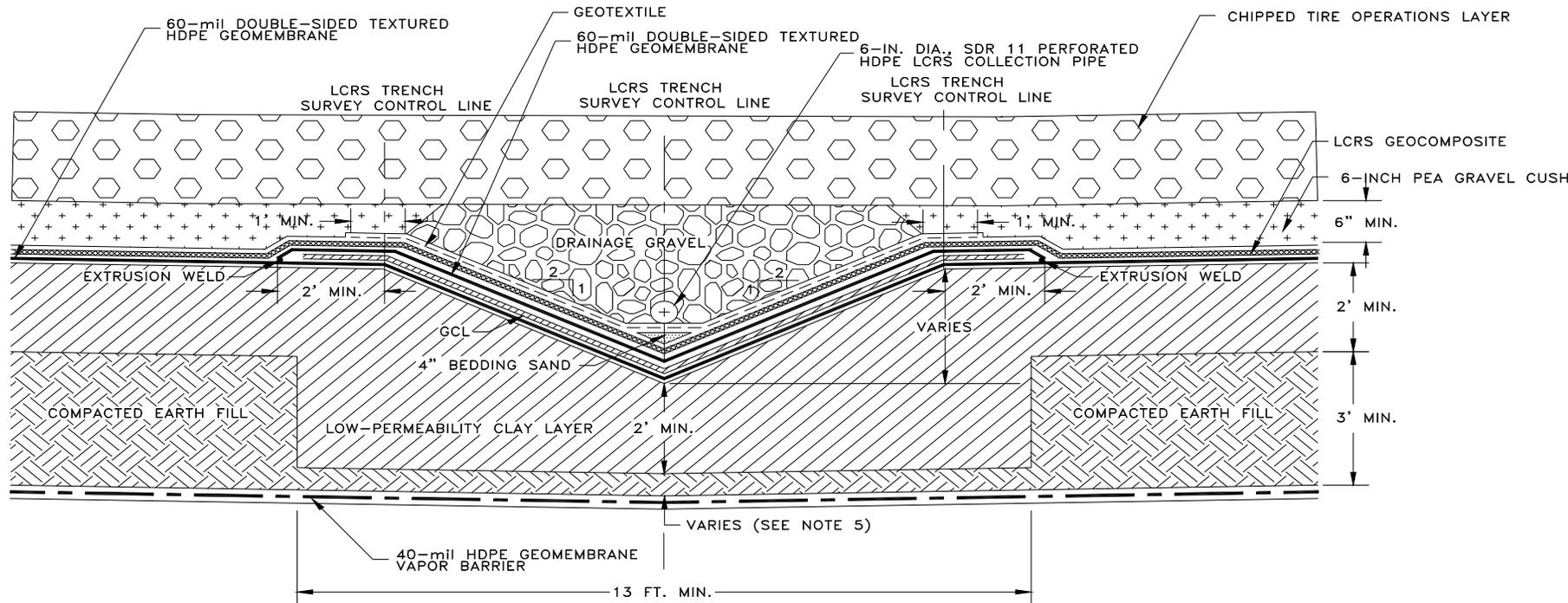


Figure 2. Module 6D bottom liner and leachate collection trench cross-section

Photo Credit: Yolo County Planning & Public Works Department; Photo Credit: Golder Associates 1999

The Module 6D 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 ($k < 6 \times 10^{-9}$ cm/sec), 3 ft of compacted earth fill ($k < 1 \times 10^{-8}$ cm/sec), and a 40-mil HDPE vapor barrier layer (Golder Associates 1999) (Figure 3). The chipped tire operations layer was not placed during initial liner construction, but was placed immediately before waste placement.

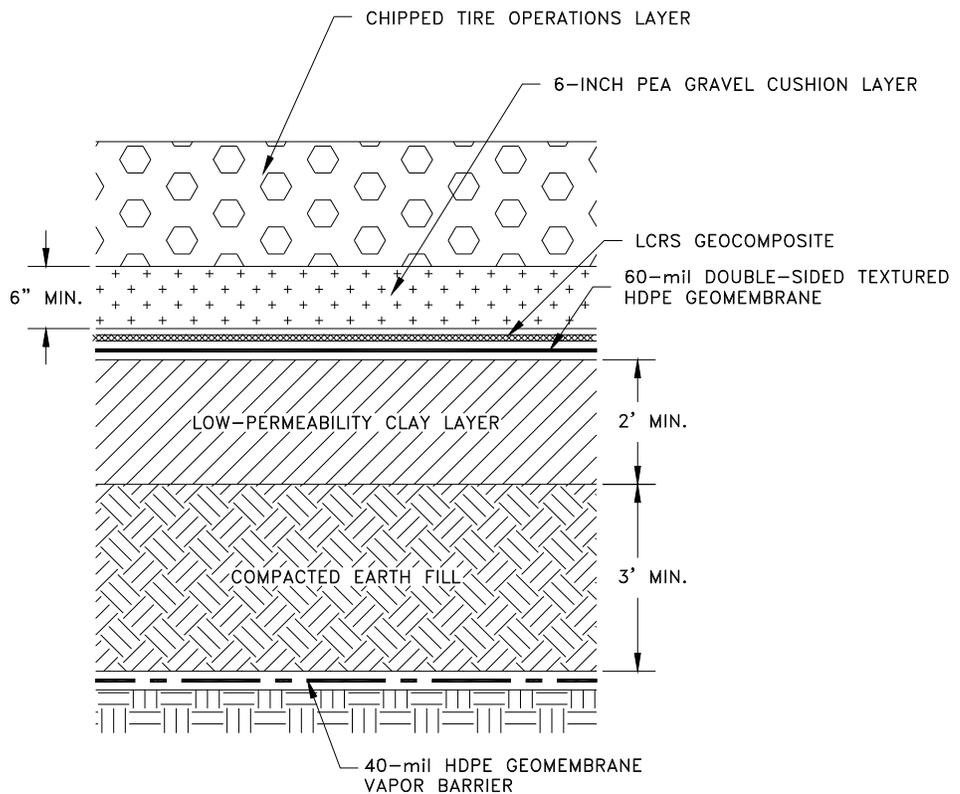


Figure 3. Module 6D bottom liner cross-section

Photo Credit: Yolo County Planning & Public Works Department; Photo Credit: Golder Associates 1999

The permeability of the clay liner, as constructed, was on average about 6×10^{-9} cm/sec and the earth fill averaged about 1×10^{-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, the project team estimated that the peak liquid addition would be up to 10 gallons per minute (gpm) of liquid per 10,000 ft² (44 gpm per 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 liquid flow results of the Pilot-Scale 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 per 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 will be about 4.6×10^{-4} gpm/ft² of disposal area. It is approximately 200 ft between the ridge and collection trench. Using these values, the peak flow through the geocomposite will 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 more than 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 would provide adequate drainage. Due to the large particle size of the chipped tires (more than 6 inches), the calculated effective permeability of the tire 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-foot 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 is better than the Title 27 prescriptive system. This is 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 the Module 6D liner is 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 has 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 foot of head over a HDPE geomembrane and 1×10^{-7} cm/sec clay liner) would be 1×10^{-4} gpm from a standard 1-cm² hole in the liner. With the Module 6D liner (4 in of head over a 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 will 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 will act as a vadose zone monitoring system for early detection of leakage across the entire Module 6D disposal area. This added feature provides another level of protection to the groundwater that standard Title 27 systems do not have.

Monitoring the base layer consists 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 is 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).

2.1.2 Design of Waste Monitoring and Data Collection System

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 linear low-density polyethylene (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 (Figure 4). A total of 47 temperature sensors and 70 moisture sensors were placed in the northeast 3.5-acre cell. For the west 6-acre cell, equal numbers of temperature and moisture sensors were placed, totaling 126 sensors. Appendix A, Table 6, gives a summary of the sensors placed in both the bioreactor cells.



Figure 4. Moisture, temperature, and tube installation

Photo Credit: Yolo County Planning & Public Works Department

Thermistors monitored temperature with a temperature range of 0°C to 100°C to accommodate the temperature ranges expected in the anaerobic cells. ¹ 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

1. QT06005, Quality Thermistor, Inc., Boise, Idaho.

by the change in thermistor resistivity (ohms). As temperature increased, thermistor resistance decreased.

Yolo County designed the polyvinyl chloride (PVC) moisture sensors and they were 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 zero to 40 equated to no free liquid, 40 to 80 equated to some free liquid, and 80 to 100 meant complete saturation.

Pressure within cells was monitored with ¼-in inner diameter and ⅜-in outer diameter LLDPE sampling tubes. Each tube can be attached to a pressure gauge 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.

A summary of sensors installed on the base liner is provided in Appendix A, Table 7. 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. Refer to Appendix D, Detail 1, for a sensor location diagram.

Efficient data monitoring and operation of the bioreactor was accomplished by using the Supervisory Control and Data Acquisition (SCADA) system. All sensors were linked to the SCADA system for near real-time data collection and control. Data is transferred to a computer at the Woodland office by high frequency radio.

Major components of the SCADA system include two Allen-Bradley Model 5/05 small logic controllers (SLC), which control and monitor the raw data acquisition. Each SLC has a 10-slot rack capable of receiving up to ten different input or output (I/O) cards. Analog output cards were used to monitor flow meters, pressure transducers, temperature, and moisture sensors, all of which provide a signal of zero to 5 volts that is proportional to their reading.² Because the large number of moisture and temperature sensors would have required a significant number of analog output cards (each card can accept eight readings), Campbell Scientific multiplexers were utilized to allow up to 16 temperature or moisture sensors to be connected to each analog output.³ Digital output cards were used to power the multiplexers as well as control the leachate injection solenoid valves (both of which required 12-volt direct current (VDC) power.⁴ Finally, a digital input card was used to monitor leachate pump status and run time.⁵

2. Allen-Bradley 1746-NI8, Rockwell Automation, Milwaukee, Wisconsin.

3. Model AM416, Campbell Scientific, Inc., Logan, Utah.

4. Allen-Bradley 1746-OW16, Rockwell Automation, Milwaukee, Wisconsin.

5. Allen-Bradley 1746-IB16, Campbell Scientific, Inc., Logan, Utah.

The user interface for the SCADA system was provided through a customizable program called Wonderware InTouch. This program received the raw data from the SLC and converted it to real world values such as “degrees Celsius,” “range of wetness,” “flow rate in cubic feet per minute,” 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 (either the 3.5 or 6-acre cell) and then into a separate screen for each lift of sensors. A click on the module and lift of interest will yield a screen display providing current (within 15 minutes) 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 as Images 9 through 14 in Appendix C.

As the SCADA computer collected and stored data from the bioreactor, it created a file 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.

2.1.3 Design of 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 3.5- and 6-acre bioreactors to allow for continued operation should one of the pumps fail. Reliable operation of the pumps installed in the leachate collection sumps is 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 Yolo County Central Landfill. As part of the original design and construction of these leachate ponds, the county installed a series of pumps and sprinkler emitters 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. Injection lines were spaced every 40 ft within each lift of waste with an additional line installed around the perimeter of the top deck of the module. For the northeast 3.5-acre cell, each injection line consisted of a 1.25-in diameter HDPE pipe perforated by drilling a 3/32-inch hole every 20 ft. The design was slightly modified for the west 6-acre cell. Injection lines on top of Layers 2 and 3 consisted of a 1.25-in diameter HDPE pipe perforated by drilling either a 3/32, 1/8, or 1/4-inch hole every 20 ft. Injection lines on top of Layer 4 consisted of 2-in diameter HDPE pipe perforated by drilling a 1/8-in diameter hole every 10 ft. Each injection lateral was connected to a 4-in 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 gravel and tires placed over the pipe or holes clogging 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 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.

2.1.4 Design of Landfill Gas Collection and Removal System

A biogas collection system was designed to enable maximum gas recovery from the bioreactor cells. The gas collection system incorporated horizontal biogas collection lines between each lift of waste and directly under the surface liner. Biogas collection lines consisted of various

combinations of alternating 4- and 6-inch 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-foot intervals. Design drawings of the biogas 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 the well is 10 inches of water.
- The maximum available vacuum is 25 inches of water for the northeast cell, and 27.5 inches of water for the west cell (which is roughly half the actual available vacuum from gas-to-energy facility).
- The maximum flow rates expected from each of the cells are proportional to the original pilot scale project. This corresponds to a design flow rate of 350 CFM for the 3.5-acre cell and 831 CFM for the 6-acre cell.

The results of the sizing analysis indicated that a 6-inch diameter header line would be required for the northeast 3.5-acre cell and a combination of 8-inch and 6-inch pipe would meet the requirements of the west 6-acre 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.

2.1.5 Design of Surface Liner Cover System

A final cover system for the northeast 3.5-acre and west 6-acre bioreactor cell was designed to allow for maximum landfill gas recovery and emissions control. The County retained the services of Vector Engineering 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 five 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 reinforced polypropylene (RPP) geomembrane as the preferred choice for an exposed geomembrane cover (Appendix E). RPP offered distinct advantages over the other potential material including long service life (with a 20-year warranty), superior strength due to the nylon reinforcement, and low thermal expansion and contraction.

