LANDFILL OPERATION FOR CARBON SEQUESTRATION AND MAXIMUM METHANE EMISSION CONTROL

Controlled Landfilling Demonstration Cell Performance for Carbon Sequestration, Greenhouse Gas Emission Abatement and Landfill Methane Energy.

Phase II Topical Report (Draft)

Reporting Period: July 1, 1999 to February 27, 2001

Prepared by
Don Augenstein
Institute for Environmental Management (I E M)
4277 Pomona Avenue
Palo Alto, CA 94306

Cooperating co-workers and co-authors
Ramin Yazdani, Deputy Director, Public Works, Yolo County, California

Other contributing Yolo County Staff;
Rick Moore, Michelle Byars, Jeff Kieffer

Others Contributing
Professor Morton Barlaz, Assistant Director, Civil Engineering Department and
Rinav Mehta, Masters' Degree Graduate, Civil Engineering Department,
North Carolina State University (NCSU), Raleigh, North Carolina

Supported by
National Energy Technology Laboratory Contract DE-AC26-98FT40422
Sean Plasynski, Contracting Officer's Representative (COR)

February 26, 2000

DISCLAIMER

ABSTRACT

Worldwide, landfill methane emissions are responsible for an estimated 3 to 5% of the total increase in "radiative forcing" due to buildup of all greenhouse gases in earth's atmosphere, in simplified terms, the "greenhouse effect". Controlled landfilling is an approach to manage solid waste landfills, so as to rapidly complete methane generation, while maximizing gas capture and minimizing the usual emissions of methane to the atmosphere. With controlled landfilling, methane generation is accelerated to more rapid and earlier completion to full potential by improving conditions (principally moisture, but also temperature) to optimize biological processes occurring within the landfill. Gas is contained through use of surface membrane cover. Gas is captured via porous layers, under the cover, operated at slight vacuum. A field demonstration project has been ongoing under NETL sponsorship for the past several years near Davis, CA. Results have been extremely encouraging. Two major benefits of the technology are reduction of landfill methane emissions to minuscule levels, and the recovery of greater amounts of landfill methane energy in much shorter times, more predictably, than with conventional landfill practice. With the large amount of US landfill methane generated, and greenhouse potency of methane, better landfill methane control can play a substantial role both in reduction of US greenhouse gas emissions and in US renewable energy.

The work described in this report, to demonstrate and advance this technology, has used two demonstration-scale cells of size (8000 metric tons [tonnes]), sufficient to replicate many heat and compaction characteristics of larger "full-scale" landfills. An enhanced demonstration cell has received moisture supplementation to field capacity. This is the maximum moisture waste can hold while still limiting liquid drainage rate to minimal and safely manageable levels. The enhanced landfill module was compared to a parallel control landfill module receiving no moisture additions. Gas recovery has continued for a period of over 4 years. It is quite encouraging that the enhanced cell methane recovery has been close to 10-fold that experienced with conventional landfills. This is the highest methane recovery rate per unit waste, and thus progress toward stabilization, documented anywhere for such a large waste mass. This high recovery rate is attributed to moisture, and elevated temperature attained inexpensively during startup. Economic analyses performed under Phase I of this NETL contract indicate "greenhouse cost effectiveness" to be excellent. Other benefits include substantial waste volume loss (over 30%) which translates to extended landfill life. Other environmental benefits include rapidly improved quality and stabilization (lowered pollutant levels) in liquid leachate which drains from the waste.

Under the NETL Phase II, work has also been initiated to scale up and operate a bioreactor landfill on scale of several hundred thousand tons. This "full-scale" bioreactor operation will apply both the promising anaerobic technology and the aerobic landfill technology that is receiving increasing attention.

Federal and state policies are in general developing very positively towards acceptance of "bioreactor" and controlled landfill technology. The potential methane recovery and

abatement for the US as a whole has been estimated at approximately 80 million tonnes/year. Given uncertainties inherent in any such estimates, the likely reduction potential in greenhouse methane emissions is 50-100 million tonnes/ year, amounting to about 1-2% of total fossil carbon dioxide (CO_2) emission for the United States. An additional similar amount of US greenhouse gas reduction can result from sequestration of photosynthetically fixed carbon in landfills, and in "offsets" of fossil CO_2 emissions through use of landfill methane fuel. The same technology offers potential to fuel approximately 1% of US electricity generation, comprising a modest but significant renewable electricity resource. Controlled landfilling offers an attractive option for the United States to meet a significant portion of its greenhouse gas reduction targets and to meet a modest and helpful fraction of its renewable electricity needs. The estimated worldwide potential for greenhouse emission abatement and renewable energy generated is subject to uncertainties but is at least threefold that of the United States.

ACKNOWLEDGMENTS

IEM and the authors acknowledge the considerable help and support of the following, and their contributions:

Sean Plasynski, of the National Energy Technology Laboratory (NETL) for helpful guidance and consultation throughout this report.

Vicky Shears, and also Raymond Jarr, of the Federal Energy Technology Center (FETC) for helpful guidance and consultation on contract issues through this report.

John Pacey, for his advice and support in all aspects of the project since its inception. Also for his personal work in enabling the increasing acceptance of this technology.

Ramin Yazdani, Director of the Yolo County, California Department of Public Works and Planning. For all his work critical to success of this project, since his beginning as a new Yolo County employee to his present position, deputy director of Public Works. His work includes contributions in instrumentation, construction management, and other areas--too many to detail here. He is thanked for his recent expert review of this report.

Rick Moore, of Yolo County, (in fact alternating his employment among Yolo County, the US Peace Corps and a non-governmental organization in Africa, to the benefit of all) who contributed in ways too numerous to detail here to all phases of the demonstration.

Michelle Byars, who's attentiveness to project field work, and data collection and management was invaluable to the success of the project.

To Karina Dahl, Civil Engineer for Yolo County, for contributions to success of this project in managing the demonstration field operations for the last three years and her recent expert review of the report.

To W. Greg Vogt, Vice President, SCS Engineers for much advice and assistance, and particularly for past review of the economic analysis of "greenhouse effectiveness"

Rinav Mehta, M.S., and Professor Morton Barlaz, Associate Head of the Civil Engineering Department, North Carolina State University, Raleigh, for extremely helpful analytical work providing insights on extracted waste samples.

TABLE OF CONTENTS

DISCLAIMER ii

ABSTRACT iii

ACKNOWLEDGMENTS v

TABLE OF CONTENTS vi

LIST OF FIGURES, TABLES, AND BOXES viii

EXECUTIVE SUMMARY 1

- Greenhouse Gas Emssion Control 1
- Bioreactor Implementation 2
- Yolo County Demonstration 3
  - *Project Sponsors.* 3
  - *Project approach.* 3
- Regulatory And Policy Factors 6
- Potential For Greenhouse Gas Reduction 7
- Larger-Scale Operation 7

INTRODUCTION AND BACKGROUND 8

- Rationale 8
- Quantities and units 9
- Fugitive Emissions 9

CONTROLLED LANDFILLING 11

- Greenhouse Gas Emission Savings 11
  - *Emission Reduction* 11
  - *Carbon Dioxide Sequestration* 11
  - *Fossil Fuel Offsets* 11
- Steps to Controlled Landfilling 11
- Energy Potential 12
- Carbon Sequestration 13
- Gas Capturing Inefficiencies 13

GENERAL PROCESS APPROACH 14

- Biological Conditions 14

YOLO COUNTY CONTROLLED BIOREACTOR DEMONSTRATION 17

General Objectives 17

Expected Benefits 17

Demonstration Project Design 18

Base layer containment. *19*

Cell filling. *19*

Instrumentation. *20*

Liquid Addition 22

Leachate Quality Results 26

Thermal Effects 27

Gas Recovery Performance 29

Implications of observed thermal behavior. *30*

Surface Membrane Performance 30

Decomposed Waste Sampling 30

Observations. *31*

Moisture distribution and hydraulic considerations. *32*

Methane yield vs. theoretical. *34*

Moisture content and pH of liquid from samples. *36*

Biochemical methane potential analysis. *37*

Additional drilling event observations. *37*

REGULATORY AND POLICY ISSUES AND DEVELOPMENTS 38

Regulatory Involvement 38

California Integrated Waste Management Board Support *38*

SWANA Survey *38*

Earlier Federal Policy: Climate Change Action Plan item 37. .... *38*

Nomination for EPA Project XL *39*

Solicitation of Comments on Bioreactor Landfills: Federal Register *39*

EPA Workshop on Landfill Bioreactors *39*

Leachate Containment Integrity 39

Other Policy and Regulatory Considerations 39

Contribution to US Energy self-sufficiency 40

LARGE-SCALE DEMONSTRATION 41

SUMMARY AND CONCLUSIONS 42

APPENDIX 46

LIST OF FIGURES, TABLES, AND BOXES

Figure ES- 1 *Liquid inflows, outflows and retention in demonstration cell.* 4
Figure ES- 2 *Moisture sensor readings for the enhanced cell.* 4
Figure ES- 3 *Gas yields of enhanced, control and "conventional" landfill cells.* 5
Figure ES- 4 *Subsidence of enhanced and control cells.* 6

Figure 1 *Methane production rate versus moisture content.* 14
Figure 2 *Arrhenius Plot showing dependence of rate on temeprature for methane fermentations of solid substrates (Ashare et. al.).* 15
Figure 3 *Isometric view of the control and enahanced demonstration cells.* 18
Figure 4 *Enhanced and control cell base liner prior to waste placement.* 19
Figure 5 *Cross section of the control and enhanced demonstration cells.* 21
Figure 6 *Liquid injection design for the enhanced cell.* 24
Figure 7 *Liquid inflows, outflows and retention in demonstration cell.* 25
Figure 8 *Moisture sensor readings for the enhanced cell.* 27
Figure 9 *Temperature sensor readings for the enhanced cell.* 28
Figure 10 Temperature sensor readings for the control cell. 28
Figure 11 *Gas yields of enhanced, control and "conventional" landfill cells.* 29
Figure 12 *Drilling into the enhanced cell to allow waste sampling.* 31
Figure 13 *The warm waste in the enhanced cell was steaming in the cold ambient temperatures during the drilling event of October 1999.* 32
Figure 14 *Moisture distribution determined by core length.* 34
Figure 15 *Methane yield versus theoretical.* 35
Figure 16 *Cellulose plus hemicellulose over lignin versus pH.* 36
Figure 17 *pH versus moisture content.* 36

Box 1 16

EXECUTIVE SUMMARY

“Conventional” solid waste sanitary landfills are among the largest emitters of anthropogenic (human-made) methane emissions to the atmosphere. Even where landfills may be equipped with gas collection controls mandated under federal regulations, a substantial volume of methane may escape and be emitted to the atmosphere (referred to as “fugitive” methane). The fugitive landfill methane emissions occur in part due to inefficiency of conventional collection systems, and partly due to the difficulty of collection over a typically several-decades-long term of methane generation. Methane generated at long terms is often not easily controlled in conventional landfill operation Adding to the emission problem worldwide, methane emissions from most waste landfills and dumps around the world are not controlled at all. Methane is a highly potent greenhouse gas, and so emitted landfill methane is documented in many studies as highly significant to climate change. Thus, improved landfill methane abatement offers opportunity for substantial "greenhouse" and climate benefit.

At the same time that landfills convert part of the photosynthetically fixed waste carbon they receive to methane, which can offset fossil CO_2 emission, they also sequester large quantities of photosynthetic carbon (such as that of wood) which remains unconverted and sequestered in the landfill.

Greenhouse Gas Emssion Control

Implementation of a controlled landfill bioreactor can abate greenhouse gas emissions in three ways. First, the controlled approach reduces “fugitive” landfill greenhouse methane emissions by improving biological reaction conditions and using a very low permeability cover over a very highly permeable gas collection layer. The improved biological conditions speed methane generation to rapid completion with maximum yield. In combination with high-efficiency collection of generated gas. Fugitive emissions are estimated at about 700 million tonnes CO_2 equivalent (EPA, 1995). Depending on how widespread the application (i.e. if worldwide), the greenhouse gas abatement from using controlled landfill bioreactor technology could amount to over 500 million tonnes CO_2 equivalent annually for the world.

The second approach to greenhouse gas emission abatement occurs in the removal of CO_2 from the atmosphere. Photosynthetically fixed CO_2 enters and remains undecomposed (sequestered) within landfills. Roughly 200 million tonnes per year of CO_2 can be removed from the atmosphere. The net "greenhouse" benefit depends on the basis for comparison because conventional landfills sequester carbon dioxide as well. Still, such landfill sequestration of photosynthetically fixed carbon clearly provides greenhouse benefit relative to the common practices of aerobic composting, increasingly applied in developed countries, or to the open burning so common in developing countries.

The third way that greenhouse gas emissions can be abated is by methane conversion to energy. Photosynthetically fixed carbon which enters landfills and is decomposed, produces methane (contained in the landfill gas) which can be converted to energy, therefore “offsetting” (substitute for) other fossil fuel requirements and CO_2 production. An estimated in the order of 30 million metric tons per year of methane can be used for fuel, therefore "offsetting" over 100 million tonnes of fossil CO_2 which would otherwise be emitted.

Although carbon sequestration and fossil fuel offsets are not so widely recognized, these environmental benefits have substantial positive climate effects due to atmospheric CO_2 reductions. The amount of disposed waste represents substantial atmospheric CO_2 fixed and sequestered. There is considerable net climatic benefits of methane-to-energy conversion because landfill methane fuel offsets fossil CO_2, however it does not add net CO_2 to the atmosphere because landfill CO_2 circulates in "closed loop" to and from atmospheric CO_2 in the first place.