Because the west 6-acre cell was built following the northeast 3.5-acre 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 6-acre 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 mph.

2.1.6 Design of Leachate Field and Laboratory Testing

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 (BOD₅), chemical oxygen demand (COD), organic carbon, nutrients (ammonia [NH₃], total Kjeldahl nitrogen [TKN], total phosphate [TP]), common ions, heavy metals, and VOCs. 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 were 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 EPA XL Final Project Agreement (FPA), which is located in Appendix F.

2.1.7 Design of Landfill Gas Field and Laboratory Testing

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.⁶ The GEM-500 and GEM-2000 are capable of measuring methane (either as a percent by volume or percent of the lower explosive limit), carbon dioxide, and oxygen. 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 the northeast 3.5-acre area and with a 1/8-inch pitot tube for the west 6-acre area.⁷ 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.⁸ The meters were calibrated for landfill gas and automatically corrected for temperature. Field-testing was performed on a weekly basis for both the northeast 3.5 and west 6-acre cells.

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 CFR60

6. CES LANDTEC, Colton, California.

7. Dwyer Instruments Inc., Michigan City, Indiana.

8. 8240MP (northeast 3.5-acre) and 8840MP (west 6-acre), Eldridge Products, Inc., Monterey, California.

EPA 3C (methane, carbon dioxide, carbon monoxide, oxygen, nitrogen), sulfur compounds using Method EPA 15/16, non-methane organic compounds (NMOC) using Method CFR60 EPA 25C Modified, and VOCs using Method EPA-2 TO-15. A complete list of LFG monitoring parameters and frequencies can be found in Table 3 of the Final Project Agreement (FPA), which is located in Appendix F.

2.1.8 Design of Methane Emission Monitoring

Under current federal guidelines (40 CFR 60.752), landfills exceeding a specific size must monitor 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 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. in Houston, Texas. 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-meter (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 handheld 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.

2.1.9 Design of Waste Sampling and Solids Analysis

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 as a result the county decided to limit the sampling.

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-Liter (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 dried, NCSU analyzed them for the concentrations of cellulose, hemicellulose, lignin, volatile solids (VS), and biochemical methane potential (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.

2.1.10 Design of 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. Airspace recovery is an extremely important parameter 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.

Ground surveys were performed using global positioning system (GPS) survey equipment and collected data was used to create topographic contour maps of each cell with either 1/2 foot or 1 foot contour intervals. Initial and subsequent topographic maps were compared using AutoCAD Land Desktop to calculate the volume reduction (amount of settlement) that occurred in each cell.

2.1.11 Design of 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/ft³. 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.

2.2 Project Construction

Yolo County separated the project into two bioreactor cells designated as the northeast 3.5-acre cell and the west 6-acre cell. This configuration allowed the northeast cell to be constructed and

operated prior to completion of the west cell. In addition, the county incorporated experiences gained from the construction of the northeast cell into the west-side cell's construction.

2.2.1 Construction of Base Liner System

Nordic Construction installed the majority of the Module 6D primary liner system in 1999. Golder Engineering provided construction quality oversight of the liner system, and they were 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), an LLDPE tube, and selected locations received a PVC moisture sensor. Refer to Appendix D for the location of the base liner sensors.

2.2.2 Construction of 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 (Figure 5). 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 alternate daily cover 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 one foot of soil cover.

Following final placement of waste, final grading on the northeast 3.5-acre cell was performed in August and September 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.

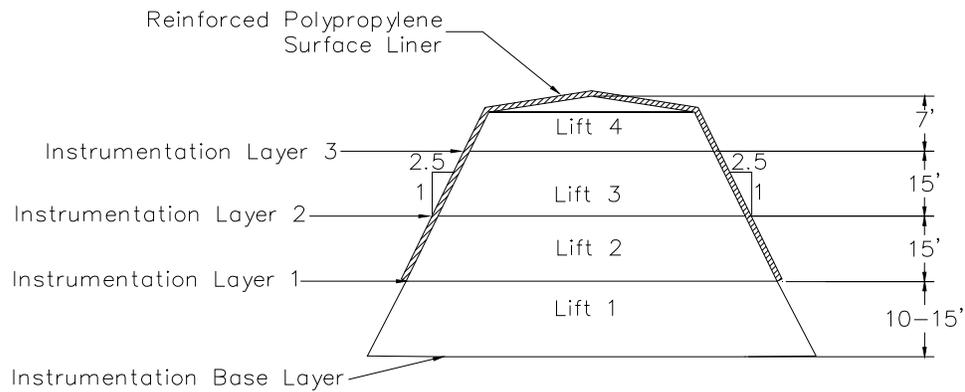


Figure 5. Northeast Anaerobic Cell Cross-Section

Photo Credit: Yolo County Planning & Public Works Department

Waste placement for the west 6-acre cell began on March 8, 2001, and ended 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 (Figure 6). 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. The project team believes this is one of the causes of the leachate seeps, which are discussed later in the section on Liquid Addition and Recirculation.

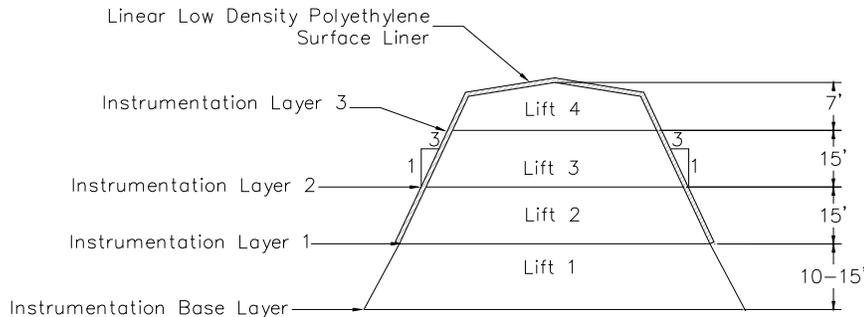


Figure 6. Cross-Section of West-Side Anaerobic Cell

Photo Credit: Yolo County Planning & Public Works Department

2.2.3 Construction of Supervisory Control and Data Acquisition (SCADA) System

Hardware installation for the 3.5-acre cell began in December 2001 and continued through March 2002, with system troubleshooting continuing through May 2002. Hardware installation for the 6-acre 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 in Appendix D.

2.2.4 Construction of Waste Temperature Sensors

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 location of the temperature sensors are in Appendix D.

2.2.5 Construction of Waste Moisture Sensors

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.⁹ Moisture sensors

9. MM4, Electronics Unlimited, Sacramento, California.

were installed adjacent to temperature sensors and were placed in the same bedding material as the temperature sensors.

The gypsum blocks are manufactured by Electronics Unlimited 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 3.5-acre cell.

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

2.2.6 Construction of Pressure Transducers and Pressure Sensing Tubes

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 were installed at three locations adjacent to each leachate collection trench. Additionally, tubes were installed that terminated adjacent to each of the pressure transducer locations.¹⁰ The pressure transducers provided an output current between 4 and 20 mA, which was directly proportional to pressure. Their pressure range was zero to 1 pounds per square inch (psi) and had an accuracy of $\pm 1\%$ full-scale.

Pressure sensing tubes were installed at the same locations as temperature and moisture sensors installed on the base liner and within the northeast 3.5-acre cell. Tubes were also installed in the west 6-acre cell, but only at select locations in each layer. A total of 41 tubes were installed in the northeast 3.5-acre cell and a total of 13 tubes were installed in the west 6-acre cell.

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

2.2.7 Construction of 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-inch 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-inch

10. Model PTX 1830, Druck, Inc., New Fairfield, Connecticut.

holes every 10 or 20 ft (depending on which line). A total of 7185 ft of injection piping was installed with a total of 321 injection holes.

The area to receive the injection line was first graded and then bedded with greenwaste to create a relatively smooth surface for line installation. The injection line was 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-inch diameter HDPE injection header. For the northeast 3.5-acre cell, flow was initially controlled with solenoid valves, which were subsequently removed due to leaks at the valves as well as the mechanical saddle connections between the laterals and the header (discussed further in the Project Operations, Control, and Preventative Maintenance section). For the west 6-acre cell, flow was controlled through manual valves and individual rates and totals 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.

2.2.8 Construction of Liquid Addition Pumping Systems

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 in Appendix D.

2.2.9 Construction of Horizontal Landfill Gas Collection System

For the northeast 3.5-acre cell, horizontal LFG collection lines were installed between each lift of waste and directly under the RPP geomembrane cover. Biogas collection lines consisted of various combinations of alternating 4 and 6-inch diameter schedule-80 PVC pipe as well as several variations of corrugated HDPE pipe. At each line, shredded tires were used as the permeable media. The gas collection lines between layers were spaced approximately 40 ft apart and the lines directly under the RPP membrane were spaced at 25 ft intervals. A total of 16 biogas collection lines were installed.

For the west 6-acre cell, biogas collection lines were installed between lifts 2 and 3, 3 and 4, and on top of lift 4. The biogas collection lines consisted of various combinations of alternating 4 and 6-inch diameter schedule-80 and schedule-40 PVC pipe, as well as several variations of corrugated metal pipe and electrical conduit. At each line, shredded tires were used as the permeable media. A total of 18 biogas collection lines were installed.

A summary of gas collection lines for the northeast and west anaerobic cells are provided in Appendix A, Tables 8 and 9, and as-built drawings are in Appendix D.

2.2.10 Construction of Landfill Gas Removal System

The bioreactor landfill gas 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 6-acre cell. From that point, gas was conveyed a short distance to the gas-to-energy facility.

Each biogas collection line was connected to a 6-inch or 8-inch diameter biogas collection header that conveys the gas to the on-site biogas-to-energy facility (Figure 7). Each biogas 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 3.5-acre cell was constructed concurrently with the installation of the surface cover system, by the same contractor. Construction occurred during fall 2001.

County staff completed the gas collection system associated with the west 6-acre cell following the installation of the surface cover system in December 2002.

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



Figure 7. Biogas collection lines connected to the main header on the west 6-acre cell

Photo Credit: Yolo County Planning & Public Works Department

2.2.11 Construction of Surface Liner Cover System

Construction of the northeast 3.5-acre cell cover system consisted of subgrade preparation for the surface liner, installation of the 36-mil RPP liner, placement of anchor trenches to prevent wind uplift, and installation of the sandbag ballast system to provide additional hold-down force during operations. The installation of the surface liner began on September 4, 2001, and ended on December 14, 2001.

Construction of the west 6-acre cell cover system coincided with the construction of a new waste module (Module 6D, Phase 2) at the landfill. Plans were prepared and included with the bid package for the new module; however, the bids received exceeded the County's budget. Subsequently, the County made several changes to the design and hired the new module contractor to install the liner on a time and materials basis. Installation of the liner consisted of subgrade preparation for the surface liner, installation of the 40-mil LLDPE liner, and placement of anchor trenches. The installation of the surface liner began on October 10, 2002, and ended on October 19, 2002. Installation of the anchor trenches and surface ballast system continued through December 2002.

2.2.12 Construction of Landfill Settlement Monitoring System

The initial topographic survey for the northeast 3.5-acre 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 northeast 3.5-acre cell 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 four cross-sections, and the re-surveying of 22 separate control points established on the surface liner.

The first surveying event of the west 6-acre 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, eight cross-sections, and re-survey of 30 separate control points established on the liner.

Copies of settlement surveys are in Appendix D.

3.0 Project Outcomes

3.1 Project Monitoring Data and Analysis

3.1.1 Waste 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 10. Waste placement commenced in the northeast 3.5-acre bioreactor on January 13, 2001, and halted on August 3, 2001. Waste placement commenced in the west 6-acre bioreactor on March 8, 2001, and halted on August 31, 2002.

Table 1 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 was placed in loose lifts not exceeding 2 ft with either a Caterpillar D-7 or D-8 dozer, and then was compacted with three to five passes using a Caterpillar 826C sheep foot compactor.

As presented in Table 2, 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 slightly 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 been a small contributing factor in the more effective liquid permeation of the 3.5-acre cell (see the discussion on the Northeast 3.5-acre cell in the Project Monitoring and Data Analysis section).

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 3.5-acre cell	65,104	11,060	132,295*	984	123,760	1,052
West 6-acre cell	166,294	27,570	324,209**	1,026	315,290	1,055

* Initial survey of the northeast 3.5-acre cell was conducted on 11/15/2002

** Initial survey of the west 6-acre cell was conducted on 1/16/2003

Data collected by authors on 11/15/2002 and 1/16/2003

3.1.2 Waste Temperature Over Time

An array of thermistors placed throughout the waste monitored temperatures. 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. Beginning in March 2002, the County collected readings through the SCADA system.

The average temperature for the northeast 3.5-acre cell over time is provided in Appendix B, Figure 1. Typical waste temperatures have remained between 40 and 50°C for the last several years (with the exceptions of some drops corresponding to liquid addition. The drops and subsequent rebound in temperature (for instance Layer 3 around March 2003) is the typical response to liquid addition to that layer. 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 to 60°C (Appendix B, Figures 1 and 2) are well above the ambient air outside the cells. Such elevated temperatures are consistent with many other bioreactor results and allow for optimum anaerobic decomposition of the waste by the thermophilic microorganisms living in the waste. In addition, observed temperatures are higher than those observed in the Pilot Scale control cell (which was set up to represent a conventional dry landfill) and as such, it is apparent that bioreactor operation maintains the waste moisture content at an optimum level which allows the thermophilic microorganisms to degrade waste at higher temperatures than would be typical of a conventional dry landfill.

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 Appendix B, Figures 1 and 2, and do not vary significantly from lift to lift (with the largest differential 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 more than three-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.

3.1.3 Waste Moisture Content & Uniformity of Water

An array of moisture sensors installed during the waste placement phase monitored moisture distribution within the cells. 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 the 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% corresponded to the presence of free liquid in the PVC pipe but less than saturated conditions. Readings of greater than 80% indicated saturated conditions, i.e. the PVC sensor is full of liquid.

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

3.2 Northeast 3.5-Acre 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 3.

Optimum operation of a bioreactor landfill requires the moisture content of the waste be near “field capacity.” The “completely saturated” moisture content at which some free liquid just starts to drain from the waste is defined as moisture at “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, this amounts to about 43 gal/ton of waste. Table 2 provides a summary by layer for the amount of liquid added.

Table 2. Northeast 3.5-Acre 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	242,777	43.9

Data collected by authors from June 2002 October 2004

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 the discussion on Waste Solids Sampling and Biochemical Methane Potential Analysis), conducted on June 4 through June 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:

$$PMC = \left(\frac{L_0 + P + LA - LCH}{M + LA + P - LCH} \right) \times 100 \quad (1)$$

Where:

- PMC = estimated potential moisture content of waste mass (%)
- L_0 = 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:

- Precipitation is assumed to be zero for the northeast anaerobic cell because the waste sampling event for which L_0 is based occurred after the module was covered with a geomembrane liner, thus no precipitation has entered the waste.
- 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.
- 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:

- Total waste in the 3.5-acre cell = 65,104 tons
- Total greenwaste ADC in 3.5-acre cell = 11,060 tons
- Total waste + greenwaste = 76,164 tons = 152,328,000 lbs
- Initial moisture content of waste = 18.37%
- Initial weight of water = $(152,328,000 \times 0.1837) = 27,982,653$ lbs
- Amount of water added = 2,809,490 gal = 23,431,146 lbs

Solution:

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

$$\begin{aligned}
 PMC &= \left(\frac{L_0 + L}{M + L} \right) \times 100 & (2) \\
 &= \left(\frac{27,982,653 + 23,431,146}{152,328,000 + 23,431,146} \right) \times 100 \\
 &= 29.25\%.
 \end{aligned}$$

The calculated moisture content is 29.25% (rounded to 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 Energy Commission 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 3) 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 deeper and more compacted 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 was less pore volume per ton due to higher compaction. It takes less liquid per ton to fill what is likely a lower pore volume, i.e. a given moisture addition “goes farther.” Landfill gas would be expected to displace liquid occupying the pore space, spreading the added liquid farther. 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, the 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 West 6-Acre 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 4. The “completely saturated” moisture content at which some free liquid just starts to drain from the waste has been 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 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 6-Acre Cell Moisture Addition by Layer

Layer*	Volume of liquid added (gal)
2	965,428
3	859,279
4	2,333,044

*No liquid injection piping was installed in layer 1

Data collected by authors from June 2002 October 2004

From the first waste sampling event conducted on June 4 through June 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 L_0 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:

- Total waste in the 6-acre cell = 166,294 tons
- Total greenwaste ADC in 6-acre cell = 27,570 tons
- Total waste + greenwaste = 193,864 tons = 387,728,000 lbs
- Initial moisture content of waste = 22.54%
- Initial weight of water = $(387,728,000 \times 0.2254) = 87,393,891$ lbs
- Amount of water added = 3,436,946 gal = 28,664,130 lbs

Solution:

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

$$\begin{aligned}
 PMC &= \left(\frac{L_0 + L}{M + L} \right) \times 100 && (3) \\
 &= \left(\frac{87,393,891 + 28,664,130}{387,728,000 + 28,664,130} \right) \times 100 \\
 &= 27.87\%.
 \end{aligned}$$

3.4 Liquid Levels Over the Base Liner

To date, liquid build-up on the base liner has not been an issue. The base liner under the bioreactor cells was continuous; however, it was hydraulically separated (see the section on

Project Construction) such that leachate draining from each of the cells cannot commingle. The California Regional Water Quality Control Board (CRWQCB) has limited the liquid level above 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 levels on the base liner are monitored through the use of pressure transducers installed at three locations adjacent to each leachate collection trench. The pressure transducers provide an output current between 4 and 20 milliamps, which is directly proportional to the level of liquid (pressure). The pressure transducers installed on the Module 6D liner are Model PTX 1830 manufactured by Druck, Inc. Their pressure range is zero to 1 psi and has an accuracy of plus or minus 1% of full scale.

Appendix B, Figures 5 and 6, provide graphs of the liquid level over the base liner for both of the cells. To date, the highest leachate level recorded has been just under 2 inches in the west 6-acre cell. It must be noted, however, that only minimal leachate has been generated by the cell and as such, the capacity of the LCRS has not truly been tested.

In August 2004, two out of the three pressure transducers located on the base liner began indicating large, random, fluctuating pressure readings. The project team 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. An attempt was made to remove the pressure transducers; however, the cable that the transducers were attached to snapped.

3.5 Leachate Quantity and Quality Analysis

3.5.1 Liquid Addition and Recirculation

Throughout the course of this project, significant volumes of liquid was added and re-circulated into the bioreactor cells. The majority of the liquid added to the cells has been leachate generated from other landfill units at the YCCL and stored onsite in the lined leachate ponds. In fall and winter 2002 the leachate stored in the ponds reached a pH of 9.2 and precipitating of calcium carbonate was observed inside the liquid injection lines (see Leachate Pumping and Injection System discussion in the Project Operations, Control, and Preventative Maintenance section). The injection lines were subsequently cleared using a citric acid solution mixed with groundwater and leachate pH was adjusted by adding groundwater.

Figure 8 presents the cumulative liquid addition and re-circulation volumes to the northeast 3.5-acre cell. Appendix B, Figure 7, presents the average monthly recirculation (which is equivalent to the flow through the LCRS system).

Based on the results of the original Energy Commission 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

$\times 10^{-5}$ 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 ($3.5 \text{ acres} \times 20 \text{ gpm/acre} = 70 \text{ gpm}$).

As presented in the graph, the average flow to-date was approximately 1031 gal/day-acre (or 2.5 gpm/acre), which is simply the slope of the liquid addition curve (3608.1) divided by the area of the cell, which is 3.5 acres. The r squared term represents how well the measured data conforms to the calculated curve with a value of 1 representing a perfect fit.

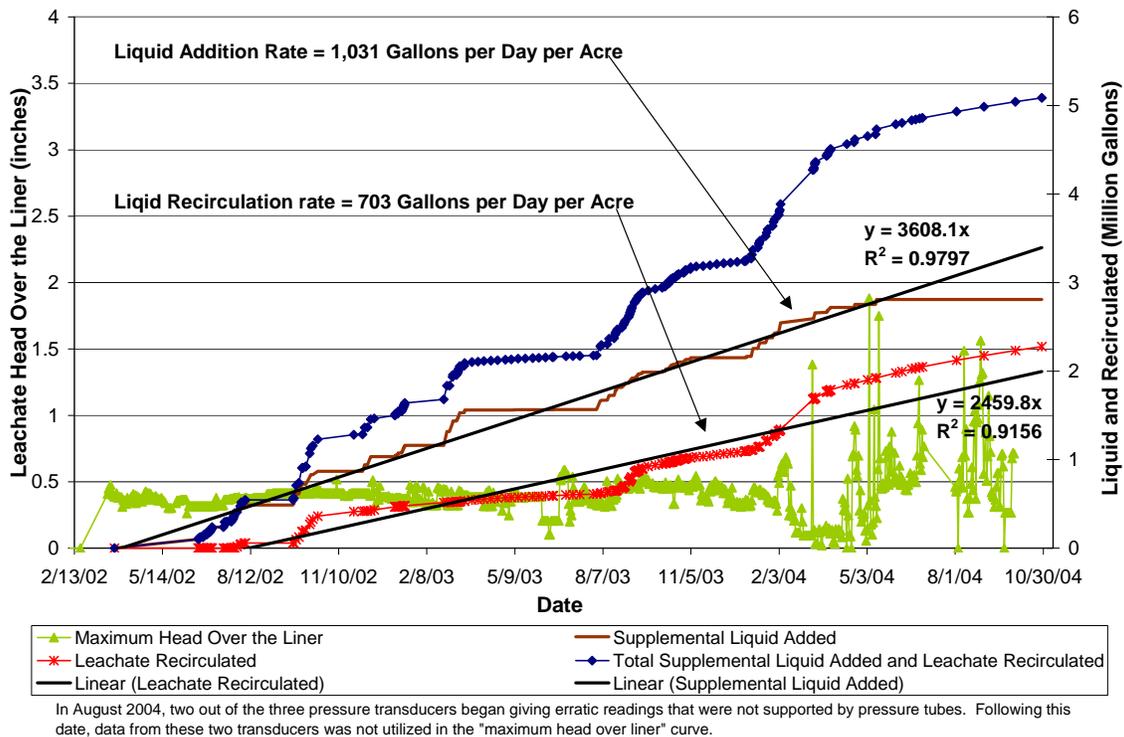


Figure 8. Northeast 3.5-acre cell liquid re-circulation and addition volumes

Photo Credit: Yolo County Planning & Public Works Department

Figure 9 presents the cumulative liquid addition and recirculation volumes to the west 6-acre cell. Appendix B, Figure 8, presents the average monthly 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 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 a path to the Module 6D LCRS for any leachate that drained down the side of the cell. 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.

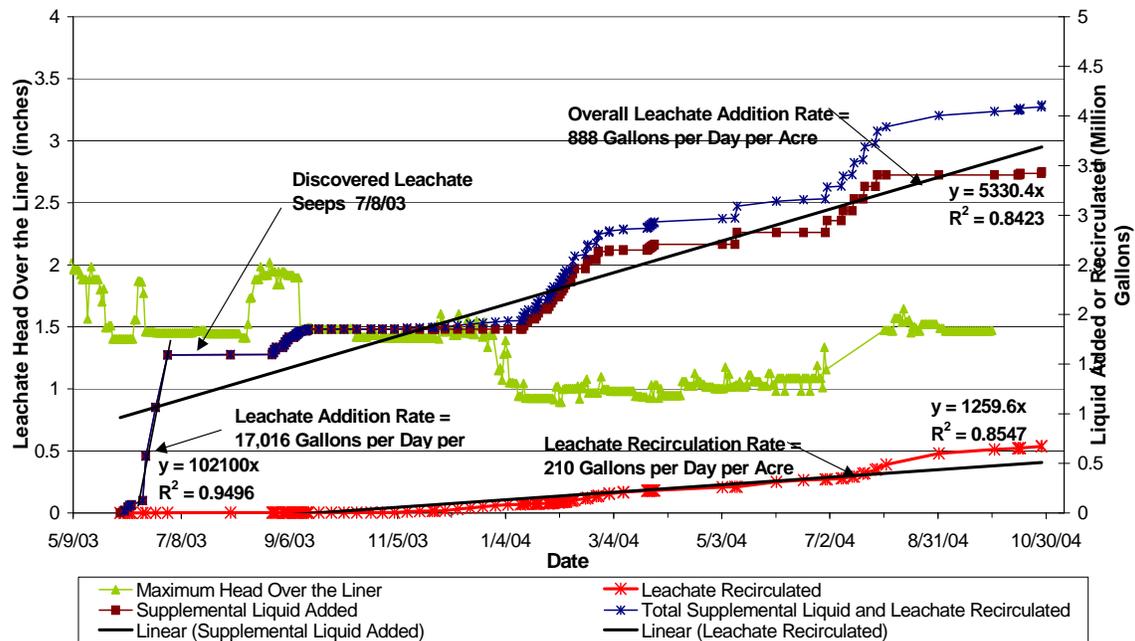


Figure 9. West 6-acre cell liquid re-circulation and addition volumes

Photo Credit: Yolo County Planning & Public Works Department

Liquid addition and re-circulation rates and volumes for both of the bioreactor cells have been lower than originally predicted during the development stage of the FPA. This has been attributed to two main factors: remnant soil cover impeding the vertical permeability and 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 seven 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 not removed, but was broken up and incorporated into the waste. The project team hoped the measures taken to break up the cover soil would be sufficient; however, the members suspect the remains of the wet-weather deck constructed in the west 6-acre cell in addition to high rate of leachate addition contributed significantly to the leachate seep problem.

The cell geometry is another significant factor in limiting the rate in which liquid can be added. 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 Leachate 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 both of the bioreactor cells can be found in Appendix B, Figures 9 and 10. 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 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 9, along with a rise in oxidation-reduction potential (ORP).