Bioreactor Implementation

The "controlled landfill" or "bioreactor" landfill approach is intended to take maximum advantage of the benefites described above in limiting greenhouse gas emissions. An additional objective has been to use procedures that will be relatively easy to implement over the range of landfills both in the US and worldwide. The "controlled landfill" or "bioreactor" landfill process being investigated involves the following steps:

1. Placing waste in the landfill while waste is relatively dry, hence, landfill gas generation rate is low.

2. Contain and cover waste, combined with the use of permeable layers so as to capture maximum gas volume.

3. Employ a highly efficient gas collection system.

4. Enhance methane generation by raising the moisture content and taking advantage of elevated temperature to the maximum extent feasible.

5. Collect and convert methane to energy to offset fossil fuel use (such as by reducing electricity generation necessary elsewhere).

6. Complete gas generation much sooner than normal. This helps to eliminate the problems inherent with long-term low-rate gas generation ("tailing") in conventional landfills.

Controlled landfill bioreactors offer several other operational, energy, and environmental benefits are obtained as well. These include, but are not limited to, greater waste volume reduction, as more waste solids are transformed more rapidly to gas, and rapid reduction of leachate pollutant levels, distributed energy generation potential, feasibility of landfill gas-to-energy projects.

Yolo County Demonstration

One approach to reducing landfill-related greenhouse emissions, maximizing methane energy capture, and taking advantage of landfill carbon sequestration has been under intensive investigation at the Yolo County Central Landfill near Davis, CA.

Project Sponsors.

The Yolo County Bioreactor Demonstration Project has been sponsored by many different parties. Prior to NETL involvement, a consortium of sponsors helped fund the construction of the demonstration cells. Consortium participants included Yolo County, California, the California Energy Commission (CEC), and Sacramento County, CA. The Institute for Environmental Management (I E M) provided consulting services, some of them pro bono. Other parties also provided very valuable pro bono work. The California Integrated Waste Management Board (CIWMB) and the Western Regional Biomass Program and the Urban Consortium Energy Task Force of the U. S. Department of Energy gave further very useful early support.

Project approach.

Two test cells were constructed of essentially equal size, One cell was "enhanced" by liquid addition while the other, without liquid supplementation, served as control. Cell bases were lined and liquid additions to enhanced cell waste were carefully metered at controlled rates to 14 addition points (1 m^3 shredded-tire filled pits) atop the cells. Efficient gas collection was obtained by surfacing the test cells (both the "enhanced" and “control” cells) with surface geomembrane atop a highly porous (> 10^6 Darcy) shredded tire gas collection layer. Each test cell had a surface area ("footprint”) of about 0.27 acres.

Controlled liquid supplements continued until moisture sensors showed moisture to be well-distributed at measurement points throughout the waste and until liquid outflow reached a predetermined level that was easily managed by the drainage system. This, in essence, constitutes a "titration" of waste by added liquid. Waste liquid content reached its moisture holding ability but did not materially exceed it. Once net liquid additions ceased, limited amounts of liquid leachate exited the cell. This leachate was recirculated through (percolated downward through) the cell. The profile of leachate input, supplemental liquid (ground water) input, and leachate recirculation is shown in figure ES-1. The results of the 56 moisture sensors distributed throughout the waste is shown in figure ES-2. These readings, rapidly rising on liquid addition, confirm that added moisture effectively reached all sensors in the waste mass. This was also confirmed by coring tests discussed later in the main text of this report.

This liquid addition in essence "titrated" the waste mass by adding liquid at a manageable rate, which for the enhanced cell was not in excess of 10 gallons per minute. The recirculation rate of leachate through the cell amounted to a superficial velocity (liquid flow rate based on empty cross section) of about 60 cm/year. The low level of this circulation is evident from the fact that it is comparable to the rainfall impinging on a

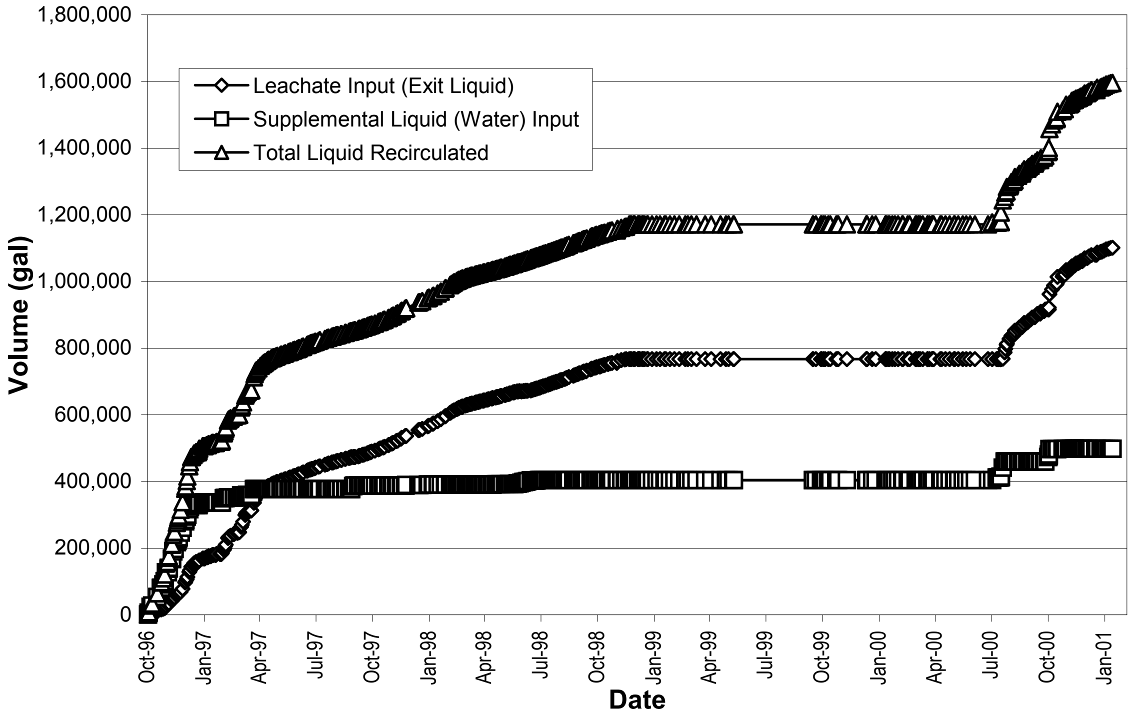


Figure ES- 1 *Liquid inflows, outflows and retention in demonstration cell.*

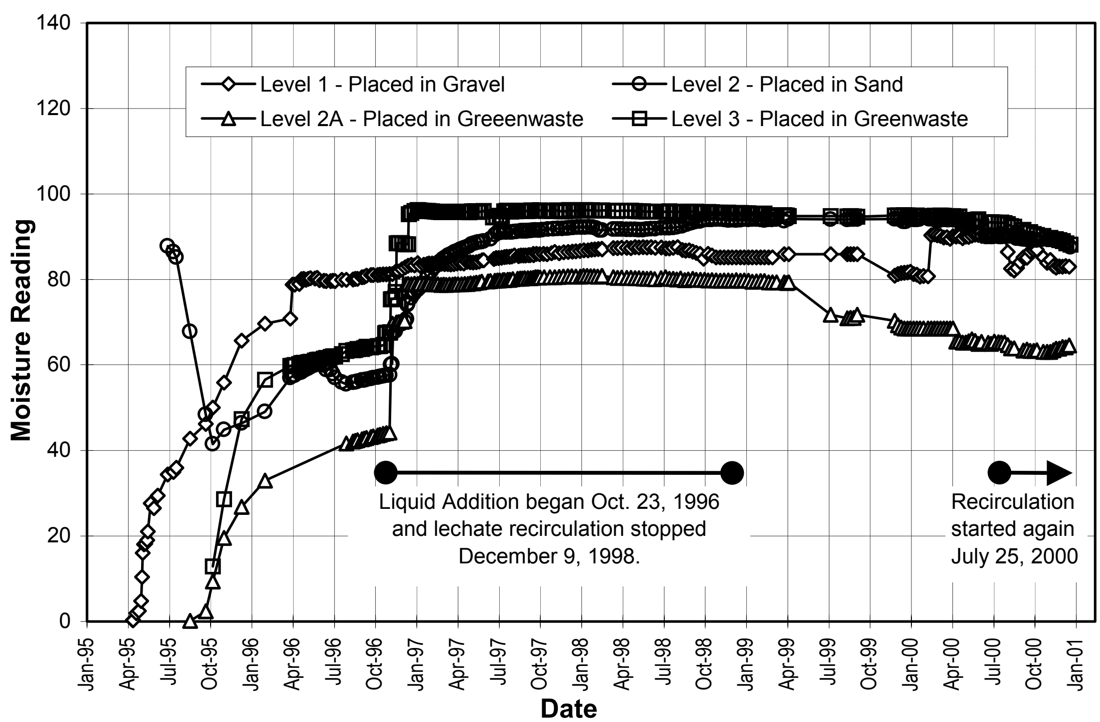


Figure ES- 2 *Moisture sensor readings for the enhanced cell.*

landfill in a semi-arid region (25" per year). Such low infiltration levels are easily controllable. Further control avenues are available discussed later in this report.

The work supported by NETL, the National Energy Technology Laboratory, between mid-1999 to the present (February 2001) continued the controlled landfilling demonstration to obtain key measurements such as gas yield, volume reduction, moisture balance, and liquid leachate pollutant abatement. The field demonstration already constitutes the longest-term carefully monitored tests of anaerobic bioreactor to date, and additional information, as it continues to be gathered adds further value. Figure ES-3 compares the gas yield of the "enhanced" and controlled demonstration cells compared to the expectations of "normal" Subtitle D landfills, Figure ES-4 shows the subsidence, or surveyed volume reduction.

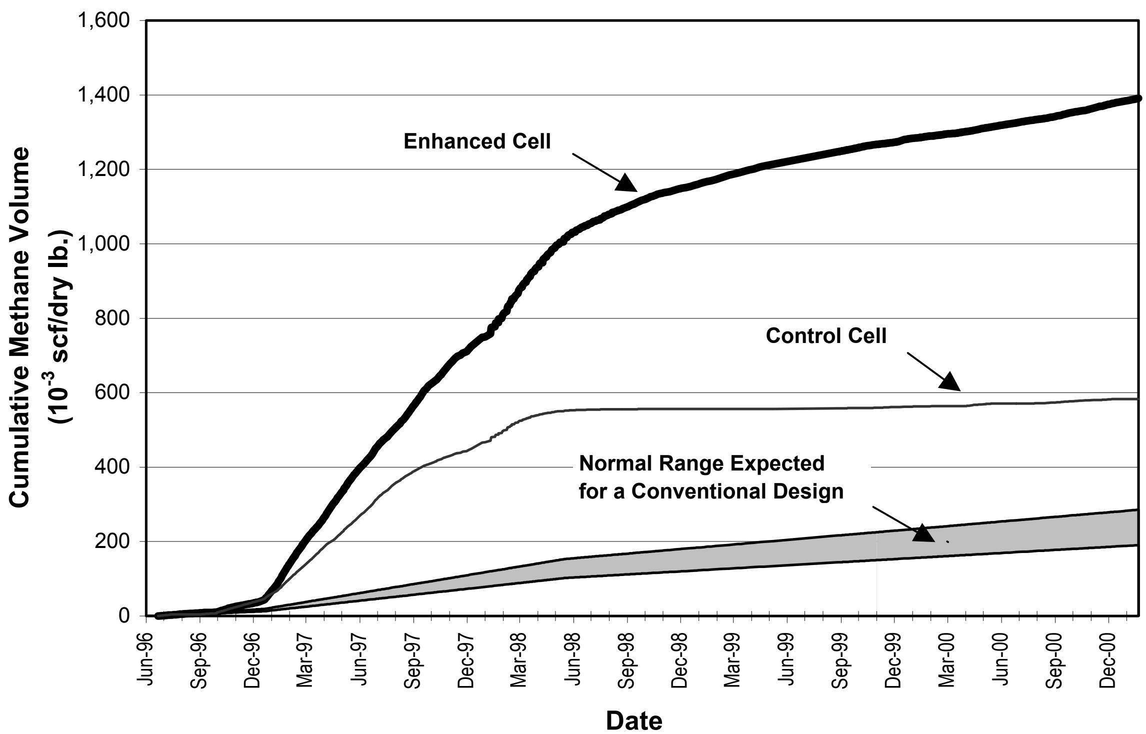


Figure ES- 3 *Gas yields of enhanced, control and "conventional" landfill cells.*

It is appropriate here to briefly review results of Phase I of this program, which was the preparation of a document submitted to NETL "Cost Effectiveness and Potential - Controlled Landfilling for Greenhouse Gas Abatement", submitted in January, 1999. Phase I evaluated "greenhouse cost effectiveness" of methane abatement by controlled landfilling and also, estimated the technology's cost for obtaining additional amounts of methane from waste in US landfills, and also worldwide. Altogether, throughout a considerable number of possible variations in parameters, the performance of greenhouse gas abatement and also the generation of renewable electricity by controlled landfilling appear attractive when judged against other extant renewable energy costs and standards.