3.5.3 Leachate Biochemical and Chemical Oxygen Demand

Normally in wastewater treatment processes, the ratio of BOD₅/COD is used as a measure of wastewater biodegradability (Tchobanoglous et al. 1993). Ratios of BOD₅/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 BOD₅/COD for the northeast 3.5-acre cell is presented in Figure 10 below and is typical of a landfill in this

phase. The BOD₅/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.

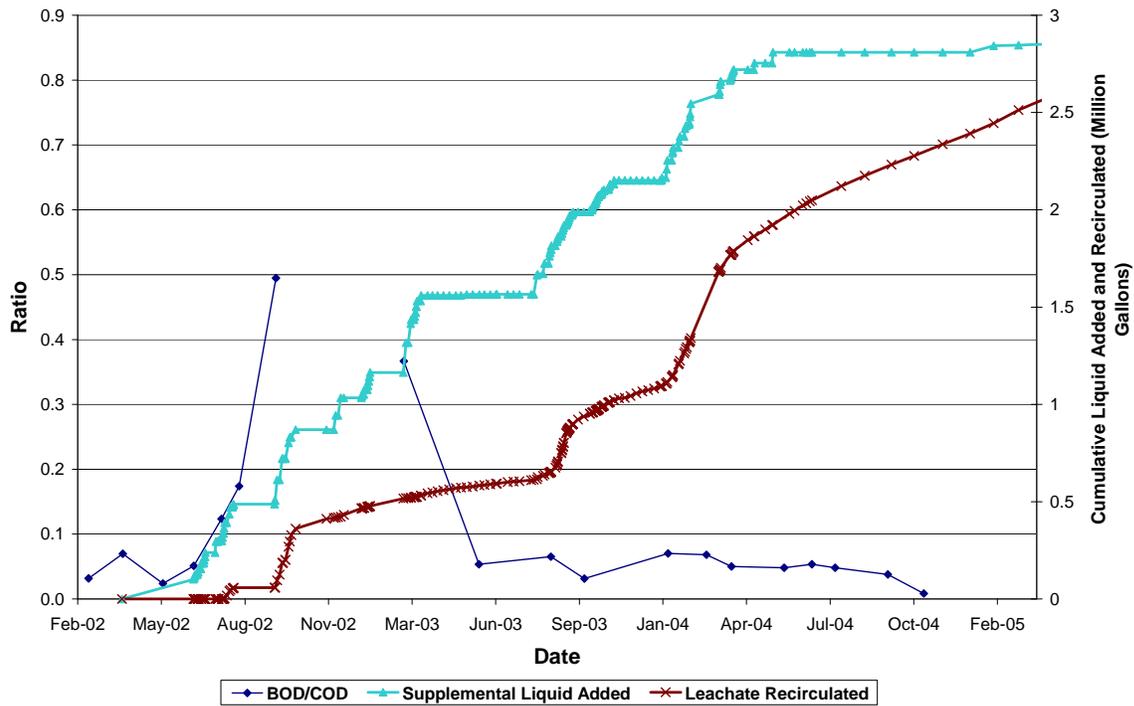


Figure 10. Northeast 3.5-acre area—BOD₅/COD over time

Photo Credit: Yolo County Planning & Public Works Department

In Appendix A, Table 11, an anomaly existed for the October 17, 2002, sampling event where the BOD₅ value of 3,000 mg/L was higher than the COD value of 1,810 mg/L. BOD₅ 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 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, BOD₅ levels declined and stabilized between 100 and 150 mg/L, which were in the range of what was measured in the pilot-scale cell during the same time period.

To date, BOD₅ 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 the BOD₅/COD ratio. In general, there typically will be a fairly low base level of BOD₅ 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. This can result in variable ratios of BOD₅/COD that are not typical of long-term

operation. In addition, quantities of fresh high-organic content leachate breaking through can contribute to variations in BOD₅/COD. Still, the degree of variation is hard to explain. Given the still relatively early operation of the cell, we expect BOD₅/COD ratios to stabilize as waste decomposition progresses.

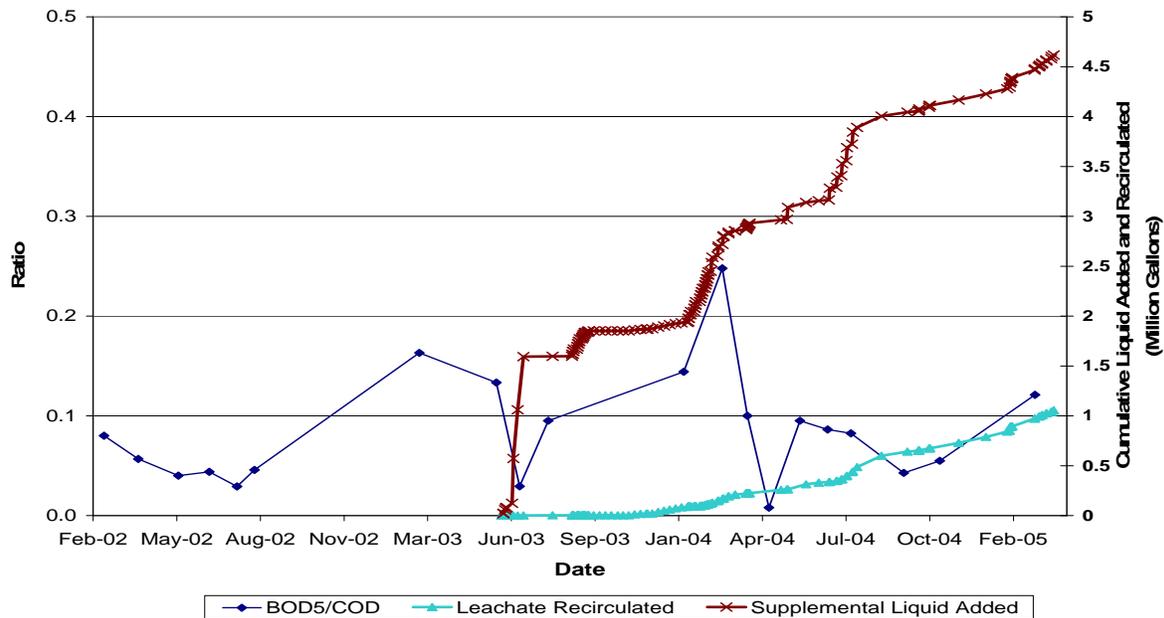


Figure 11. West 6-acre cell— BOD5/COD ratio

Photo Credit: Yolo County Planning & Public Works Department

3.5.4 Leachate Total Organic Carbon (TOC)

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 are mostly derived from wood lignin or lignin-like components, and such things as tannins, appear in solution. It is typically difficult for microorganisms to degrade them. It is likely that newsprint, comprised of fibers of ground 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 BOD₅, 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 that can escape into the environment. Graphs of TOC over time for both of the bioreactor cells can be found in Appendix B, Figures 11 and 12.

3.5.5 Leachate Nitrogen Content

The rising nitrogen in the leachate is a consequence of degradation of nitrogenous waste, principally food wastes, although other materials (e.g. small amounts of sewage sludge, disposable diapers, etc.) also contribute. Nitrogen (principally from amine groups of amino acids) surplus needed by the anaerobic organisms is freed as wastes break down and appears in solution. The behavior of nitrogen levels seen here is 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 both of the bioreactor cells can be found in Appendix B, Figures 13 and 14.

3.5.6 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 (North Carolina State University) 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 15 and 16.

3.5.7 Leachate Semi-Volatile and Volatile Organic Compounds

Dissolved VOC concentrations are presented in Appendix B, Figures 17 and 18. 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 BOD₅. The VOC's initial levels are low, then rise to a peak in October 2002 and then fall again as leachate recirculation continues and as anaerobically degradable VOCs are 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,



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.

3.5.8 Leachate 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 and are subsequently consumed as pH increases. Appendix B, Figure 19, 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 during 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 (Appendix A, Tables 11 and 12). In addition to the potential water quality impacts of high dissolved metal concentrations, dissolved metals can also be toxic to bacteria growth and impede 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 metal concentrations were somewhat variable as seen in Appendix B, Figure 20. The pH in the range of 7 to 8 is close to optimum for keeping all metals of concern to a minimum. Another item to note is there has been no evidence of metal toxicity in these or any known landfill experiments.

Appendix B, Figure 21, 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 during 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.

3.6 Landfill Gas Methane Quantity and Composition Analysis

Background samples of landfill gas were collected from the northeast 3.5-acre area and west 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. Analytical results are presented in Appendix A, Tables 13 and 14. As time progressed, the LFG methane content stabilized toward a range of 45 to 55% as expected and also illustrated in Figure 12.

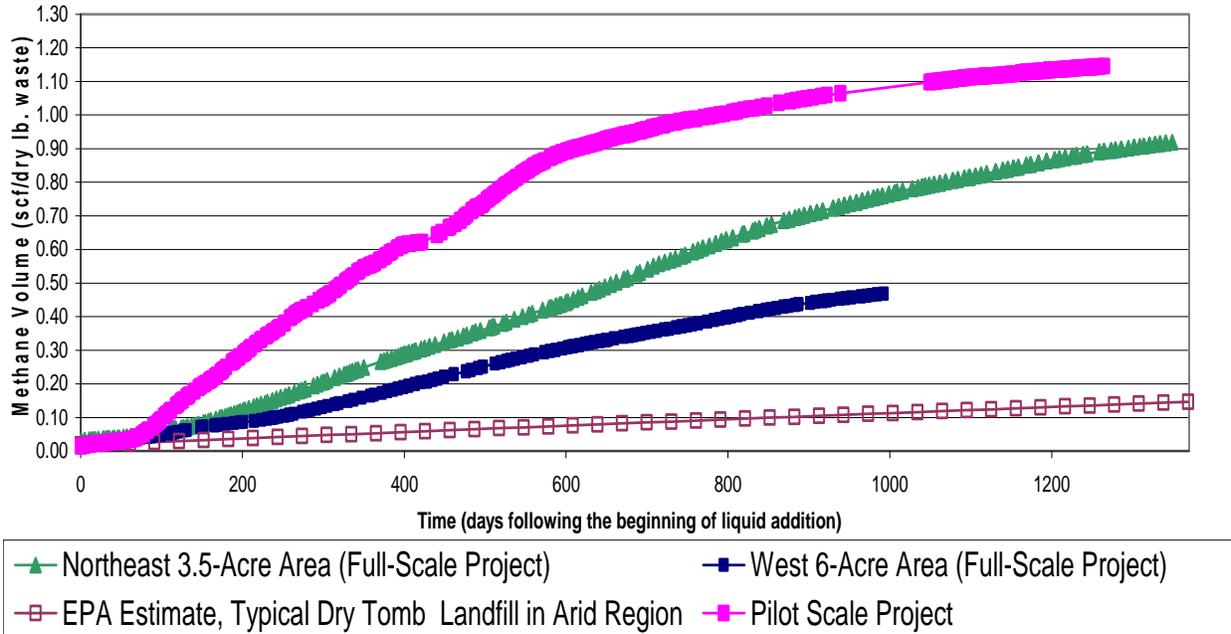


Figure 12. Cumulative methane per dry pound of waste from the northeast 3.5-acre, the west 6-acre cell, previous pilot-scale project, and what would typically be expected in a dry-tomb landfill

Photo Credit: Yolo County Planning & Public Works Department

3.7 Landfill Gas

3.7.1 Landfill Gas Flow Rate

Average landfill gas flow rate from each of the bioreactor cells is presented in Figures 17 and 18. In each case, flow rate has dramatically increased following leachate injection and, following the initial increase, remained relatively stable.

As evident in Figures 17 and 18, 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 factor is adjusting a gas extraction system. When adjusting a gas system, a person tries to match extraction exactly to generation, which 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. The other factor responsible for some of the most extreme variations is attributed to partial or complete shutdown of the gas-to-energy facility for maintenance or breakdown.

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.

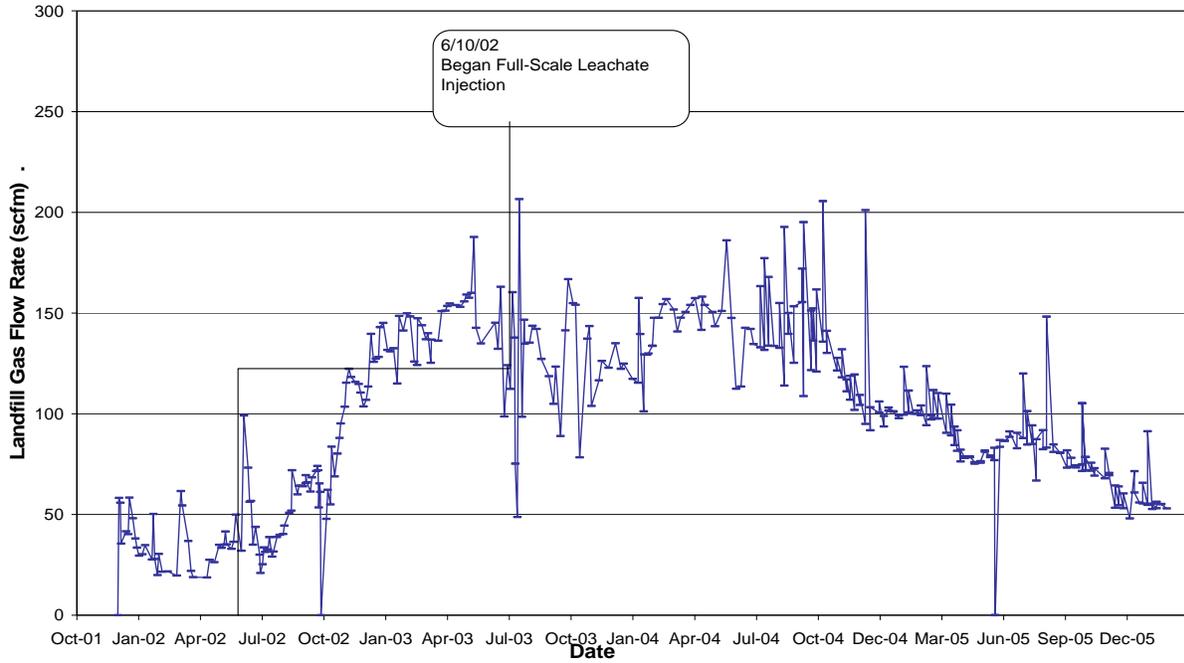


Figure 13. Northeast 3.5-acre cell average daily flow rate

Photo Credit: Yolo County Planning & Public Works Department

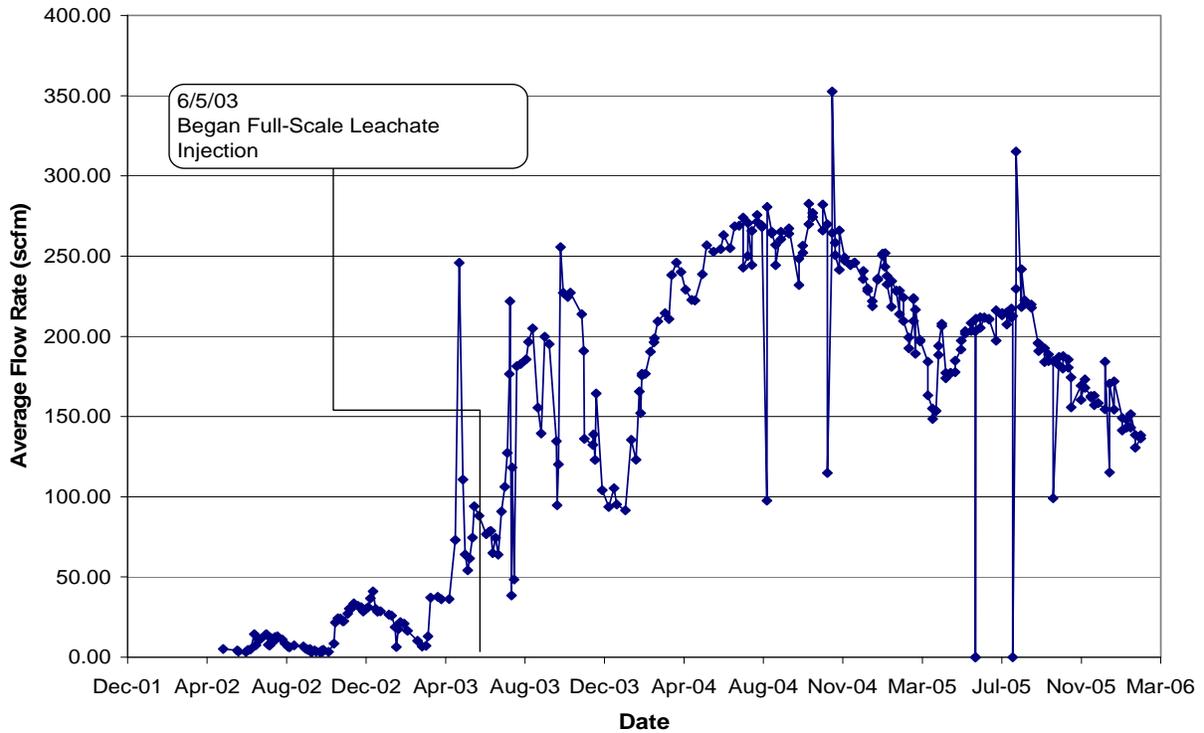


Figure 14. West 6-acre cell average daily flow rate

Photo Credit: Yolo County Planning & Public Works Department

3.7.2 Landfill Gas Volume

Appendix B, Figure 23, 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 $40 \pm 5\%$ to $50 \pm 5\%$.

Appendix B, Figure 24, 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 12 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 $0.685 \text{ ft}^3/\text{lb}$ for the northeast 3.5-acre cell. Comparing this to the estimated maximum methane potential of municipal solid waste of $1.4 \text{ ft}^3/\text{lb}$, the northeast 3.5-acre cell has undergone 48.9% of its estimated potential decomposition. Based on the U.S. EPA Landfill Gas Generation model, a typical dry-tomb landfill would be expected to produce approximately $0.10 \text{ ft}^3/\text{lb}$ of dry waste over the same time period. This translates to a nearly seven-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 standard cubic feet (scf) of methane, which is equivalent to approximately 12,426 barrels of oil or 6,525 MWh of electricity (at 12,000 scf methane per MWh).

Also included in Figure 12 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 $0.26 \text{ ft}^3/\text{lb}$. Comparing this to the estimated maximum methane potential of municipal solid waste of $1.4 \text{ ft}^3/\text{lb}$, 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 $0.07 \text{ ft}^3/\text{lb}$ of dry waste over the same time period. This translates to a nearly four-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 MWh of electricity.

The normalized methane generation rates (or in alternate technical terms, rate constants) for the northeast 3.5-acre 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. A small portion of the methane generated from each of the cells comes from decomposition of the "greenwaste" ADC (less than 17% by weight), but this material (chipped twigs, leaves, etc.) gives relatively low methane yields, less than half the yield from waste (Appendix A, Table 10

provides an itemized summary of the types of waste and quantity of greenwaste within each of the cells). The fraction of methane due to greenwaste ADC versus waste is irrelevant, given the widespread use of ADC as a cover material at many landfills and the fact that the bioreactor operation would also accelerate methane production from this greenwaste. Regardless of the percentage of methane due to greenwaste ADC, it should also be noted that calculated BMPs take into account methane generation from greenwaste because during waste sampling greenwaste ADC was present in the collected samples.

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 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, and also better cell geometry may be possible at other landfills.

3.7.3 Landfill Gas Methane, Carbon Dioxide, and Oxygen Content

Landfill gas constituent composition over time is plotted in Figures 25 and 26 in Appendix B. These figures show that as time progressed, the LFG methane content stabilized toward a range of 45 to 55% as was expected. A landfill gas composition at around 50% methane $\pm 5\%$ is acceptable for all landfill gas adapted equipment operation, especially including electricity generation. The variations in concentration are largely due to variations in extraction vacuum or draw.

3.7.4 Landfill Gas Collection System Pressure

Appendix B, Figures 27 and 28, 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 3.5-acre 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 3.2 ppm versus 0.8 ppm for the 3.5-acre cell.

3.7.5 Landfill Gas Collection System Temperature

Landfill gas temperature is monitored at each wellhead with either a permanently installed temperature probe 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%, which is not significant when considering the total volume of liquids added. Gas temperatures fluctuated between 50 and 90°F, and waste temperatures averaged around 110°F.

3.7.6 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 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, as it 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 of the condensate returns to the cell.

3.8 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.

3.8.1 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>.

3.8.2 Field QA/QC and Instrument Calibration

Field 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 the event of an odd (defined as values outside the normal range seen) gas reading, 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, it was calibrated by Total Safety, Inc. No field calibration of the equipment was necessary, and readings were taken following the instructions manual accompanying it.

3.8.3 Record Management

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

Data collected using the SCADA system was recorded onto two computers, one 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 was also manually entered into the spreadsheet. All leachate data entered was inspected for errors by other staff members in the office. A main database known as Adept was also used for organizing and validating all leachate data.

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

3.9 Surface Liner Emission Monitoring

3.9.1 Northeast 3.5-Acre Area

Scans to detect methane surface emissions from the northeast 3.5-acre cell have been performed quarterly since April 2002. Appendix B, Figure 29, 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 plots use different scales than the other surface plots. This is due to emissions of more than 200 ppm for September 2003 and 75 ppm for November 2004. Again, the project team 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, 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 (U.S. EPA and California) have chosen combustible gas measurements as the best and most practical indicators to give feedback on control effectiveness. (Emissions of biogas containing methane will be referred to 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 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 10-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 biogas flux.

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. Experience across the nation shows that data from emission scans as conducted in this project are extremely useful in such areas as tracking down cover leaks. 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 in Table 4. 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,

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

Table 4. Summary of surface scans for the northeast 3.5-acre cell

Date performed	Weighted average emissions (ppm)	Maximum emission (ppm)	Average vacuum applied by LFG extraction system (inches H₂O)
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

* First date after liquid addition

Data collected by authors; Data collected by Yolo County Planning & Public Works Department Personnel

Several times within the last year the biogas-to-energy facility was shutdown, either for maintenance or mechanical failure, which resulted in some moderate “ballooning” of the surface cover. However, during normal operation of the gas collection system, no ballooning was observed. Only a small amount of pressure is necessary to lift the liner. Calculations based on the weight of the sandbags and liner material indicated that only an extremely low positive pressure on the order of 0.20 in H₂O (0.007 psi) was necessary to lift the cover. Even on windy days when aerodynamic uplift would have a tendency to lift the liner, it was observed that the liner was being held tightly to the surface, indicating an inward pressure gradient, and that negative pressure was created as gas was being pulled from the cell.

The current regulatory guidelines for comparing the surface emissions from the bioreactor are found in 40 CFR 60, Subpart WWW, Standards of Performance for Municipal Solid Waste Landfills. Specifically, 40 CFR 60.755 requires landfills over a certain size to maintain surface methane emissions below 500 ppm. Comparing the readings obtained from the northeast 3.5-acre area to the regulatory threshold of 500 ppm, it is evident that the overall surface emissions from the 3.5-acre cell are extremely low.

As summarized in Table 5, the surface emission readings are widely scattered for reasons mentioned (variations in extraction vacuum or draw, subsurface pressure, effects from external winds and barometric effects). But despite scatter, it is emphasized that the average emissions over the surface were under 1/50 of the allowable standard of 500 ppm.

3.9.2 West 6-Acre Area

As presented in Table 5, higher emissions were detected on the west 6-acre area. This can also be seen in Appendix B, Figure 30, in which the emission scale is from zero to 650 ppm. Note that the maximum value presented for the August 2004 scan was more than 1,000 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 5. Summary of surface scans for the west 6-acre cell

Date performed	Weighted average emissions (ppm)	Maximum emissions (ppm)	Average vacuum applied by LFG extraction system (in H₂O)
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

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

Despite scatter, it is emphasized that the average emissions over the surface were under 1/50 of the allowable standard of 500 ppm.

Data collected by authors; Data collected by Yolo County Planning & Public Works Department Personnel

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 biogas-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 inch) 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 biogas 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 biogas collection system was shutdown. This was most likely because any excess gas buildup was escaping from 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 to 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 dependent on the suction applied by the landfill gas extraction system. Appendix B, Figure 31, 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.

3.10 Waste Solids Sampling and Biochemical Methane Potential Analysis

3.10.1 Testing and Results

Waste samples have been collected prior to liquid addition and following each year of liquid addition. These samples were 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 15, and are plotted in Appendix B, Figures 32 through 35.

The first sampling event occurred on June 4 and 5, 2002; the second, July 15 and 16, 2003; and the third, 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 36 through 38 in Appendix C show the sampling events.

As presented in Figure 15, the waste samples have indicated an increase in moisture content in the northeast 3.5-acre cell over the last three 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%. Figure 16 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.