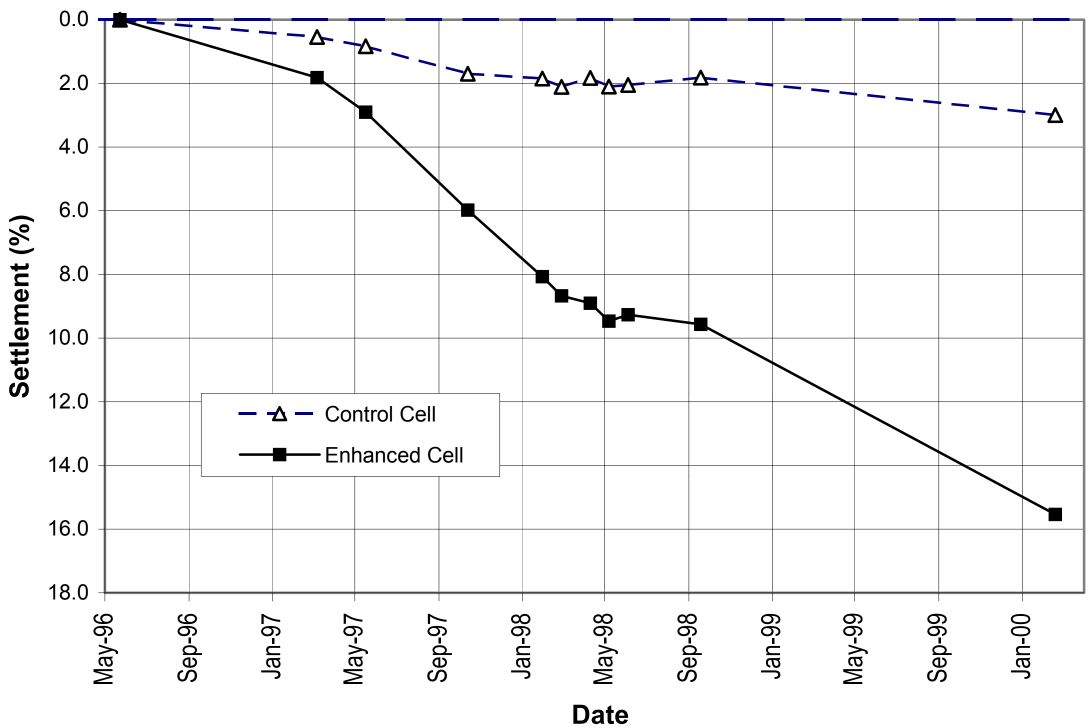


Figure ES- 4 *Subsidence of enhanced and control cells.*

The Phase II field work confirms this. Table ES-1 shows estimates of US renewable energy attainable if the controlled landfilling technology were to be applied to 60% of US waste. Depending on reference bases against which the technology is judged,. as well as estimates of amounts of waste landfilled around the world, the controlled landfilling approach should be able to abate approximately 500 million to 1 billion tonnes of CO_2 (equivalent) at costs between \$1 to \$5 US per ton of CO_2 mitigated (translating to \$3 to 13/tonne CO_2 carbon abated). The potential energy recovery worldwide is approximately 1 billion cubic feet of methane annually (1 quadrillion Btu or approximately 1 pentillion Joules, in simpler terms (acknowledging uncertainties) about 0.2 to 0.5% of world energy production.

A second portion of the Phase II work addressed scaleup of the technology to full-scale. The scaleup under way, is expected to ultimately give performance data which can allow the confident application of the technology to landfills across the US. Needed design work, as well as base layer construction and instrumentation, have comprised a portion of the Phase II work and is described later below.

Regulatory And Policy Factors

An intricate regulatory and policy situation is evolving in favorable directions, Changing regulatory stances should facilitate controlled landfilling in several ways and enable its wide application. This is discussed in later sections. For example, an earlier Solid Waste

Association of North America (SWANA) survey shows that state regulators are coming to at least consider "bioreactor" and "controlled landfills" as viable waste management options. Necessary liquids additions to landfills, previously opposed by many states' regulators, are now interpreted as allowed amendments under governing Federal code (40 CFR 258.28). Federal policy in the 1993 Climate Change Action Plan calls for use of bioreactor landfills as one tool to address climate change. Finally, potential environmental benefit of controlled landfilling is recognized, to such extent that the Federal Register of April 6, 2000 has solicited comments on needed rule changes and other factors that may be needed in its implementation. Other activities in the direction of acceptance and recognition of benefits are discussed in later sections

Potential For Greenhouse Gas Reduction

Example calculations were carried out to evaluate possible magnitude of greenhouse gas abatement benefits if controlled landfilling were widely applied in the US. It is estimated that application of controlled landfilling to a majority of US wastes could lead to methane emission reduction equivalent to CO_2 reductions of about 80 million tonnes/year (implying a likely range of 50-100 million tonnes/year). To this can be added approximately equal climate benefit potential (50-100 megatonnes CO_2/year) from the combined effects of (carbon sequestration + fossil fuel CO_2 offsets). The cost range in the Phase I NETL report was estimated at U.S. $1-5/ metric ton [tonne] of CO_2, corresponding to $3-13/ton CO_2 carbon or its equivalent in other greenhouse gases Calculation details were presented in the phase I Report prepared for this contract.

Larger-Scale Operation

The scaleup of controlled landfill technology is warranted, to research the process at full scale and provide the necessary confidence in it as one promising avenue to future low-cost greenhouse gas abatement as well as a welcome source of renewable electricity. Scaleup, intensively instrumented to determine the "science" and experimental performance aspects, would provide a great deal of necessary information. Favorable views of scaleup have been expressed in writing and support by, among many others, the Electric Power Research Institute, the U.S. EPA, and the California Integrated Waste Management Board. In particular, the California Integrated Waste Management Board is supplying a portion of the support that would enable the larger scale operation.

INTRODUCTION AND BACKGROUND

The project, although supported over time by several sponsors most recently NETL, is a single coherent program of work.. This document will present a complete history, to the extent possible, including rationale, and details of early stages of the Yolo County project, as well as the recent accomplishments with NETL sponsorship.

Rationale

Within the US, sanitary landfilling dominates municipal solid waste disposal. With present practice, wastes received at landfills are spread, compacted, and covered with thin soil or other cover on a daily basis until a planned depth is reached. Wastes are then covered with permanent cover, most frequently clay. This practice, while meeting all present or anticipated regulations, nonetheless has several associated environmental impacts. In particular, though there is ordinarily no effort to control landfill biological conditions, waste slowly decomposes to generate and emit landfill gas (LFG).

Landfill gas is comprised of methane (CH_4), carbon dioxide (CO_2) and small levels of other local air pollutants regarded as significant under the Federal Clean Air Act. The gas is generated, generally over decades, as microorganisms decompose the organic fraction of landfilled waste. For cellulose, the principal decomposable component of "typical" mixed wastes, the overall simplified conversion reaction, to landfill gas is:

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow 3n\ CH_4 + 3n\ CO_2$$

(cellulose monomer + water + bacteria → methane + gaseous carbon dioxide)

Methane generation from decomposing US waste is very significant from a climate perspective, simply because of the huge amounts of decomposable waste landfilled in the US alone. US methane generation estimates are being refined, based on studies such as the major 19-landfill study sponsored by the Department of energy [DOE]/Solid Waste Association of North America [SWANA] study (Vogt and Augenstein, 1997). A default yield of 2800 ft3/ton (87 M3/kg) and a US landfilling rate estimated at 160 million tons/year (145 million tonnes/year) leads to US landfills' estimated methane generation at 6-10 million US tons or 5.5-9 million metric tons (tonnes) per year. At accepted methane potency 21-fold greater by weight than CO_2, 5.5-9 million tonnes per year (for example) of methane emitted would be "greenhouse-equivalent" to 115-190 million tonnes of CO_2 per year for the US alone. Though statistics are fragmentary, methane emitted worldwide, from wastes either landfilled or dumped, is several times the US emission level. Worldwide estimates vary, but the emission globally of over thirty million tonnes of methane annually amounts to the equivalent of over 700 million tonnes of carbon dioxide, per year. As discussed later, major fractions of generated methane may be emitted even when all presently mandated control strategies are applied. Thus more widespread and better landfill methane control, the overall objective of this project, can offer substantial climate benefit.

Quantities and units

Before proceeding to further discussion, comments are necessary here about units to be used in this document. U. S. units (US tons, cubic feet of gas, thousands of cubic feet of gas or MCF, and pounds) will be used when these are traditional measures in both the waste management and energy fields. Metric equivalents will also be stated for the appropriate parameters used in both fields.

Fugitive Emissions

Much present design of landfills is governed under the recent federal “Subtitle D” regulations. The regulated control of landfill gas falls under the New Source Performance Standards (NSPS) and the Clean Air Act as amended (CAA). It is useful to reiterate information provided in previous reports about the effectiveness, and where effectiveness may be lacking, with present controls. Methane is emitted to the atmosphere even with NSPS and CAA regulations in effect due to several factors:

- The emissions of methane before controls are implemented. Under present rules the period before controls are implemented can be as long as 5 years (however this issue is under US EPA and other regulatory review).

- Inefficiency of existing controls. As an illustrative example, ICF, a contractor to the US EPA, uses a default level of 75% for recovery using the usual and "conventional" vertical wells.

- For conventional landfills, there clearly may be methane emission for some time after the mandated 30-year postclosure period during which controls are required. Long-term fugitive emissions (beyond 30 years postclosure) are to some extent estimates, but it is worth noting that gas generated slowly over long terms is expensive to collect, so that collection is mostly inefficient or absent. Thus, for rate constant of 0.04 $year^{-1}$ (consistent with Los Angeles County Sanitation District’s data and experience) it is straightforwardly shown that a mass of waste will emit 30% of its methane over 30 years after placement.

- Not only are controls inefficient, but the exemption from collection of all gas emitted by "smaller" United States landfills of less that 2.5 million metric tons [tonnes] design capacity adds significant additional emissions into the atmosphere

- Volatile Organic Compound (VOC) emissions are the only basis under existing law, by which landfill gas control and recovery can be compelled. For numerous landfills with over 2.5 million tonnes design capacity, testing by prescribed methods establishes that emissions of volatile organic compounds is well under the 50 metric (55 US tons) per year that would compel recovery. This means even very large landfills can "opt put" from landfill gas controls (see below).

Discussion here must be somewhat qualitative in view of partial statistics and continuing changes. However, much landfill methane in the US clearly reaches the atmosphere even given all existing gas control rules. Also important is that landfill gas VOC's (air pollutants) have fallen to about 10% of EPA default assumptions because of improving exclusion of volatile hydrocarbon and similar wastes from landfills. These VOC's, by law not methane, provide the only federal statutory basis for gas controls under NSPS and CAA. It is readily established using validated predictive methods (Peer et. al., 1992, Vogt and Augenstein, 1997, Walsh, 1997) that landfills well above the 2.75 million ton/year limit, up to 5-10 million tons, can "test out" of gas controls at low VOC emission levels now routinely measured. A judgment (on incomplete statistics) is that 25-45+% of generated US landfill methane could escape controls completely--that is, continue to be emitted from landfills that will have no controls at all--given expected control criteria and practice. It is difficult to estimate fugitive emitted fractions of emitted landfill methane, except to note that they easily amount to 100-200 million tonnes CO_2 equivalent for the US alone. Calculations and estimates in support of this were provided in the Phase I report under this contract[1]. Globally, emissions may range up to as much as a gigatonne of CO_2 equivalent. This large amount of methane provides opportunity for substantial greenhouse gas abatement with proper incentives (such as renewable energy revenue and emission reduction credits) that should lead to control. Further example calculations are presented later in this report.

US landfills, even those equipped with gas controls under modern standards, can still emit substantial quantities of methane because (a) emissions prior to installation of controls (b) inefficiencies while controls operate, (c) long-term emissions that may occur after control (gas extraction) ceases, (d) size criteria are not met, and (e) VOC emissions are too low to compel controls. It is judged that even the landfills with gas controls conforming to all regulations would for the most part appear to collect only 50-75% of the gas they generate (supporting estimates were presented in the Phase I report, Augenstein, 1999). For reasons noted the stated large fraction of US methane, perhaps 25 to 45%, may be emitted.

[1] Also note that the US Energy Information Administration (EIA, 1998) has estimated landfill methane emission of 9.8 million tonnes annually, with CO2 equivalence (21-fold by weight) of 205 million tonnes annually.

CONTROLLED LANDFILLING

The question has been, given current circumstances, how might landfill methane emissions be abated if or when greater control of climate active gases becomes necessary? Better control of landfill methane emissions is clearly a route to enable substantial greenhouse gas emission savings. Landfilling can be modified to take full advantage of three major mechanisms, to substantially abate greenhouse emissions.

Greenhouse Gas Emission Savings

Three primary mechanisms for "greenhouse gas" savings, with approximate CO_2 equivalent abatement potential by each individual mechanism, are:

Emission Reduction
Reducing fugitive landfill "greenhouse" methane emissions. These are estimated at about 700 million tonnes CO_2 equivalent (EPA, 1995). Depending on how widespread the application, i. e. if worldwide, the greenhouse gas abatement from the technology could be up to 500 million tonnes CO_2 equivalent annually for the world

Carbon Dioxide Sequestration
CO_2, photosynthetically fixed, entering and remaining undecomposed ("sequestered") within landfills, should comprise roughly 200 million tonnes per year of CO_2 removed from the atmosphere. The net "greenhouse" benefit clearly depends on the basis for comparison (after all, conventional landfills sequester. as well). Still, such landfill sequestration of photosynthetically fixed carbon provides clear greenhouse benefit relative to common practices of aerobic composting, increasingly applied in developed countries, or to the open burning so common in developing countries.

Fossil Fuel Offsets
That photosynthetically fixed carbon which enters landfills, and does then decompose, provides methane fuel (landfill gas) which can "offset" (substitute for) fossil fuel and CO_2. Used for fuel, this methane, estimated in the order of 30 million metric tons per year, can "offset" over 100 million tonnes of fossil CO_2 which would otherwise be emitted.