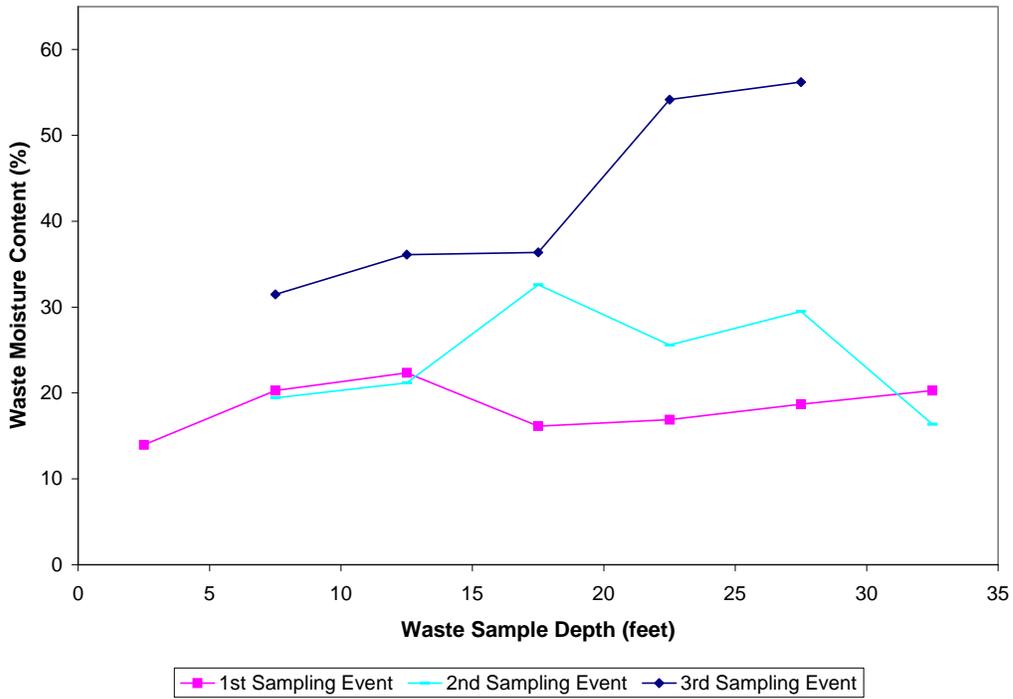


Figure 15. Waste moisture content for the northeast 3.5-acre cell

Photo Credit: Yolo County Planning & Public Works Department

Figure 5 - West 6-Acre Cell Moisture Content

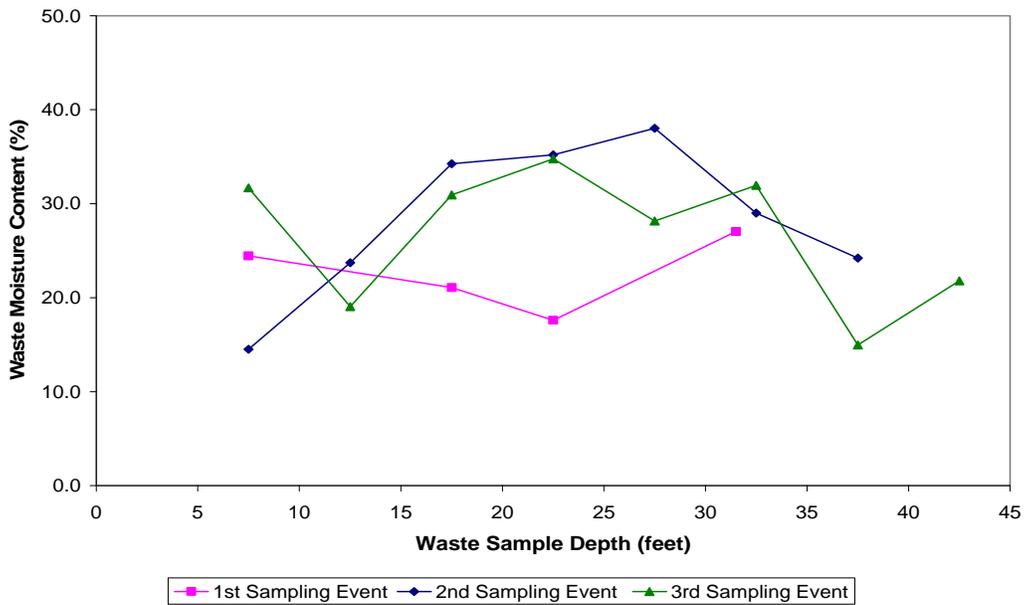


Figure 16. Waste moisture content for the west 6-acre cell

Photo Credit: Yolo County Planning & Public Works Department

3.10.2 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 and Woelders (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 or flow characteristics of the waste.” The observed scatter with these samplings “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 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 progresses, and analysis of additional waste samples could provide 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 comments 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 five 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 (1) BMP samples are finely ground and (2) their decomposition is carried out for a shorter time in the North Carolina State University lab, for only 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 likely due to remnant daily cover soil. The soil at Yolo is clay and has low permeability. Although diligent attempts were made to

remove it, enough evidently remained to impede liquid percolation. Evidence for better liquid distribution with more permeable cover is found in results from the 9,000-ton pilot-scale cell, where more liquid permeable greenwaste cover was used rather than soil.

3.10.3 Waste Settlement and Volume Reduction

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 6. Summary of Topographic Information for the West 6-Acre 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	1 st Year	315,290	8,919	2.75

Data collected by authors ; Data collected by Yolo County Planning & Public Works Department Personnel

Table 7. Summary of Topographic Information for Northeast 3.5-Acre 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	1 st Year	128,613	3,682	2.78
01/28/2004	2 nd Year	123,760	8,535	6.45

Data collected by authors ; Data collected by Yolo County Planning & Public Works Department Personnel

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 6 and 7 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.

Figure 17 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.

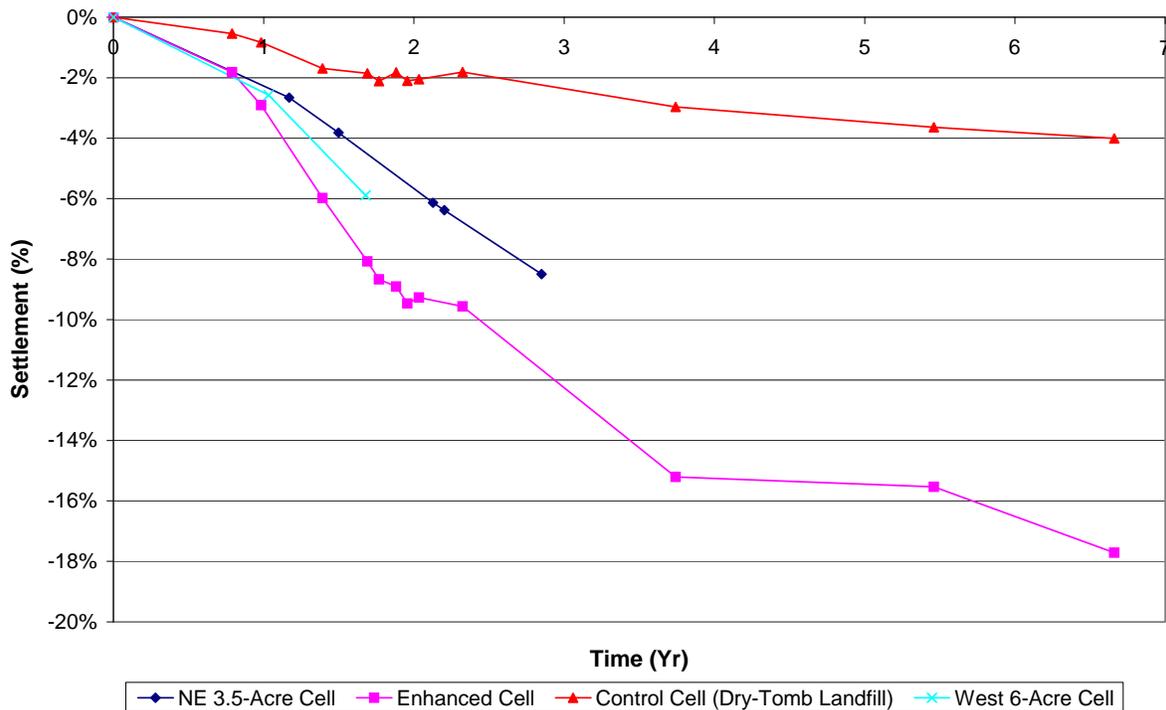


Figure 17. Settlement over time for the northeast 3.5-acre and west 6-acre cell, along with the previous pilot-scale enhanced and control cells

Photo Credit: Yolo County Planning & Public Works Department

To rate the progress of each of the cells, the project team compared settlement measured from the cells 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 coincides 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 enhanced cell (May 1997 to May 1998), the rate of settlement increased significantly to approximately 1% every two 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 enhanced 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 two to three-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 enhanced cell.

3.11 Methane Production Modeling

A landfill methane generation model is a tool to estimate methane generation over time from waste mass in a landfill. This 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's 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, an alternative means of estimating landfill methane generation is by 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.

3.11.1 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 analytical and microbial kinetic models, such as the Monod equation, that predict the performance and activity of microbial processes for known biological conditions. Biological conditions are very difficult to determine for landfills. Another impediment in modeling landfill methane generation is that methane recovered from landfills 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). 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 its version of the first order landfill gas emission model (LandGEM) available 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 .

The U.S. 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 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 landfill gas generation, and the variance in k values reported by the U.S. EPA, field data bear out models' utility. 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. The uncertainty of -30 to +50% cited above is much better than results of some earlier models (including early versions from U.S. 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 landfills, so the question of how to model these is just now being answered by studies at Yolo County as described below.

3.11.2 Methodology

The objective of this modeling is to estimate the first-order gas generation rate constant for the northeast and west bioreactor cells 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-acre 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 23 and 24. Methane generation figures over the first long-term interval of increased methane production were used 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 taken up to the most recent time that data was available. A straight-line regression was performed on each curve as shown in Figure 18. This regression line was superimposed on the cumulated methane curve for northeast and west cells in Appendix B, Figures 23 and 24. 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 18.

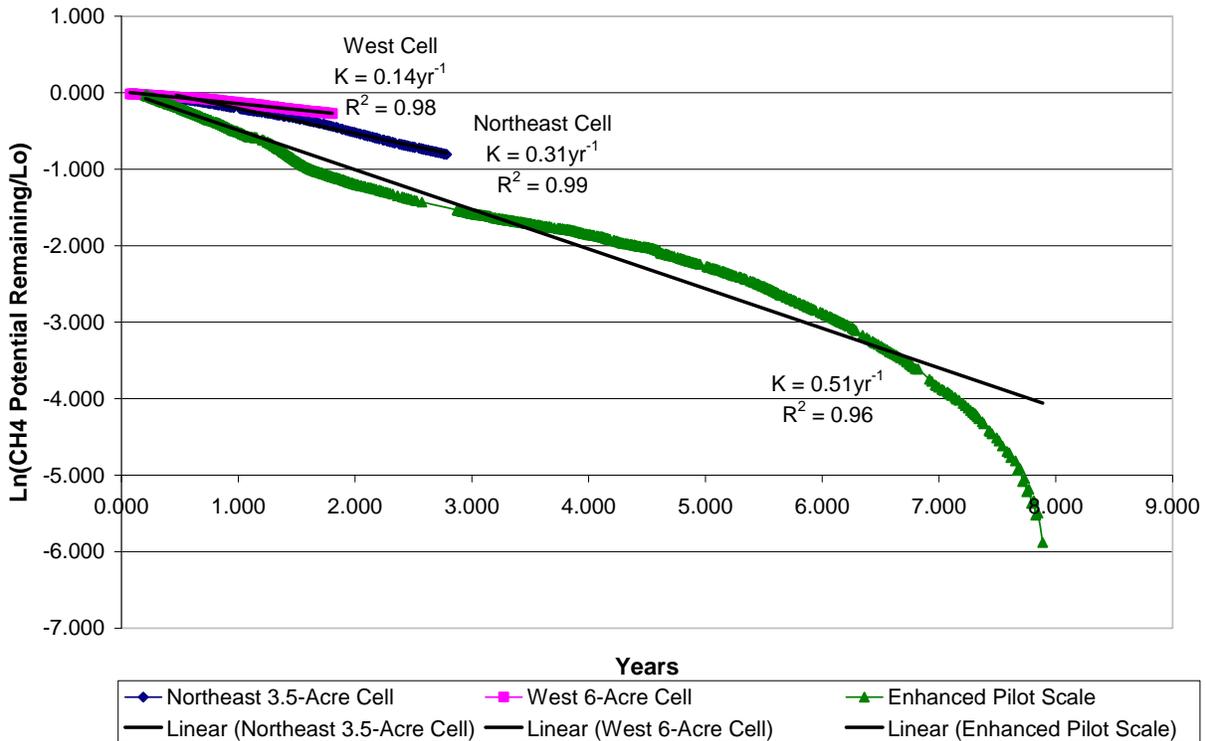


Figure 18. Calculation of k value for all cells, including previous enhanced cell

Photo Credit: Yolo County Planning & Public Works Department

The best estimate of ultimate methane potential was assumed to be 1.4 ft³ methane/lb dry waste, or 1.12 ft³/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 L₀ = 1.4 ft³ methane/lb dry waste). From this, the project team estimated the fraction of remaining methane potential 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 18). Also shown in Figure 18 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 more than 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 as liquid percolates, and self generated temperature. Some degree of change in the best-fit k values is likely and best long-term k values will become known more accurately with time.

3.12 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 ft³/lb dry waste (1.12 ft³/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 H₂O, about 0.15 psi. See Appendix B, 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 actually 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 ft³ 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 × 0.95 = 2,128 ft³ methane.

Energy, methane equivalents per ton for gas pumping = 2,128 ft³/ton × 1/(0.5 = fraction methane in gas) × 144 ft•lb/ft³ × (1/ 2.6552 × 10⁶ ft•lb/kWh) × 11.4 ft³ CH₄/kWh = 2.63 ft³ methane equivalent.

Energy, methane equivalents for liquid pumping = 30 (estimated) gal/ton × 8.32 lb/gal × 100 ft elevation × 2 cycles percolating through waste × (1/ 2.6552 × 10⁶ ft•lb/kWh) = 0.21 ft³ 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	<u>- 0.21</u> 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.

A recent review of the compiled waste-to-methane literature (Verma 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 to 75% of organics' methane potential can be realized in economically allowable vessel detention times (two weeks to two 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 to \$30/ton would translate to prohibitive expense, adding more than \$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 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.

3.13 Project Operations, Control, and Preventative Maintenance

This section is divided into three subsections associated with the major systems for the bioreactor cells. Each subsection discusses the operation and maintenance activities for both the northeast 3.5-acre and west 6-acre cell.

3.13.1 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.

Operation and Process Control

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 is controlled manually and typically involves pumping for a 24-hour cycle, with a down period to allow the liquid to infiltrate. Leachate recirculation, on the other hand, is automated. When leachate levels reach a certain level in the sumps, pumps automatically cycle and the liquid is removed from the sump and recirculated to the cell (to whichever bank of laterals was open).

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 warranty. 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 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 more than 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) was added to the bioreactor through the fall and winter 2002. Following this timeframe, the leachate stored in the storage pond was sufficiently dilute (due to rainwater and additional leachate through the winter) to allow its resumed use.

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 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 (see Appendix C, Image 43). 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.

3.13.2 Gas Collection System

The gas collection system for the northeast 3.5-acre and west 6-acre cell consists of the main collection header, the horizontal collection lines, and the on-site LFG-to-energy facility.

Operation and Process Control

The gas collection systems on the northeast 3.5-acre and west 6-acre cell are both operated manually. The main collection header valve is opened so that enough suction is available for collection of gas across the entire cell. Adjustments to the wellheads at each biogas collection line are performed manually during the weekly field readings, and are based on the gas composition. High methane contents above 50% mean an increase in flow is desired for that particular collection line, whereas concentrations below 45% mean a reduction in flow.

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 fall 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 was 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 line was 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.

On August 25, 2003, the landfill gas flow meter for the west 6-acre cell was 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 biogas-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, the County installed perforated piping 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 piping installation 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 cells. As leachate is injected into the cells, liquid levels build up to such a level inside the shredded tires layer (that includes 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. 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 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 four 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 seven weeks. Even though significant leachate was drained out of these lines, they remained blocked, most likely due to liquid buildup deeper in the cell.

3.13.3 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.

Operation and Process Control

The SCADA system incorporates two main components. An Allen-Bradley small logic controller (SLC), essentially a small computer, controls the data collection from all the various sensors. A personal 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.

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 the County was unable to remove them. The inability to remove these sensors was compounded by the fact that Pressure Transducers 4 and 5 were showing 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 with the transducers in hopes of determining the cause of the cable break and confirming the lack of liquid buildup on the liner.

3.13.4 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.

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 three and five years were used, however, damage began to occur almost immediately following installation of the sandbags. 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 resulting 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, rainwater did not collect in the bottom because they were solid. To reduce the costs associated with this work, the County utilized labor from its probation department. 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 forego installing geomembrane boots at each of the liner pipe penetrations. This was done as an experiment to see if surface emissions could be controlled, with the benefit of 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 the County installed permanent geomembrane boots 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 the project team believes will eliminate any residual emissions.

3.14 Project Economics

This section first presents costs actually experienced at the YCCL for the scaled-up northeast and west anaerobic bioreactor cells. Following these are the projections for a commercial operation.

3.14.1 Capital Costs

The total capital costs for the Full-Scale Bioreactor Landfill at YCCL during the contract interval are shown in Table 8. An explanation of the derivation of each capital cost item is presented in this section.

Table 8. Summary of capital costs for Yolo County Central Landfill’s full-scale bioreactor project during the contract interval

Item	Description	Capital cost
6.1.1	Base Liner Costs	\$ 3,365
6.1.2	Surface liner Costs	\$ 454,924
6.1.3	Liquid Addition and Pumping	\$ 193,607
6.1.4	Landfill Gas Recovery	\$ 102,855

6.1.5	Instrumentation	\$ 126,203
6.1.6	SCADA	\$ 137,430
6.1.7	Total “other” design, administrative	\$ 82,843
	Total capital costs	\$1,101,227

Data collected by authors

3.14.2 Base Liner Costs

The marginal cost of the base liner attributable to the bioreactor has been minimal, at \$3,365. This is because the base liner and its experienced costs would be required in any event.

3.14.3 Surface Liner Costs

The surface liner cost is high, at \$454,924 for 9.5 acres, or more than 400,000 ft² 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/ft², and possibly much lower. This reflects the fact that the purchased cost of the liner material (without installation) generally runs under \$0.25/ft². 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.

3.14.4 Liquid Addition and Pumping Costs

Liquid addition and pumping costs were \$193,607. This included the cost of design and construction for liquid injection and pumping capital cost.

3.14.5 Landfill Gas Recovery and Utilization Costs

Landfill gas recovery capital costs were \$102,855, covering the horizontal gas collectors placed in trenches in the waste as landfilling proceeded, and the associated piping system.

3.14.6 Instrumentation Capital Costs

Instrumentation capital costs were \$126,203. This includes the design and material costs for installation of instruments.

3.14.7 Supervisory Control and Data Acquisition System (SCADA)

The SCADA System capital cost totaled \$137,430.

3.14.8 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 and \$24,715, respectively, for a total “other” of \$82,843.

3.14.9 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. The project team estimates that most of the costs below could be considerably reduced in a commercial operation.

The total operating costs are summarized in Table 9.

Table 9. Summary of total operating costs for Yolo field experiment

Item	Description	Capital cost
6.2.1	Waste sampling and analysis	\$ 41,354
6.2.2	Field testing and monitoring of Landfill gas	\$127,208
6.2.3	Leachate Sampling and Testing	\$ 61,695
6.2.4	Methane Emission Monitoring	\$ 34,517
6.2.5	Landfill Settlement Surveys	\$ 35,629
6.2.6	Methane Production Modeling	\$ 7,771
6.2.7	Instrumentation and Equipment Maintenance	\$ 62,938
6.2.8	Project Management and Data Analysis	\$114,404
	Total Operating Cost	\$485,516

Data collected by authors

3.14.10 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.

Costs experienced for field testing and monitoring of landfill gas totaled \$127,208. 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.

Leachate sampling and testing costs were for the purpose of determining leachate pollutant loads. This is related to the reduction of risk for groundwater contamination as discussed elsewhere in this report. Total cost was \$61,695.

3.14.11 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.

3.14.12 Methane Emission Monitoring

Methane emission monitoring is a standard requirement to determine landfill emission compliance under U.S. 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 about three times more frequent than would be required in a commercial operation. The total cost was \$34,517.

3.14.13 Landfill Settlement Surveys

Landfill settlement (see Tables 6 and 7) 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.

3.14.14 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 \$7,771.

3.14.15 Project Management and Data Analysis

Project management and data analysis costs were \$114,404. This project management and data analysis category includes the management activities and data interpretation needed for the project activities in the contract interval.

3.15 Cost for a Full-Scale Commercial System

3.15.1 Summary of Costs for a Commercial System

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, independent of energy recovery, justify implementing a bioreactor by themselves.

- For most landfills where a bioreactor would be implemented, gas must be recovered using the 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, the authors will not attempt to cost out the operational costs of engine-generator sets in detail. The project team’s expertise is less than other organizations more experienced in landfill gas conversion to energy. The project uses the costs reported by Waste Management, Incorporated (WMI), which generates more than 600 MW of its own electricity from solid waste sites and fuels, including more than 200 MW powered by internal combustion (spark-ignited) engines on landfill gas. The presentation cited here is that of WMI Vice President Paul Pabor, “The Energy Value of Landfill Gas.” This talk was presented at various symposia including the Recycle Minnesota Symposium in October 2002 and can be found at: http://www.recycleminnesota.org/2002_conference.htm.

For discussion purposes, Pabor notes the following parameters for the average landfill gas to energy (LFGTE) Project:

- 1,600 cfm of landfill gas.
- 400,000 mmBtu/yr.
- 4000 kW.
- About 32 million kWh/yr.

For this size plant the capital cost is \$3.2 to \$5 million (\$800 to \$1250/kW) 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 cost.
- 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 WMI is based on the largest experience base in the world, and estimates of more cost detail by the project team would not add significantly to precision.

Landfill Gas Price

Electricity cost in following sections does not include any biogas 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. An energy system must simply be self-justifying on its own merits, i.e., the cost is that of an engine or turbine supplied with fuel in the form of landfill gas at no marginal cost. The long-term economic picture is good but there are non-technical barriers of other sorts, specifically permitting requirements, so the picture is not nearly as 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 10.

Table 10. 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

Data collected by authors

This summary represents only two examples distilled or culled from the wide range of complex power generation scenarios. The detailed calculations and determinations of performance and power revenue/cost data are presented in subsequent sections. 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.

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:

- 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 mandated for all landfills to prevent groundwater contamination.

- Waste surface coverage will be required in any event to standards that assure continuing coverage with time, as well as assuring rodent and bird exclusion, etc.
- All normal maintenance and operation work will be required in any case. Cost assumptions are based on the professional judgment and experience of the project team, 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.

3.16 Kinetics of Gas Generation and Capture

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

A methane generation yield of 3000 ft³ (3 million Btus 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.

3.17 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 implemented at typical United States 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 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/ft³ or 1,350 lb/yd³ for the total landfill volume. At this density, an acre-foot of waste weighs 1089 tons. An acre of waste 50 ft deep will contain 54,450 tons, and 100 ft deep, 108,900 tons. These assumptions will be used below.

3.18 Startup and Management of Landfilling and Gas Recovery Operation

3.18.1 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 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.

3.18.2 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 1500 mmBtu/day, is 1425 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 MW. At 1,000 tons/day, recoveries double.

3.19 Scenarios for Calculating Methane Recovery and Power Generation

A 25-year continuous filling operation is considered. From assumptions above, and estimates based on accepted kinetic models (parameters given above), about 7% of one year's biogas generation is lost to energy use at the start of filling. To use the remaining biogas 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 six-engine combination becomes fuel limited. At the assumed kinetic rate constant of 0.2 yr⁻¹, this occurs nine years after closure. In this "optimistic" scenario, the total biogas 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%, i.e. 94% 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 MW (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 MW
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 four years and averaging two (given a three-year 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 making a limited difference to cost estimates as will be seen below. The time value of money also drops if discount rates are 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.

3.20 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/kW 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, the authors use 3 to 3.5 cents/kWh at various points below.

3.21 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 systems 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 “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, NO_x offsets must be available, which they often are 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 University of California, 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.

3.21.1 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 as the state moves toward adopting the new federal standards.

3.22 Estimated Benefits

3.22.1 Airspace Recovery

The results from the Yolo County enhanced cells 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:

- The Yolo volume reduction is by no means complete.
- 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 to 10% more of the original gate waste. Aerobic landfill operation is already permitted and encouraged at some sites.
- The cost of additional landfill sites has been increased at greater than the cost of inflation, as landfills become progressively more difficult to site near populated areas in California and the nation.

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, the value of volume reduction for this analysis is between \$4.80 and \$9/ton of waste.

Table 11. Summary of the Benefits

Fill Rate (Tons per day)	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

Data collected by authors

3.22.2 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 significantly 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 would 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 modeled by both D. Augenstein (unpublished) and the University of Delaware working

in cooperation with Yolo County. 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 lowers or “zeros 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 credit or benefit costing are attempted in the analyses below.

3.22.3 Gas Recovery

In this analysis, any gas value is normally embedded in the electricity output, whose value is already counted. There will normally be no other sale of gas energy with electrical generation. 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 a negligible addition to the gas cost that fuels generation.

Thermal uses. A moderate but significant fraction of biogas projects, about 20%, sell the biogas 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 per million Btu under long-term contracts, sellers have 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/mmBtu 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 United States energy situation.

Thus, revenue from landfill gas, other than the electric revenue, may range all the way from zero to \$8-plus 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.

3.22.4 Greenhouse Gas Emissions

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

The party desiring credits must demonstrate it can sell a greenhouse emission that can be abated. Greenhouse credits were discussed at symposia sponsored by the U.S. EPA's Landfill Methane Outreach Program (LMOP) in the talk by Michael Carolan and can be found at http://www.epa.gov/lmop/conf/01_greenpower/carolan.pdf.