Steps to Controlled Landfilling

The specific steps by which controlled landfilling may be carried out are:

1. Limiting the emission of methane in early stages of waste placement in landfills, This is accomplished by placing waste as rapidly as possible in the landfill while waste is relatively dry and while landfill gas generation rate is low. Combined with this is provision for gas control and recovery of gas from waste as early as possible. Cover with low-permeability cover as early as possible after waste is filled.

2. During filling and after waste coverage, use near-surface permeable layers so as to allow maximum gas capture. Extremely efficient (>> 90%) gas capture layer can be accomplished by highly permeable (> 10^6 Darcys) layer of shred tires, wood chips or gravel, beneath a low-permeability cover at the waste surface or a short distance beneath it. The gas capture layer is kept at very modest vacuum (< 1 cm negative water head) compared to atmospheric. This vacuum will be uniform throughout the permeable layer. Pulling gas from such a capture layer, having 3-4 orders of magnitude greater permeability compared to the average of overlying cover, guarantees the goal of capture of well over 90% of generated gas.

3. After an efficient gas collection capability is in place, enhance methane generation using carefully controlled additions of moisture. Also take advantage of elevated temperature resulting from initial air entrainment to the maximum extent feasible.

4. Collect methane as it is generated, and use to offset fossil fuel use (such as by reducing electricity generation necessary elsewhere).

5. Complete gas generation much sooner than normal. This helps to eliminate the problems inherent with long-term low-rate gas generation ("tailing") in conventional landfills.

Energy Potential

The purpose of the NETL program is, in effect, atmospheric CO_2 abatement. However in addition to environmental impacts from "greenhouse" gas emissions and local air pollutants, landfill methane emitted rather than captured represents substantial energy potential to be captured (or lost). For example if electricity were the energy product, estimates by both EPA (EPA, 1993) and the Electric Power Research Institute (Gauntlett, 1992) suggest that sufficient landfill gas could be recovered to generate between 5000-7000 megawatts (MW). This could meet close to 1% of current US electric need, and be sufficient to supply total electrical requirements associated with all activities of over 2 million US citizens.

Currently, landfill gas recovered by “conventional” approaches is in fact used for energy at about 150 sites in the US (Thorneloe et. al.; 1997 Augenstein and Pacey, 1991). However, there are several times this number of sites with over 1 million tons of waste in place (by EPA's estimate over 700). Present generation of about 900 MW, which includes electric equivalent of thermal at appropriate conversion efficiencies, is only about 15% of potential as estimated in several independent studies (EPRI, 1992, US EPA 1993, Augenstein et. al. 1994). The low energy recovery compared to potential is the consequence of factors including incomplete decomposition of waste to gas, inefficient recovery, and inability to accurately predict gas availability over time at landfills which are operated conventionally. The anaerobic version of the bioreactor can greatly increase the energy capture to a high (certainly > 80%) fraction of its potential. This energy is nearly all renewable in that methane nearly all derives from the components of waste (paper, food) that from photosynthetically fixed carbon (petrochemical products - plastics, etc. - do not generally degrade anaerobically).

Greater energy from landfill gas gives "greenhouse benefits" by lessened fossil fuel use elsewhere as well as via methane emission prevention. Closer control of landfill methane generation can facilitate energy use by more predictable and greater recovery (and in turn economies of energy equipment scale) and greater controllability of methane recovery. With better predictability and controllability, energy equipment can be sized properly to make full use of the greater quantity of recovered fuel gas.

Carbon Sequestration

Photosynthetically fixed organic material (the primary example being wood) does not appreciably decompose in landfills. The carbon in wood and other such undecomposed material in landfills represents sequestered atmospheric CO_2.

Gas Capturing Inefficiencies

There are a number of approaches which, though appearing attractive initially, have problems. Simply covering landfills with a plastic sheet ("geomembrane", or "membrane") can allow recovery of nearly all gas that is generated under the membrane. Membranes have been intended to be a post-closure requirement for many landfills (Federal Register, June 26, 1992). When installed over surface gas-permeable layers (such as shredded tires), membranes can capture close to 100% of generated methane.

However, a membrane used independently does not work. This is because it results in a secondary phenomenon: a water-impermeable geomembrane that prevents moisture (precipitation) infiltration and greatly slows decomposition. (Kraemer et. al., 1993, Leszkiewicz 1995, work reported later in this document). The exclusion of moisture results in what is widely called a “dry tomb” (for examples see numerous articles by Lee, 1990-2000). Decomposition is slowed, to the point where it can require a century or more of continuing effort to control slowly generated gas (as opposed to 2-5 decades of control, already a clearly substantial problem with current practice). Further, if surface containment breaks down many years after placement, decomposition occurs in uncontrolled fashion as outlined below.

The "dry tomb" disadvantages include (a) economics become very poor for gas that will be very slowly recovered over very long terms, (b) Waste fractions that stay dry are found in numerous samples with no apparent long-term decomposition at all (described in numerous popular articles by Archaeologist and "Garbologist" William Rathje) and (c) Membrane containment integrity must be maintained long-term as "entombed" waste remains un-decomposed or continues to decompose very slowly. Alternately, failure of the containment system allowing moisture to infiltrate a very long time after waste placement, would accelerate gas emission when careful control of the landfill is no longer occurring.

GENERAL PROCESS APPROACH

Controlled landfilling combines two key elements: enhancement of methane generation to rapidly complete waste decomposition to its maximum possible yield, and gas permeable layers beneath low-permeability cover to allow extremely efficient collection of gas that is generated. Much-faster completion of methane generation avoids dealing with gas generation at long terms. A surface or near-surface permeable layer at slight uniform vacuum combined with membrane over the waste can reduce emissions to nil. Methane generation enhancement, central to the approach, will be discussed next.

Biological Conditions

Although other factors can be important, the effects of moisture (Halvadakis et. al, 1983) are paramount in accelerating methane decomposition. Elevated moisture (by conventional landfill standards) is essential for accelerating biological activity and methane generation. Figure 1 shows pronounced effects of moisture typical of studies on moisture enhancement of methane generation. Temperature is quite important even though it has received rather little attention as a variable (Ashare et, al, 1978, Hartz and Ham, 1982). Figure 2 shows, as an Arrhenius plot, the effect of temperature. With temperature, an over 30-fold increase in rate constant is seen as temperature rises from 15 to 60C.

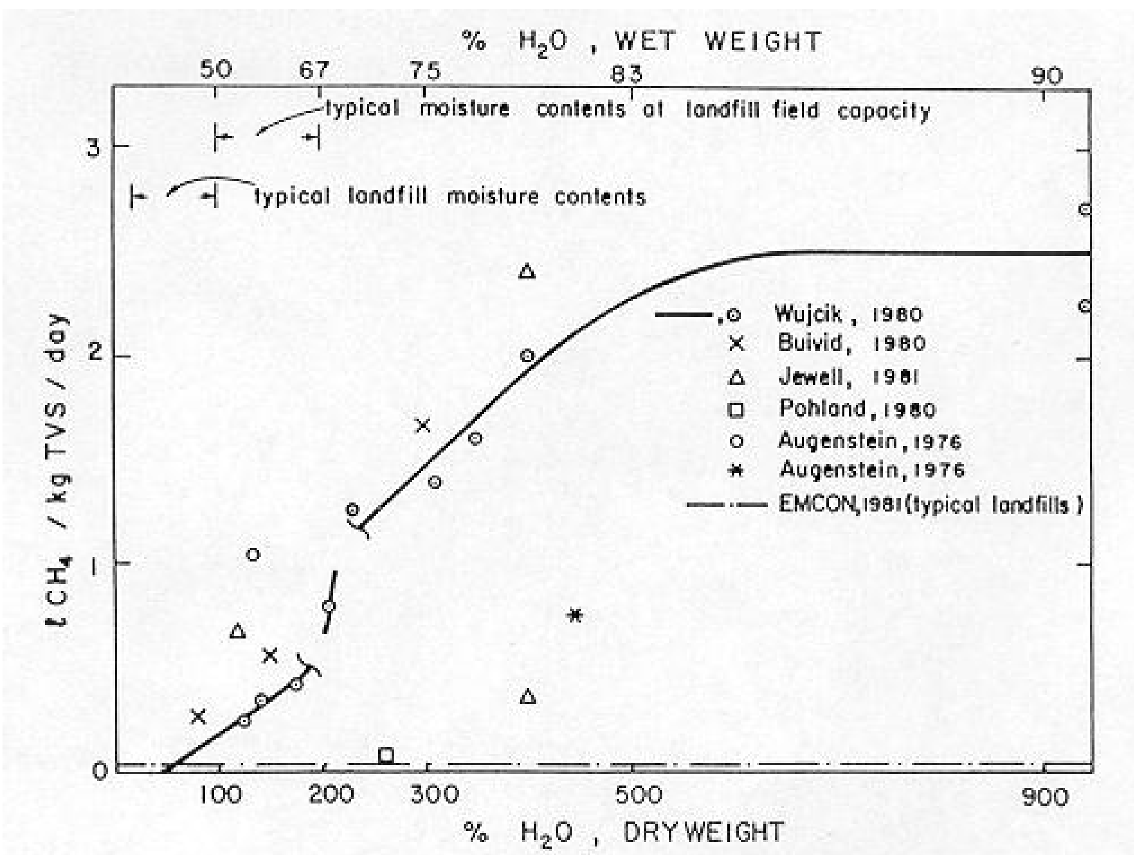


Figure 1 *Methane production rate versus moisture content.*

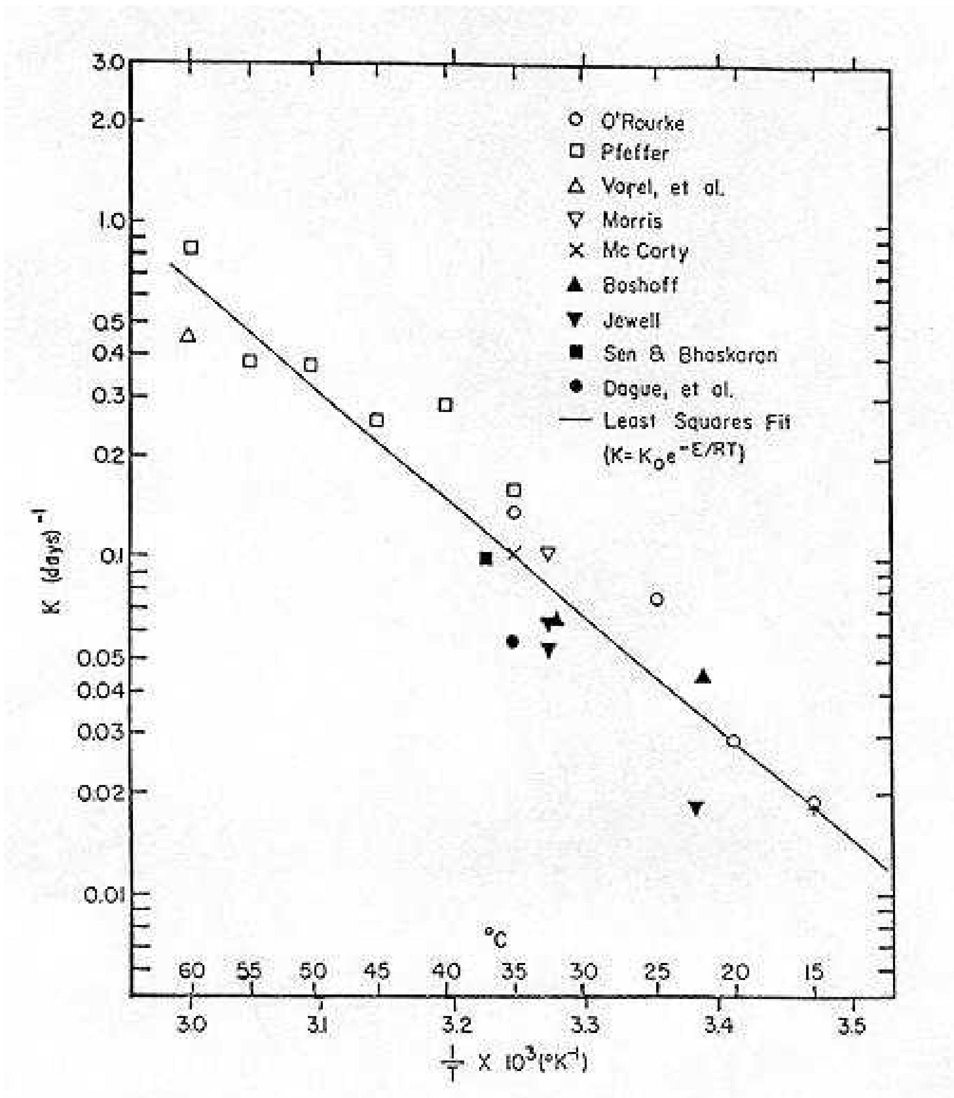


Figure 2 *Arrhenius Plot showing dependence of rate on temeprature for methane fermentations of solid substrates (Ashare et. al.).*

Moisture and temperature are, from regulatory and other (particularly cost) standpoints among the easiest parameters to manipulate in landfills and to enhance methane in controlled landfilling. Moisture is, in and of itself, highly effective in accelerating and augmenting methane generation from solid wastes.