A GHG reduction program involves various constraints:

- The emission cannot be one that would have been reduced anyhow, by regulations.
- The emission reduction must be rigorously quantifiable and verifiable.
- No other entity than the seller of credits. In this case, the party collecting landfill gas is likely to sell the same credit.
- 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 United States participation in the Kyoto Accord, the market valuation for United States sale of "carbon credits" is very poor. Therefore, few landfill gas energy projects seek, let alone have, revenue from GHG credits, although some projects are "banking" them. Those that do quantify GHG credits find that the market price is quite variable, but in the best of cases where there is a willing buyer of credits, the sale of credits can gain more than \$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 CO₂ and acceptance of abatement of methane with a global warming potential (GWP) weight ratio of 21-to-1 over CO₂, 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 CO₂ abatement credits of several dollars per ton have been under consideration in the past, the GHG credit could be extremely high at more than \$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 per ton of MSW landfilled. This amounts to:

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

3.22.5 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 and length of post-closure care. This

uncertainty and the possibility of more than 30-year ongoing care causes concern, even if projected post-closure costs may appear reasonable at some discount factor.

After closure, conventional landfill 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-plus% 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 of \$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 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.

3.22.6 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 more than \$1/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 1 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.

3.23 Economic Analysis of Full-Scale Project with Energy Generation

3.23.1 Benefit to Cost Comparison for Bioreactor Operation

In this section, the project team calculated costs for the bioreactor independent 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.

Assumptions

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

The landfill is filled using conventional operations. The specifications of a conventional LCRS, highly permeable and requiring accommodation for a 100-year 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 to be highly effective, are equivalent to below 1 inch/day precipitation. The recirculation rate in the pilot experiment at Yolo County was equivalent to below 30 inches/year 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 that will allow later liquid infiltration is used rather than conventional cover soil. This porous daily cover may be greenwaste, tarp, 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 \$2,500/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 more than 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/ft² 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 four-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 (WMI), 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 1,000 tons/day cases. This value, used as a "proxy" cost in Table 13, should be recognized as potentially 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 difficult to ascertain, but the project team estimates 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 are \$10,000/year.

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 13 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 12. 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

Data collected by authors

Cell depths of 50 ft and 100 ft are again assumed, and other assumptions, 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/ft² 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 requirements 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 electricity or waste management benefits, such as 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. Tables 13 and 14 list some estimated annual expense and benefit components for the 500 and 1,000 ton/day fill rate.

Table 13. Annual dollar expense of cost items specific to bioreactor

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

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

Data collected by authors

Table 14. Annual value of bioreactor waste management economic credits

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

(Exclusive of electricity: All figures approximate. See text for discussions.)

Data collected by authors

The MWh/yr estimated for the 500 and 1,000-ton cases are as follows (repeated from 6.3.5 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 that the value of prospective benefits exclusive of energy outweighs the costs. 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 as operational experience is 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, the benefits must be well-established with extensive operating experience. All Research, Development and Demonstration (RD&D) operations must be cautious and carefully thought out and run.

3.24 Effect of New Regulations

The recently implemented U.S. EPA Bioreactor Landfill 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 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.

4.0 Conclusions and Recommendations

4.1 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, a summary of recommendations for future bioreactor operation, and discussion of areas that require additional research.

The 9,000-ton pilot-scale cell continues to show that bioreactors can provide projected energy, environmental (GHG 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 a larger scale.

The objectives stated in the first section of this report are:

1. Acceleration of waste decomposition and leachate treatment, via liquid amendments and recirculation of leachate through 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. Documentation of the capital and operations cost of a full-scale bioreactor and determination of the economic viability of its commercialization.
4. Establishment of the environmental and renewable energy benefits to facilitate regulatory acceptance.

The results relating to the objectives are:

1. The project revealed the acceleration of decomposition, shown in Figure 12. There has been, at minimum, a four-fold increase in the methane recovery rate, with increases up to seven-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 Tables 4 and 5. Appendix B, Figures 29 and 30, support the data of these tables. 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 the section above. From a purely economic standpoint, commercialization is attractive. Public acceptance is developing and long-term performance remains to be established.
4. The adoption of the RD&D rule for bioreactor landfills by Federal and State of California EPA. On March 22, 2004, the U.S. EPA issued a final rule to allow RD&D Permits for MSW landfills under Title 40, Code of Federal Regulations, Part 258 (RCRA Subtitle D) with the rule becoming effective April 21, 2004. Subsequently, on June 14 and July 21, 2005, CIWMB and the California State Water Resources Control Board, respectively, adopted proposed regulations for RD&D. Final approval of the RD&D regulations is pending approval of the California State Office of Administrative Law and U.S. EPA.

4.1.1 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. The project team recommends 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) was 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 generated landfill gas.

4.1.2 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.

4.1.3 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 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 continue on both of these areas: alternate covers that allow high control of gas emissions and use of a biocover to further mitigate emissions.

4.1.4 Further Options: Landfill Mining

One option that requires further study would be mining and sorting waste following aerobic and/or anaerobic decomposition. One attractive option for appropriately reclaimed waste, that adds no net volume to the landfill, is it could be used in place of other cover that does occupy volume. Such use of reclaimed waste can further reduce use and extend landfill life. 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 from old cells could be used for daily cover instead.

4.1.5 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.

4.1.6 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.

4.1.7 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 data logging 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.

4.2 Commercialization Potential

The controlled landfill or accelerated anaerobic composting, as conducted at Yolo, should have excellent commercialization potential. The following is a general overview of factors affecting commercialization, and activities to date on behalf of commercialization.

4.2.1 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 the Solid Waste Association of North America (SWANA) to develop a white paper on bioreactor benefits.
2. In October 2003, Yolo County hosted a Bioreactor public workshop for CIWMB. More than 200 people attended this workshop. This workshop included a field trip for interested persons on bioreactor landfills and a presentation on the bioreactor technology. CIWMB invited panels to discuss pros and cons of this emerging technology from the perspective of a private landfill operator, public landfill operator, the Local Enforcement Agency Enforcement Advisory Council, and a representative from the composting and environmental community. An open public comment period was conducted at this workshop. State Water Resources Control Board (SWRCB) staff were also present and involved in the planning for this workshop.
3. Cooperating with regulatory agencies to modify rules to allow bioreactors. Ramin Yazdani, Don Augenstein, 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 U.S. EPA draft and final rules (RD&D rules) in the United States' Federal Register allowing bioreactor implementation across the nation. Similar rules have been issued for California and will be finalized this year.
4. Presenting papers at major conferences, particularly SWANA and also worldwide (U.S. EPA and United States Department of Energy [DOE] climate and renewable conferences in China and Russia) for the recent years. It should be of interest that these international conferences, which were cosponsored by the U.S. DOE and U.S. EPA, with Russia and Chinese counterparts have increased appreciation of the bioreactor's possible benefits.
5. Sharing project data with various public and private agencies interested in the bioreactor technology and providing information on environmental benefits mitigating environmental risks. In the past three years, Yolo County has given bioreactor tours to more than 40 small groups from the United States and abroad.
6. Assisting the Energy Commission and CH2MHill in the review of the design and operation plan for the Commonwealth Bioreactor project.

4.2.2 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 WMI is pursuing bioreactor technology is evidence of this. Other evidence is provided by the support of bioreactor advancement by SWANA, the nation's largest professional association dealing with solid waste issues. Provided a reasonable design basis is available, the expertise is available to 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 because 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. Bioreactor technology needs help from all involved stakeholders, not just landfill operators.

4.2.3 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 with incremental costs to operators precluding 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 Board's requirements for liner systems for all Class III landfills in California. In recent years there has been discussions about requiring double liner systems 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.

4.2.4 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 serious but little recognized environmental impacts that are not present with bioreactors. The same types of limitations also occur with other waste-to-energy conversion processes including (for example) MSW-to-alcohol conversions and gasification.

4.2.5 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 of the controlled landfill or accelerated anaerobic composting bioreactor must continue to be marketed to the range of stakeholders.

4.2.6 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 biogas. 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 biogas-fueled piston engines has been excellent at landfills. The emission 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.

4.2.7 Emphasizing Bioreactors’ Other Benefits

Some other drivers strongly favoring bioreactors are California’s newly active climate change mitigation initiatives that favor Yolo’s approach to maximize 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, 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. The project team believes the engineering of bioreactors is part of a bigger picture containing ancillary issues, such as regulatory facilitation and defining what adequate emissions compliance is.

These are but a few of the considerations aside from technical feasibility and economics that will determine progress toward wide commercialization in the future. The types 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.

4.3 Recommendations

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

1. Continue monitoring full-scale operations to provide long-term performance information desirable for advancing 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 on the order of three years. Several promising projects elsewhere have halted when funding ran out; however, information of great value comes after long periods. Results continue 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 other ways. 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 discovering the long-term stabilization performance, i.e. 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 gas recovery control, 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. Explore alternative gas collection methods that do not require expensive geomembrane covers.
6. Explore the use of more permeable alternative daily cover that would ease liquid infiltration and lessen events such as side seeps.
7. Explore variable-rate gas collection, thereby testing opportunities to match power output (“peaking power”) to diurnal variations in power demand.
8. Test the excavation of stabilized “old” waste to provide alternative daily cover for new cells, thereby extending landfill life.

4.4 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 improvements in waste management and landfilling, reduction of

environmental impacts, economics, and other areas. The following summarizes some of the energy, environmental, and state economy benefits.

4.4.1 Energy Benefits

The potential added renewable energy benefits to California depend on assumptions, but are in any case quite significant. The authors 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 = 3,000 ft³/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 ft³ CH₄/kWh to give time-average power generation of about 500 MW. Present California Generation is about 75% of a nameplate 240 MW, or 180 MW.

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

4.4.2 Greenhouse Emission Abatement

The authors assume that the control of California generated methane from 22.5 million tons of waste increases from 70% to 95% (data from personal communication with CIWMB staff). At the accepted Intergovernmental Panel on Climate Change (IPCC), 20-fold equivalence of methane to carbon dioxide, reduction of methane emissions by 2,400 ft³ (2,400 cubic feet of methane = 1/20 ton of methane equating to the 1 ton of CO₂) equates to a reduction of CO₂ emissions by 1 ton. The decreased CO₂ equivalent emission by this example would be 7 million tons/year.

More greenhouse benefit comes from the CO₂ equivalent emission reduction; in other terms, the fossil CO₂ offset of the methane fueled electricity. In electricity generation, certain power sources including hydro, wind, and nuclear are "must run," fixed at the maximum level afforded by fully exploiting the source. In other words, essentially 100% of hydro, wind, nuclear, and photovoltaic resources are already used. Consequently, the "swing fuel" for extra power generated "at the margin" over and above what these greenhouse gas neutral resources can provide is all fossil. Depending on the mix of displaced fossil oil or gas displaced by landfill gas fueling, the CO₂ abated by renewable methane can be calculated as about 0.75 tons/MWh generated. Assuming the 300 MW time-average above for a year, another 2 million tons of fossil CO₂ emission could be prevented.

4.4.3 Air Pollution Emission Abatement

Landfill gas contains roughly 1000 ppm of VOCs (using the U.S. EPA convention of expression as hexane) in addition to CO₂ and CH₄. This is about 0.7 grams of local air pollutant or VOCs per cubic foot. It is assumed, as above, that there is the abatement of an additional 1.68×10^{10} ft³ of methane, or $3.36 \times 1,010$ ft³ of 50% methane landfill gas. At this loading of VOCs, the VOC 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.

4.4.4 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.

4.4.5 Employment and Economic Benefits

Just as nations do, states including California run a “balance of payments.” The balance of payment is important in various ways to the state’s economy. The realization of 300 MW time-average of extra power, annually, at 10,000 Btu saved per renewably fueled kWh, would reduce the need for about 30 trillion Btus or 30 million mmBtus (in common United States energy usage). At a rather conservative cost these days for the swing fuel energy of \$5/mmBtus, 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 more than \$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 the state.

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Glossary

ADC	Alternative Daily Cover
BMP	Biochemical Methane Potential
BOD ₅	5-day Biochemical Oxygen Demand
Energy Commission	California Energy Commission
CIMIS	California Irrigation Management Information System
COD	Chemical Oxygen Demand
CQA	Construction Quality Assurance
DO	Dissolved Oxygen
FID	Flame Ionization Detector
GCL	Geosynthetic Clay Liner
GWP	Global Warming Potential
HDPE	High-Density Polyethylene
I/O	Input/Output
k	A constant measuring permeability of the soil
LCRS	Leachate Collection and Recovery System
LFG	Landfill Gas (a gaseous mixture of methane and carbon dioxide)
LLDPE	Linear Low-Density Polyethylene
LMOP	EPA's Landfill Methane Outreach Program
MTBE	Methyl Tertiary Butyl Ether
NMOC	Non-Methane Organic Compounds
ORP	Oxidation Reduction Potential
PID	Photo Ionization Detector
ppm	Parts per Million
PVC	Polyvinyl Chloride
RD&D	Research, Development, and Demonstration
RPP	Reinforced Polypropylene Geomembrane
MSOR	Mechanically Separated Organic Residue
MSW	Municipal Solid Waste
scf	Standard Cubic Feet
scfm	Standard Cubic Feet per Minute
SCADA	Supervisory Control and Data Acquisition system
SLC	Small Logic Controllers
TDS	Total Dissolved Solids
UV	Ultraviolet
VOCs	Volatile Organic Compounds
VS	Volatile Solids
YCCL	The Yolo County Central Landfill

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