However with elevated moisture gas collection can become a problem. Moist waste becomes less permeable to gas. Moisture may also be expected to lessen the normal horizontal to vertical permeability that facilitates vertical well gas recovery with "conventional:" landfills [2]. But, with moist "field-saturated" waste characteristic of enhancement, alternate gas collection methods are possible and practical. One method,

2 (in the limiting case where solid waste voids are liquid-filled, gas clearly rises straight up and cannot be pulled horizontally without pulling an enormous amount of associated liquid).

attractive enough to patent (Zison, 1980, now expired) has been to cover the waste with a highly permeable (> 10^5 Darcys) gas collection layer beneath impermeable surface membrane. The permeable layer can use shredded tires, gravel, or such discards as wood chips. A variant on this approach is to place the permeable layer at a level somewhat beneath a relatively impermeable surface, say 5-20% of the way down in the depth of he waste mass. Since the permeability of compressed, moist waste is 4 to 5 orders of magnitude less than that of such permeable layers, pulling a light vacuum on such a permeable layers will assure collection of fractions of gas expected well over 90%.

The goal of controlled landfilling is to accomplish the necessary methane enhancement and other operations in a manner that integrates most readily with present landfill practice. Conventional practice would be followed as much as possible. Some important aspects of design and operation, and the necessary variations from conventional practice, are listed for reference in box 1.

Box 1

CONTROLLED LANDFILL DESIGN AND OPERATIONAL FEATURES

1. To avoid groundwater contamination, operate in landfills having composite or double base lining. Fortunately, such lining is mandated by federal law in all new landfills or landfill expansions.
2. Design with appropriate highly permeable bottom layer drainage to preclude static head and avoid clogging as discussed by (Koerner et. al. 1993).
3. Place waste generally following standard landfill practice except freely permeable daily cover (chopped yardwaste, soluble foam etc.) serves the daily cover function, rather than soil. This allows permeation of moisture at maximum possible rates and also limits lateral moisture diversion.
4. Surface the top of waste with sufficient permeable porous material (waste tire chips or other) for a highly conductive gas collection layer to capture and conduct gas to collection point. Provide for uniform liquid addition through multiple injection points at the surface of the waste.
5. Cover landfilled waste with impermeable membrane and other necessary structural components.
6. Add liquid amendment (generally, leachate and water; possibly treated gray waters.). Addition and waste moisture content can be managed as needed to preclude base hydrostatic head. Safety factors can be afforded in at least two respects : (a) elementary hydraulic analysis indicates liquid would not exit waste faster than it enters, and addition is planned slowly over several months. (b) Base leachate collection layer can be conservatively designed so it could handle severalfold the anticipated flow while still avoiding any significant hydrostatic head (federal limits are 30 cm = 1 ft.).
7. Collect all gas as it is generated. Size collection lines and other equipment to allow for greater gas recovery. Preferably abate methane by energy use.

YOLO COUNTY CONTROLLED BIOREACTOR DEMONSTRATION

Work at Yolo County has been under way for a decade at the Yolo County Central Landfill (YCCL), near Davis, California. Major milestones have included the proposal in 1991, cell filling with waste, 1995, and enhancement start, 1996.

The Yolo County Central Landfill that hosts this demonstration, is a fullscale (500-700 ton/day) operation conforming to California environmental standards, which are among the strictest in the US. Ability to implement this technology in California makes acceptance of any developed process very likely in most other states and for that matter, around the world.

General Objectives

The first of two generalized objectives of the Yolo County demonstration project has been to show that completion of methane generation and biological stabilization of waste can be realized within ten years. Various criteria may be used to measure this, but one strong piece of evidence for near-complete decomposition would be a gas recovery rate falling to less than 1% of the maximum, (i.e. virtual cessation of flow) and stable leachate composition.

The second general objective of the Yolo County demonstration project was to show a maximum recovery fraction (95% or more) of the methane generated, hence, to maximize energy recovery and minimize emissions.

Expected Benefits

A number of energy, environmental, and landfill waste management operational benefits are expected from controlled landfilling. These can be summarized as follows:

- Reduction to minimal levels of methane emission from landfilled waste masses to which it is applied. Methane is an extremely potent climate-active gas.
- Near-complete elimination of volatile organic compounds that are significant local air pollutants.
- Decomposition over shorter terms, reducing the usual longer-term risks to the environment, and also reducing long-term gas and other management costs.
- Reduced costs for post-closure landfill care and operations and maintenance due to earlier completion of landfill gas generation and waste stabilization.
- Maximized rate and yield of methane recovery.
- Feasibility for energy use due to of greater quantities of captured gas.
- Leachate quality improvements and correspondingly, reduced threats to groundwater.
- More predictable gas recovery allowing landfill-gas-fueled energy equipment to be appropriately sized for full use of generated gas.

♦ Reduced costs for post-closure landfill care and gas systems operation and maintenance due to earlier completion of landfill gas generation and stabilization.

♦ Reduced or eliminated costs for of-site disposal and for treatment of landfill leachate.

Demonstration Project Design

The Yolo Controlled Landfill demonstration project operates two test cells. Each cell was filled with about 9000 US tons (8000 metric tons = tonnes). Moisture addition has been applied to one cell (the "enhanced" cell) with the other serving as a control. The control is filled and operated like a “conventional” landfill with an impermeable cover. The test cells (16,000 tonnes total waste placed) are located within the much larger "conventionally" operated landfill (about 4 million tonnes of waste placed).

The enhanced cell is provided with means for controlled liquid addition, to permeate the waste, and carefully bring landfilled waste to "field capacity". Field capacity is the maximum water holding capacity of waste that can be attained while still being associated with minimal drainage rates. Low drainage rate is important in light of the need to stay within federal regulations that limit the hydrostatic head over the base liner.

Monitoring and control of the process is enabled by the intensive instrumentation of both the demonstration cells. Principles and much detail have been described in previous reports to NETL and will be reviewed below. Results to date have been such that this project was the first of its type to be nominated for a "Project XL" designation by the US EPA. This process gives regulatory flexibility to waste management processes offering improved environmental benefits.

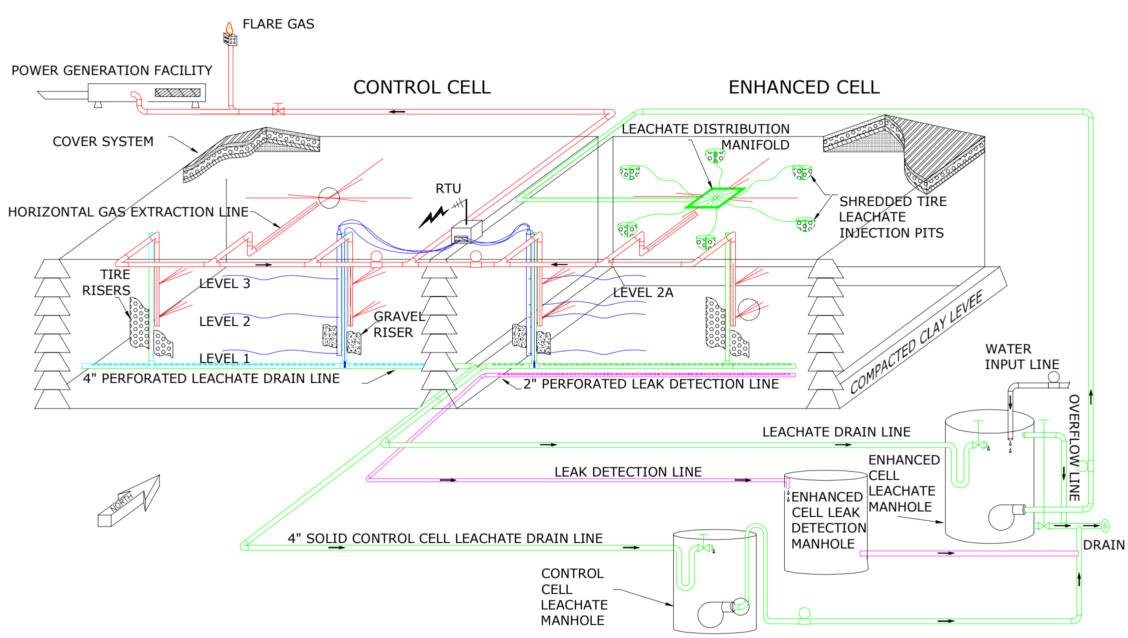


Figure 3 *Isometric view of the control and enahanced demonstration cells.*

An isometric view of the cells illustrating cell construction is provided in Figure 3. Dimensions of each cell were 100' x 100' square x 40 feet deep. Important cell features shown in Figure 3 are (a) the cell cover, shown in cutaway at top corners of the cell. This cover is a surface membrane (40-mil Linear Low-Density Polyethylene [LLDPE]) geomembrane atop a permeable gas extraction layer.

Base layer containment.
The cell base and drainage structures were first constructed in 1993. A view of the base layer and berms surrounding the cells is presented in Figure 4.. Base layer containment was largely standard; however in the enhanced (right-hand cell in the perspective of Figure 4), the primary base lining was equipped with a lysimeter for leak detection. This is basically a second lined drainage layer, lying beneath the primary liner. Outflow from this secondary drainage layer would indicate leakage through the primary layer. (However, encouragingly, no leakage has been observed)

Cell filling.
Once the cell base was constructed, the cells were filled lift-by-lift with waste using standard landfilling approaches. Lift depth was about 5 feet. The waste used was "typical" waste from packer trucks on residential and commercial collection routes. Truckloads were randomly assigned to either the demonstration or "enhanced" cell. However waste loads that were clearly non-decomposable, such as construction and demolition debris, were excluded.

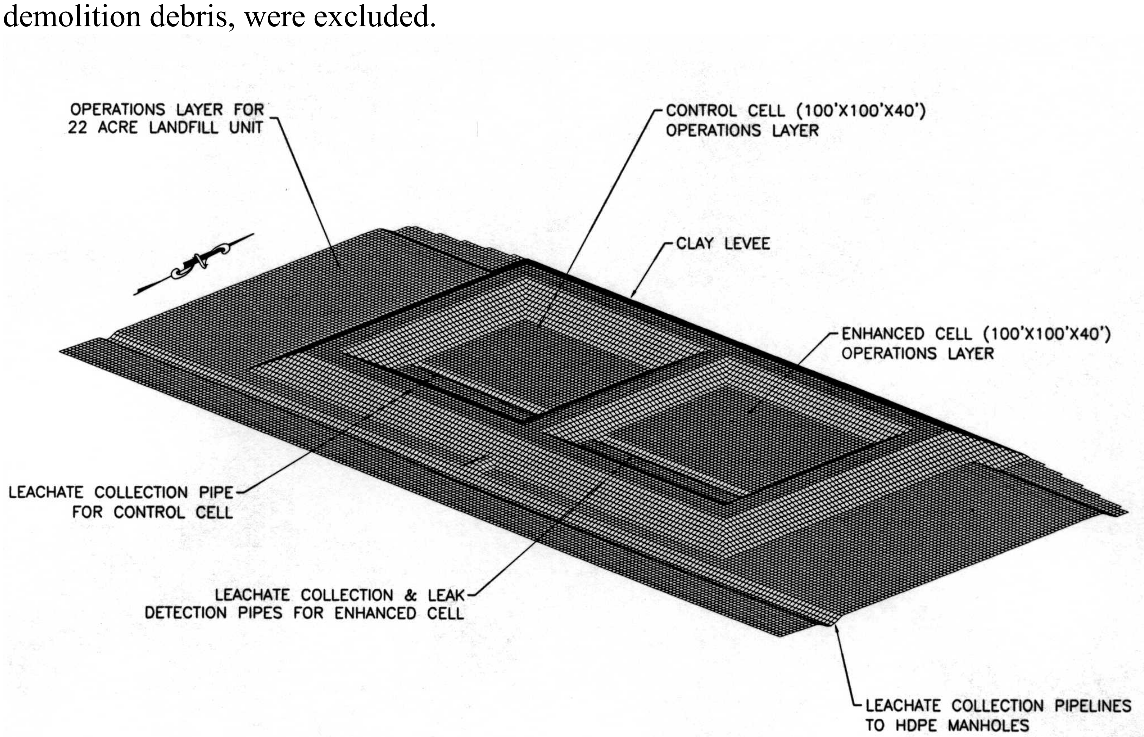


Figure 4 *Enhanced and control cell base liner prior to waste placement.*

Instrumentation.
Moisture and temperature sensors were embedded in the waste during placement. Because of the experimental nature of the project, and desire for as much data as possible, the cells were intensively instrumented with a total of 56 moisture sensors which included gypsum blocks which indicate moisture by capacitance, and also sensors which indicate moisture by electrical conductivity. There are also 15 temperature sensors distributed in each cell. Other instrumentation included corrosion-resistant temperature and pressure compensated positive gas flow meters and liquid flow meters for accurate measurement of leachate flow.

Porous gas extraction layer. The gas extraction layer consisted of a 2-foot thick layer of shredded tires lying atop the waste, and beneath the surface geomembrane. This layer was kept at a pressure very slightly below atmospheric, the order of -1 cm water vacuum. With any high permeability ($>10^6$ Darcys) porous material, the pressure will be uniform within the entire extent of the layer over the waste. It is to be noted that the porous layer could also lie beneath the waste surface. However the location would most advantageously be near the waste top surface., where fluid flow modeling shows that the layer would collect all of the flow from beneath the layer, and with proper management all or nearly all of the gas from above the layer. The porous layer could consist of many materials other than shred tires, so long as its porosity was sufficiently high. Practical examples would be wood chips, decomposition-refractory straw such as rice straw, or gravel and large-particle rubble.

Sidewall containment. Sidewalls of clay, over 10 feet in width, surrounded each cell. These have served well in this demonstration and also in similar work in the 1980's (Pacey et. al. 1987).

System for liquid delivery. The liquid was added to the waste by hoses leading from a manhole to 14 shred tire-filled "pits". The pits were easily dug in a few minutes by backhoe excavations in the waste surface. Shred tires were then added (actually, packed into) the pits so that pits retained their shape and did not collapse during later operations. These pits were used in order that liquid added to the waste would permeate the waste at the desired location,, and not run laterally (particularly where the surface might slope) across the surface of the waste. A leachate distribution manifold, was capable of metering leachate to 14 surface addition points. The rate of liquid addition was controlled by simple inline orifices.

Sensors and lead protection. Sensors above were emplaced within a surrounding protective layer of soil, which averaged moisture, so that direct contact with elements of wet waste would not result in "false positive" high moisture readings. Leads from all moisture and temperature sensors passed through a risers to a datalogger and remote transmission unit Forces on instrumentation leads can easily break unprotected leads with waste compaction, and subsidence over time. To avoid lead breakage (a big problem with in-waste instrumentation in other similar situations) the leads were housed in tough nylon reinforced PVC hose. The lead-protecting hose was undulated to about

40% over the "straight-run" distance so that subsidence from stresses such as with waste subsidence could hopefully pull the hose through the waste, rather than sever the hose. The instrumentation leads themselves were given further slack within the hose. This approach was highly successful, as indicated by the fact that only one sensor has been lost to date.

Leachate collection and removal system. The leachate that is collected in each cell flows through solid pipes which convey the leachate to separate manholes for measurement and, in the case of the enhanced cell, recirculation. To prevent either loss of landfill gas or air intrusion through the leachate removal lines, U-traps with 24-inch liquid head were constructed at the pipe outflows in the manholes. Use of the enhanced cell manhole during liquid addition is described later.

*Other sensors. S*everal other sensors and features: Liquid pressure sensors (piezometers) at the base of the cell indicate whether there is liquid head buildup at the bottom of the cell. This provides an indication about whether the drainage system is working properly and whether the head over the liner remains within federal regulations[3]. Gas pressure sensors extend out from the wells to determine pressure-flow relations that can give values for permeability of moist and dry waste to gas.

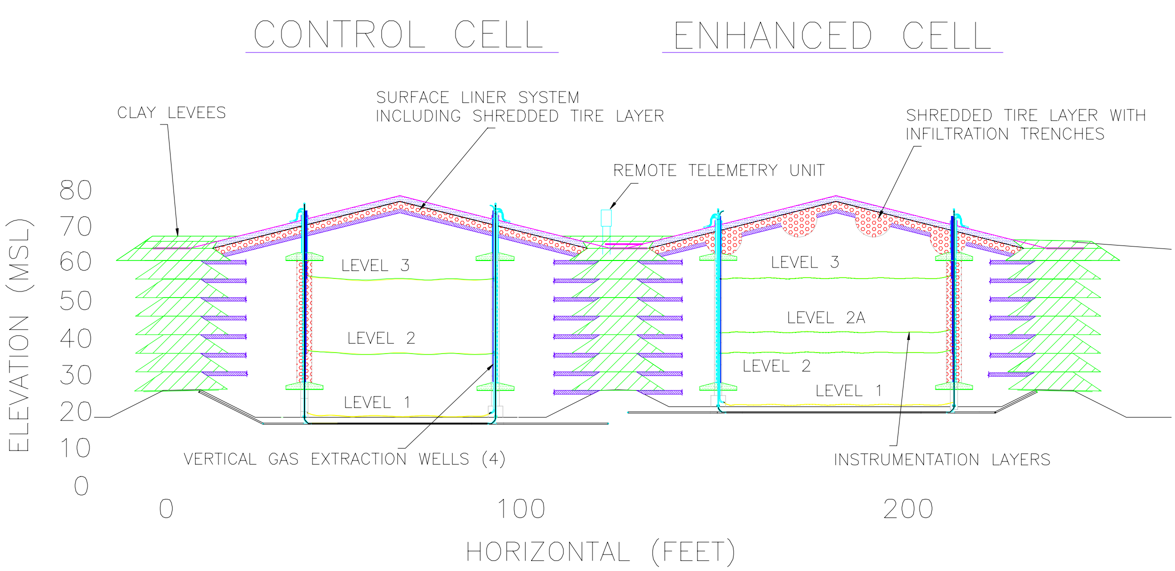


Figure 5 *Cross section of the control and enhanced demonstration cells.*

The cross section of the cells shown in Figure 5 illustrates placement of the sensors at multiple levels. There are four layers of sensors in the enhanced cell, and three in the control cell. Moisture and temperature sensors were placed within greenwaste that was

[3] In fact, the leachate head did at times exceed the federal head limit of 30 cm. However this was due to a design error, in that the leachate drainage line sloped slightly up, and is the type of mistake easily avoided.

used as an alternative daily cover. With sensor placement in the waste as filling occurs, lead wires to sensors need to be protected during and after filling of the waste. Breakage may occur with compaction after sensors are placed, or at later times as waste subsides with decomposition. To avoid lead breakage in the Yolo demonstration, the leads were housed in rugged fiberglass-reinforced PVC tubing. The wire leads themselves, within the rugged PVC housing, had further slack relative to the protective tube. This assured that stresses were borne mainly by the protective tube rather than the wire instrument lead. The workability of this approach is indicated by the fact that only one of 71 sensor leads has failed.

Computerized data collection and processing. The datalogger and remote transmission unit used in the Yolo County project stores data and broadcasts it to the engineering offices located off-site, via a remote telemetry unit (RTU). A complex system such as a landfill bioreactor can benefit from real-time monitoring, data collection and control.

Software advances and rapidly falling costs of multiprocessor instrumentation enable collection of various outputs and data from a variety of sensors simultaneously using a personal computer. The same software can control operations and further process archived data. The software has been developed for use in such applications as monitoring, control of heating and air conditioning systems, and control of chemical processing trains. It is quite adaptable to the needs of bioreactor landfill operations as well. A supervisory control and data acquisition (SCADA) system typically consists of a host computer linked to an RTU. Data collected at the landfill bioreactor, relayed by the RTU, to the host computer, can be displayed to observe trends, and archived for future analysis. The software used most recently has been Microsoft Access.

Liquid Addition

Liquid addition to enhanced cell waste was carried out conservatively, in a carefully controlled fashion. This approach was purposely chosen as one that would be easy to carry out on a large scale. Liquid addition was kept slow with the intention of keeping hydrostatic head over the cell bas drainage layer within federal limits. There have also been reports of risks from waste instability resulting from liquid (pore pressure) buildup in the waste mass which cause the waste to lose strength. (That instability is illustrated by at least one infamous "wasteslide" in water-infiltrated waste in the Midwest in the late 90's) The average flow of liquid into the "enhanced cell was about 10 gallons per minute. Given cell dimensions and likely field (moisture-holding) capacity of the waste, it was expected that at this addition rate field moisture saturation would be attained in about 4 months.

The liquid was added to the waste through 14 shred tire-filled "pits" in the waste surface. A schematic of the waste surface in Figure 6 shows arrangement of addition points. Addition points were arranged, as much as possible, to allow equal liquid addition rates over equal areas of the enhanced cell. Initially, well water was added to a manhole, which acted as a reservoir. Liquid was automatically pumped from the manhole by a manhole liquid level controller to the top of the cells. Low-cost hoses (ca. 50¢/ft) lying beneath the surface were used to duct liquid

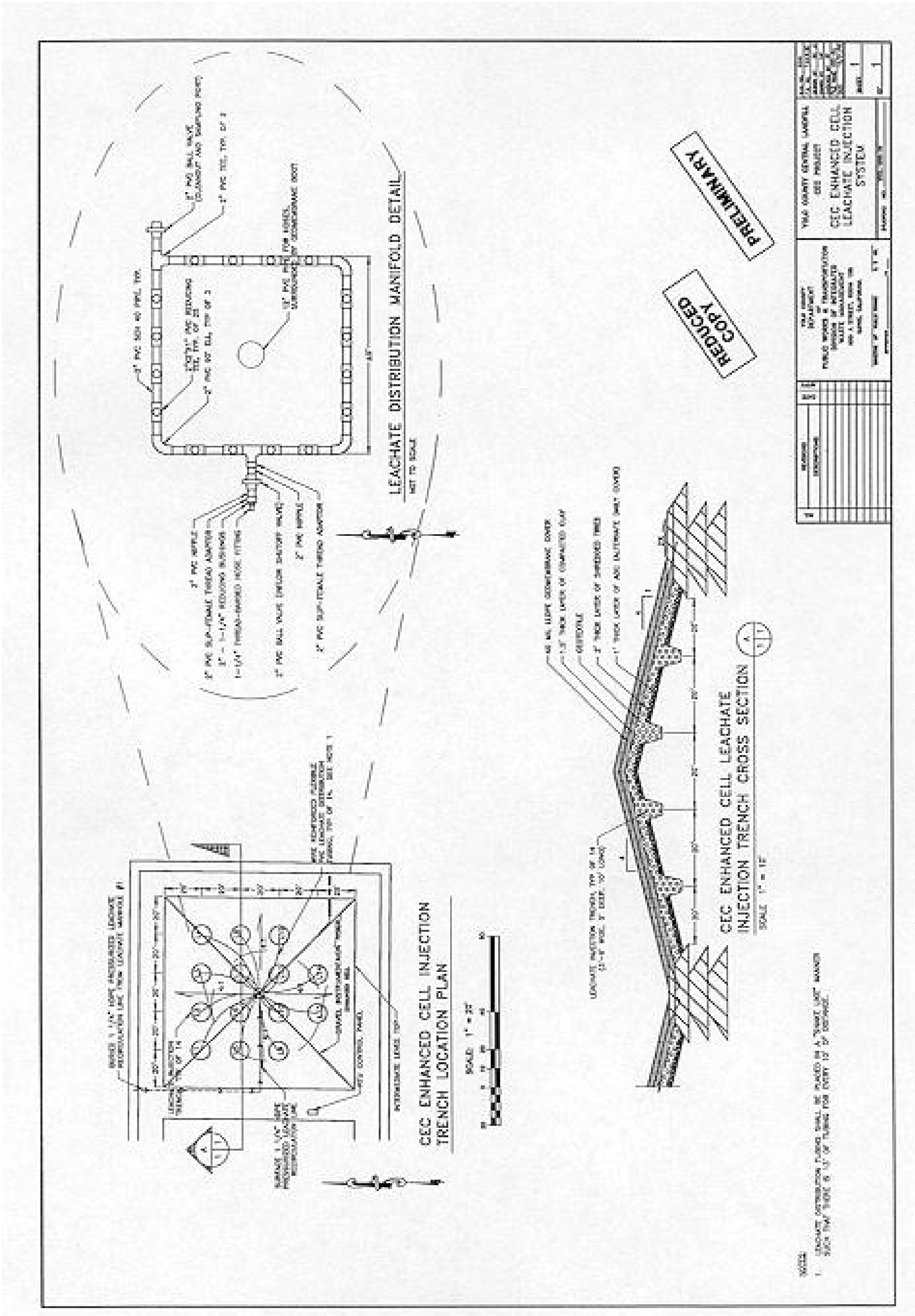


Figure 6 Liquid injection design for the enhanced cell.

to the top of the cells (Interestingly, Sears garden hose burst strength is 600 PSI). As additions continued, exit liquid (leachate) collected from the cell base in greater quantities was drained back to the manholes.

Once exit leachate flows reached half of the inflow, well water addition was halted in the "startup" phase of the experiment. The ensuing result was that leachate recirculated for a period of two years in a "closed loop". Flows of liquid into and out of the cells, as well as liquid calculated as retained, were carefully monitored using Signet 2535 and Sparling Tigermag FM625 flowmeters with results as shown in Figure 7. A very interesting and encouraging observation, easily evident from Figure 7, is that with changes in inflow, the outflow changed correspondingly with a nominal response time of a few hours. This indicates high controllability of outflow. If problems are encountered with liquid flow to one section of the base drainage, the flow may be rapidly diminished by reducing inflow in that area.

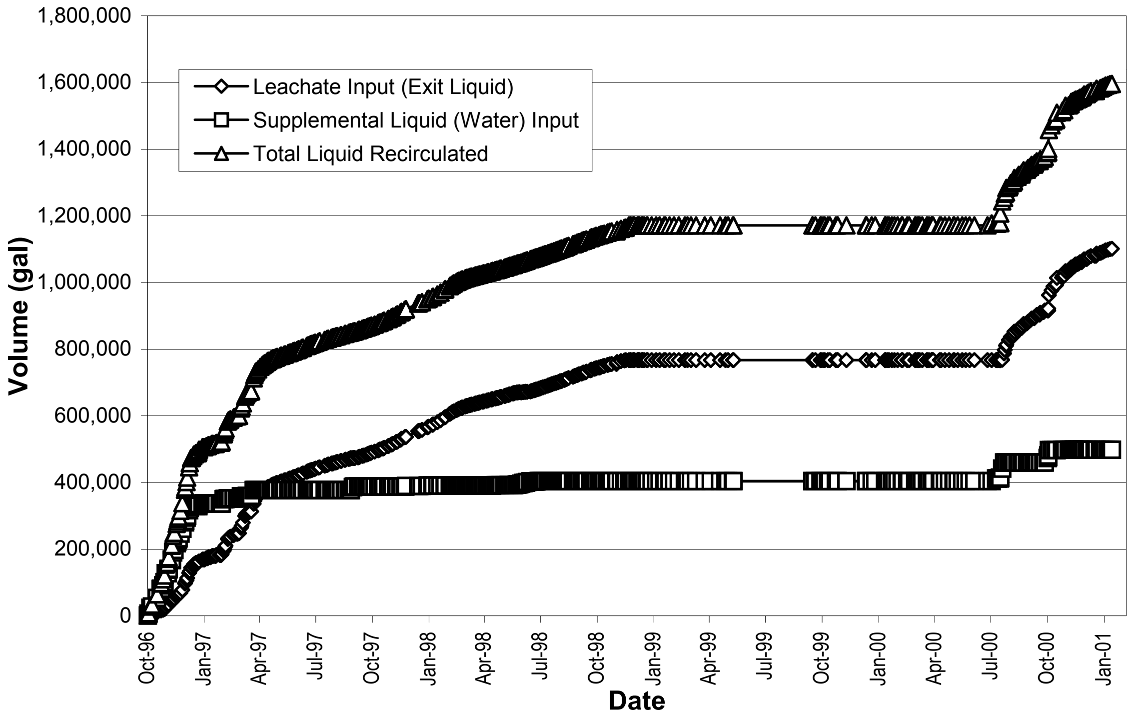


Figure 7 *Liquid inflows, outflows and retention in demonstration cell.*

Figure 8 shows the response of moisture sensors. Results of figure 8 are very encouraging in suggesting that the added moisture distributed well through the waste in the few months' time scale anticipated. More confirming information will be presented below.

Leachate Quality Results

One consequence of the controlled landfill approach is that leachate quality improves relatively quickly after startup. Contaminants in the enhanced cell leachate reached a stable minimum in under a year. Table 1 shows leachate composition data taken over time since the initiation of recycle. This is one of the non-energy environmental benefits recognized by both waste regulators and waste landfill managers.

Table 1 Abbreviated list of some leachate analytical results for the enhanced cell.

PARAMETER	Units	Nov 19 1996	Dec 6 1996	Jan 24 1997	Jul 23 1997	Jun 17 1998	Oct 8 1998	Feb 9 1999	May 31 2000	Aug 28 2000	Nov 28 2000
pH		7.62	5.75	7.2	7.09	7.3	7.21	7.19	7.10	7.10	7.17
Chemical Oxygen Demand	mg O/L	31.9	20,300	5,920	2,770	2,980	3,120	2,650	2,790	1,940	1,960
Total Organic Carbon	mg/L	9.8	8,930	1,150	850	1,080	1,690	921	844	721	746
Total Kjeldahl Nitrogen	mg/L	4	673	518	385	545	564	455	579	419	469
Total Alkalinity as $CaCO_3$	mg/L	930	4,590	5,920	4,490	4,270	4,190	4,150	4,450	2,790	3,670
Total Dissolved Solids	mg/L	1,100	19,800	9,650	6,700	7,450	7,650	7,250	8,250	6,360	6,400
Nitrate as N	mg/L	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.075	0.069	0.12
Ammonia	mg/L	3	435	345	320	444	529	422	499	427	422
Magnesium	mg/L	154	1,010	758	392	294	-	354	443	262	267
Potassium	mg/L	4.9	997	644	224	559	565	517	552	450	416
Sulfate	mg/L	7	1,040	6.4	14	0.16	25	42	16.7	517	213
Iron	ug/L	17	152,000	933	199	206	-	731	540	1000	500
Manganese	ug/L	4,900	41,900	4,000	1,740	1,060	-	946	900	900	960

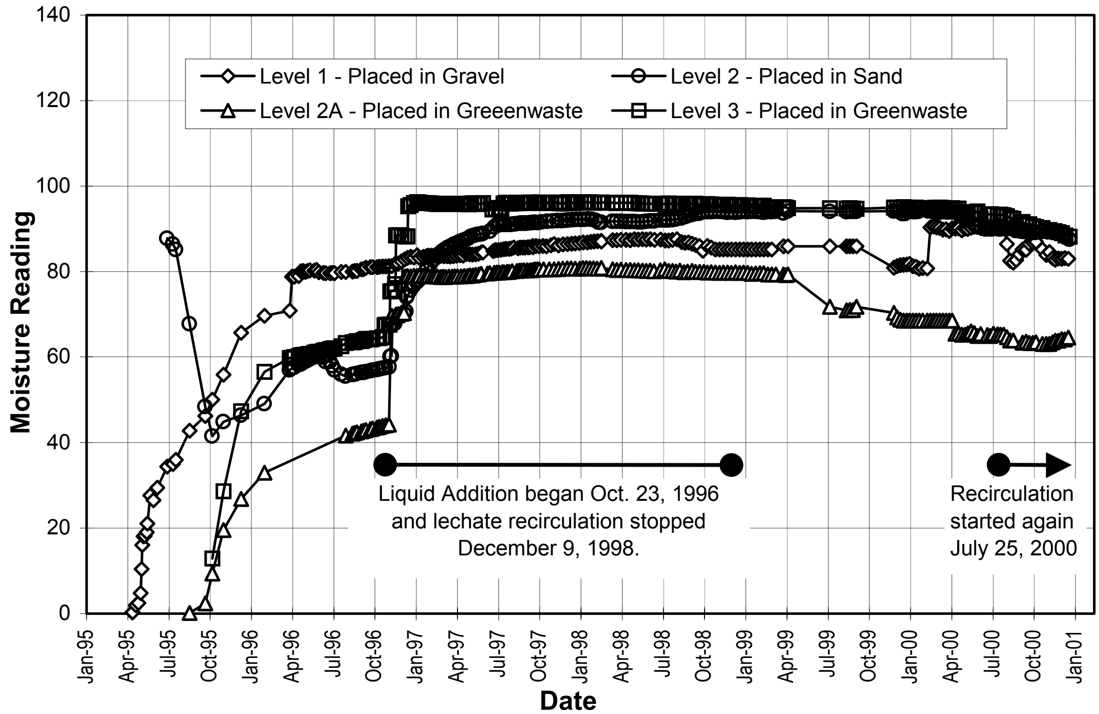


Figure 8 *Moisture sensor readings for the enhanced cell.*

Thermal Effects

With the filling sequence used, and daily cover with air-permeable greenwaste, the waste was exposed to air during filling. Waste temperature was found to be substantially elevated, considered due to the fact that the waste was initially composted aerobically due to entrained air. Waste was oxidized biologically to limited degrees such that the waste temperature, measured at the end of filling, was of the order of 45-55 °C. shown (in conventional landfilling, where waste is covered with air-impermeable soil at the end of each day, any temperature rise is much less). A graph of temperature for both the enhanced and control cells is from startup to present is shown in figures 9 and 10. These figures will be referred to below in this report as well. Temperatures were elevated to very favorable levels for digestion in both cells at the start of temperature measurements. Liquid addition temporarily depressed temperatures in the enhanced cell, particularly in the upper layers, but exothermic methane generation and other reactions caused temperature to rise once again after a fairly short time (Figure 9). As illustrated earlier in Figure 2, the rate of waste conversion to methane has a high degree of temperature dependence.

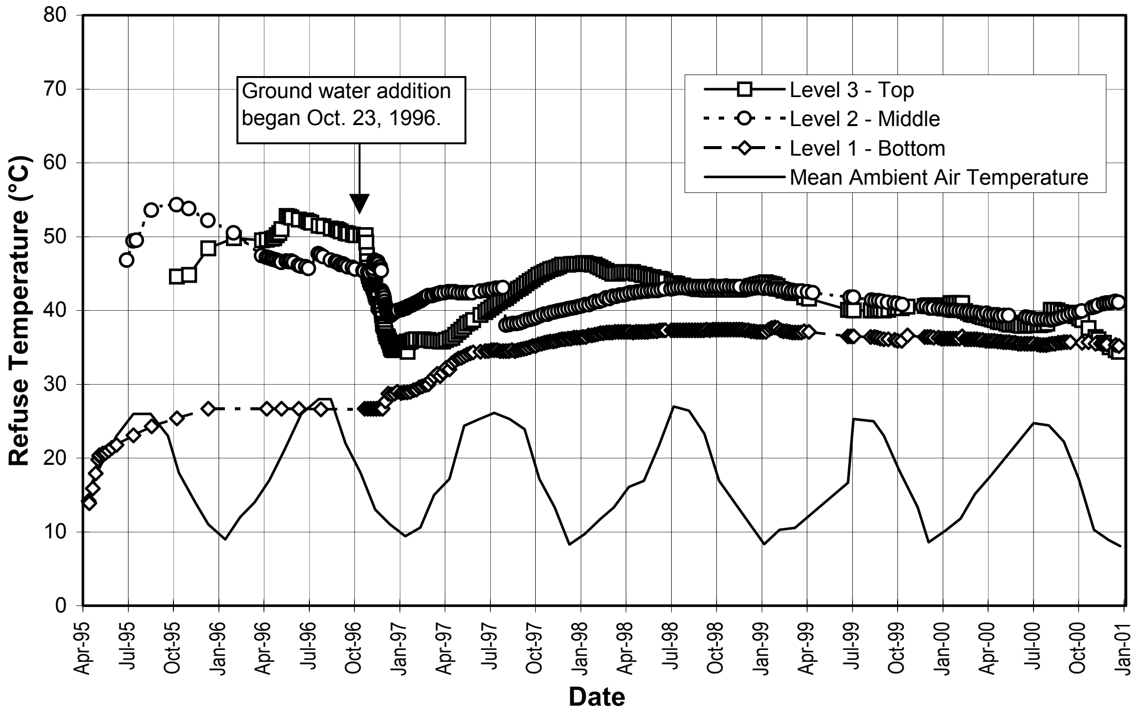


Figure 9 *Temperature sensor readings for the enhanced cell.*

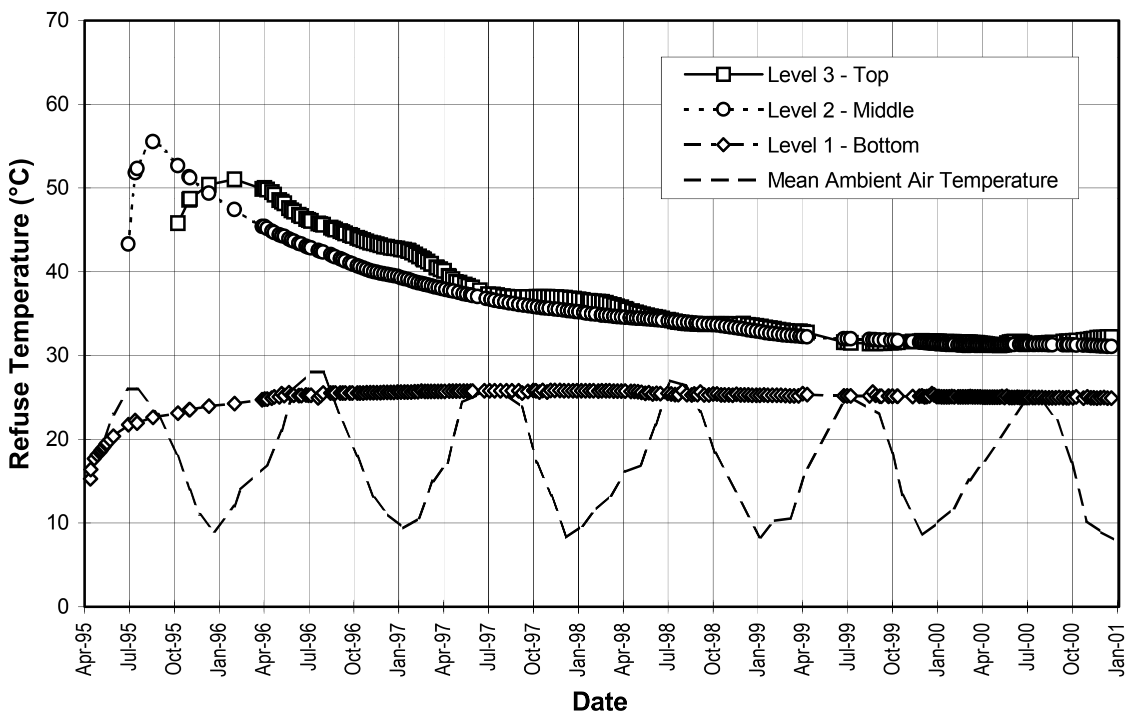


Figure 10 Temperature sensor readings for the control cell.

Gas Recovery Performance

Gas generation and recovery performance of the cells is shown in Figure 11. The enhanced cell was managed so as to safely reach the maximum practical moisture, which is field capacity. Beneficial effects of moisture were shown earlier in Figure 1. Also, (refer to Figure 2) the cell startup temperature was near the ideal of about 50 °C. The result of moisture elevation in combination with near-optimum elevated operating temperatures was that methane recovery rate from the enhanced cell was very gratifyingly high, about 10- times normal. This recovery rate from the enhanced cell represented the highest rate of cumulated methane recovery, so far as is known, from such a large mass of waste, at any time anywhere.

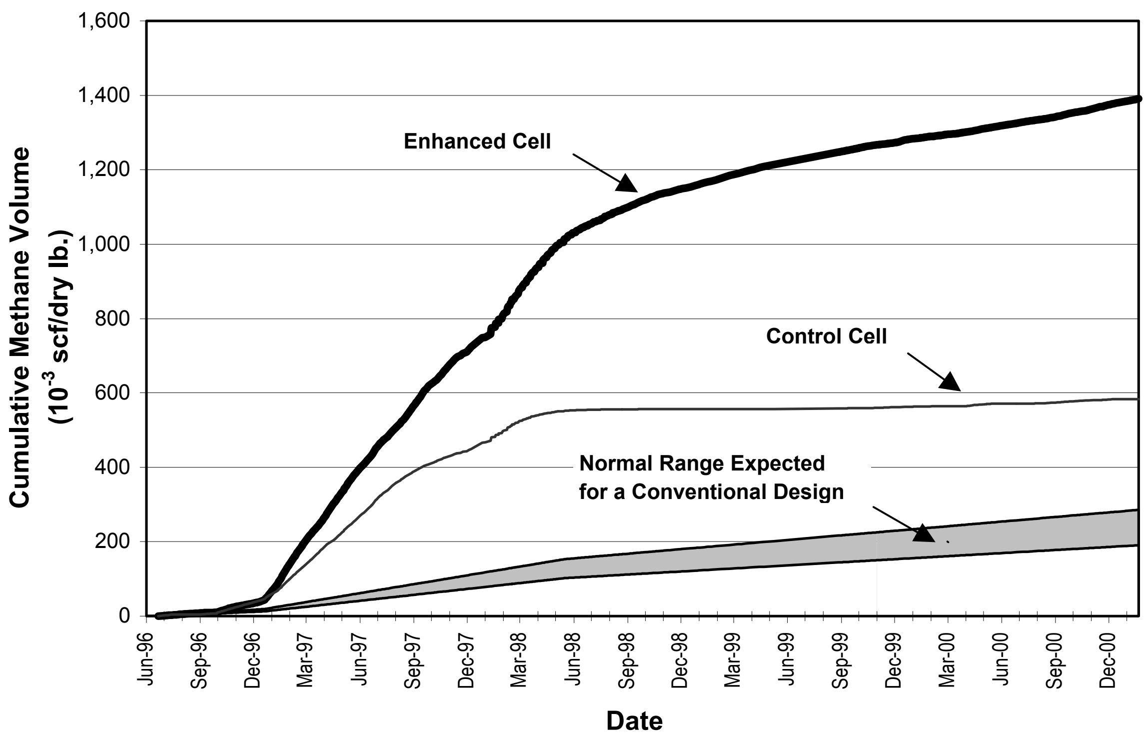


Figure 11 *Gas yields of enhanced, control and "conventional" landfill cells.*

The recovery from the control cell also began at rate over fivefold normal. This is attributed to the decomposition of some control cell waste which was moist at the outset. Decomposition of this control waste that was moist and at favorable elevated temperatures was also rapid at the outset. However, the waste in the control cell rapidly slowed to negligible levels, evidently reflecting the consumption of that moist waste.

Several decomposition reactions of waste, particularly methane generation (methanogenesis), but also others, are exothermic. The temperature of the control cell, where reactions slowed, drops down toward ambient temperatures with time (Figure 10). However the temperature of the enhanced cell fell early when the cold ground water was added. It then rose to relatively favorable levels around 40 °C. This relatively favorable elevated temperature was maintained untill cold ground water was again added in August, 2000. This water addition caused the top layer to cool off, however, the middle layer is warming, possibly due to an increase in microbial activity associated with the liquid addition.

Implications of observed thermal behavior.
An important conclusion for anaerobic bioreactor operation is that temperature may be elevated at low cost by early controlled exposure of waste to air. Thus, temperature can be elevated at low cost in initiation of bioreactor operations. An examination of heat transfer relations and heat losses indicates that heat will conduct only very slowly from bioreactor landfills. So early temperature elevation can play an important part in the operation of bioreactor landfills and the elevated temperature is relatively easy to maintain in the bulk of the landfill.

Surface Membrane Performance

The existing cover was found to develop leaks during cell operation. This was verified in the past year (2000) by allowing slight pressurization of the cell and passing a combustible gas detector over the surface. Also, as clay sidewalls dried and shrank during the summer, gaps appeared between the HDPE cover and the clay sidewall that formed the outer boundary of the HDPE. However, even when there are leaks in the surface membrane, the gas pressure can be kept negative in the collection layer to prevent fugitive methane emissions to the atmosphere. Air entrained through leaks also simply exit with landfill gas, and would be expected to pose little problem. Leakage problems could have been solved by replacing/constructing new cover. However this was not done because of high cost and available finances. Also, leakage problems are solvable and considered minor.

Decomposed Waste Sampling

Earlier moisture sensor readings and substantially accelerated gas recovery as well as other observations suggest good moisture distribution was attained in the waste in spite of early worries about channeling and bypassing of waste elements by the moisture addition method used. As it transpired, such problems did not appear to occur. In October 1999, with USDOE-NETL interest and encouragement, three years after the moisture supplementation began, the test cells were sampled using a hollow stem auger attached to a drill rig, see photograph in Figure 12. Samples were taken from a range of drillhole locations within the cell and were used to determine the decomposition status of the waste.

Two corings were taken from the control cell, with total core length adding to 41.9 feet. Three more corings were taken from the enhanced cell, total length adding to 96.3 feet. Waste from core sections (intervals ranging generally from 2-5 feet) was carefully mixed once extracted from particular sampling intervals, using shovels, on the surface of polyethylene tarpaulins near the cells. The samples were split so that replicate samples could be run on the same core samples and intrinsic compositional variability could be determined along with other waste features.

Figure 12 *Drilling into the enhanced cell to allow waste sampling.*

Observations.
For wetted waste extracted from the enhanced cell, there was no "free" water. The term "free water" is used in the sense that excess water was seen to run off the waste samples--thus the waste was not in the normal sense "soaked".

For the enhanced cell, much (but by no means all, see comments later) of the waste was clearly well-decomposed. In the enhanced cell, paper and cellulosic waste such as cloth was decomposed to such extent that original printing was illegible and the waste was blackened to a color and consistency somewhat similar to that of moist peat. The high temperature of the waste was also such that piles of freshly excavated waste was steaming as samples on tarpaulins were managed after extraction, see the photograph in Figure 13.

Figure 13 *The warm waste in the enhanced cell was steaming in the cold ambient temperatures during the drilling event of October 1999.*

The control cell waste looked "dirty", probably because of small amounts of intermixed dirt from the surface cover but not degraded. It was shredded to some extent by the extraction process, but was in essence looked as would the original waste added to the control cell.

Moisture distribution and hydraulic considerations.

The samples were initially tested for the parameters of moisture content and pH as shown in Table 2. The first overall finding of high interest was the difference in moisture contents between the core samples from the control and enhanced cells. This is plotted in Figure 14 in a mode to illustrate both ranges of moisture content and the degree of moisture distribution attained for each cell. Basically, moisture levels of figure 14 are shown in fashion similar to a particle size analysis as would be shown from a sieve analysis. This illustrates that moisture in the control cell ranged up from 13% to 26% of total sample weight whereas moisture in the enhanced cell ranged up from 25% to over 40%. It is very encouraging from these core sample findings that the moisture added to the enhanced cell, despite surface addition to discrete points, distributed well through the enhanced cell.

Table 2 Summary of moisture content and pH as a function of depth.

Enhanced Cell			Control Cell		
Depth (ft)	**% H_2O**	**pH**	**Depth (ft)**	**% H_2O**	**pH**
Drill Hole #1			**Drill Hole #1**		
4.9 - 6.9	30.3	7.7	6.5 - 8.4	13.5	6.5
4.9 - 6.9	31.7	7.7	8.4 - 9.4	18.5	6.1
6.9 - 8.9	34.8	7.5	9.4 - 11.3	14.6	7.5
6.9 - 8.9	34.0	7.5	11.3 - 15.0	11.8	6.0
8.9 - 14.0	32.7	8.2	15.0 - 17.5	14.7	6.6
14.0 - 18.4	35.0	8.4	*Average Moisture (%)* [a]	*14.6*	
18.4 - 19.5	36.4	8.8	*Standard Deviation*	*2.46*	
19.5 - 23.0	34.9	8.4			
23.0 - 27.9	39.9	8.6			
27.9 - 30.8	55.2	8.5			
30.8 - 32.4	49.6	8.3			
Average Moisture (%) [a]	*38.8*				
Standard Deviation	*8.21*				
Drill Hole #2			**Drill Hole #2**		
8.4 - 9.8	36.6	8.1	6.0 - 8.0	15.7	6.1
8.4 - 9.8	36.7	8.1	8.0 - 13.3	15.8	6.0
13.0 - 16.5	37.7	8.2	13.3 - 16.3	19.1	5.8
13.0 - 16.5	36.5	8.2	16.3 - 19.1	14.9	5.9
16.5 - 19.6	36.3	6.0	16.3 - 19.1	15.6	5.9
19.6 - 22.6	31.8	5.3	19.1 - 22.1	22.5	5.5
19.6 - 22.6	33.2	5.3	22.1 - 24.4	26.8	5.2
26.0 - 28.0	23.5	6.0	22.1 - 24.4	26.6	5.2
29.0 - 31.5	25.2	6.2	*Average Moisture (%)* [a]	*19.2*	
29.0 - 31.5	19.1	6.2	*Standard Deviation*	*4.61*	
Average Moisture (%) [a]	*31.8*				
Standard Deviation	*6.36*				
Drill Hole #3					
8.0 - 13.3	36.4	7.5			
8.0 - 13.3	39.0	7.5			
13.3 - 15.0	35.5	8.0			
16.7 - 18.2	40.0	8.0			
16.7 - 18.2	40.3	8.0			
18.2 - 21.9	38.6	8.1			
21.9 - 23.8	34.0	5.9			
23.8 - 29.6	28.1	5.7			
29.6 - 32.4	29.4	6.5			
Average Moisture (%) [a]	*34.8*				
Standard Deviation	*4.6*				
Enhanced Cell Overall Average Moisture	**35.6**		**Control Cell Overall Average Moisture**	**17.1**	

a. Samples at the same depth were averaged, then treated as one value.

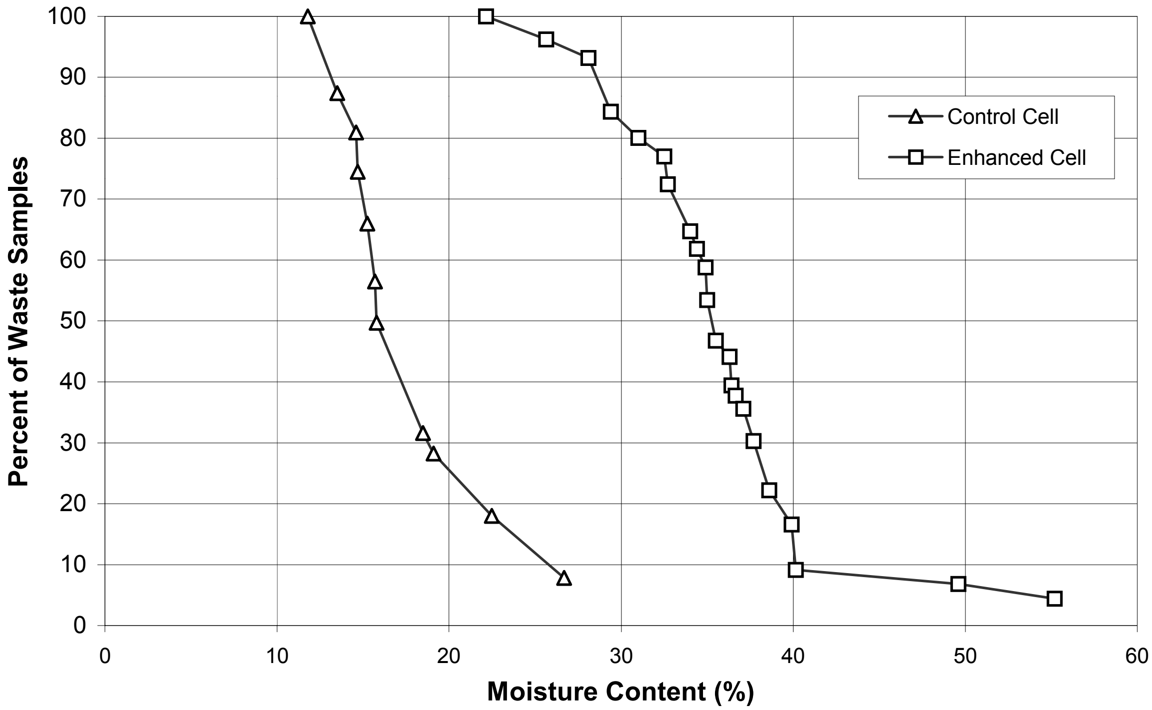


Figure 14 *Moisture distribution determined by core length.*

At least two mechanisms can contribute to good moisture distribution. First, the fact that added liquid to the surface will be displaced laterally in random fashion as it encounters obstacles such as garbage bags, etc. in the waste. A random lateral walk of this type will (in the ideal case) give a plume which widens with depth by $L/N^{1/2}$ where L is the average lateral displacement and N is the number of displacements. Second, there is also the phenomenon of "wicking" in which the waste acts in "blotter" fashion to distribute liquid. This phenomenon is often termed "capillary action". By surface chemistry calculations for a fully wetted pore, "wicking" represents a major hydraulic force capable of pulling water into the waste, even laterally or upward. The suction pressure of readily "wettable" material; with contact angle 180° will be $2\gamma/r_p$ where: γ is the surface tension (surface free energy) of the liquid, and r_p is the effective hydraulic radius of the pore.

Assuming a representative hydraulic pore diameter in compressed waste to be the order of 100μ, (rough diameter of a cellulose fibril) the wicking force can be considerable, about 70,000 dynes/cm^2 or equivalent to over 2 feet of water suction. In any event, a combination of random lateral displacement and wicking evidently helps liquid distribution and dispersion. This opens the possibility to some rather simple liquid addition strategies as well as to the possibility of timing liquid addition.

Methane yield vs. theoretical.

Figure 15 shows the correlation of the ratio of measured biochemical methane potential (BMP)/theoretical BMP vs. measured BMP for the tested samples (this work for NETL formed part of Rinav Mehta's thesis at North Carolina StateUniversity, Mehta, 2000).

The data from another landfill previously examined in Berkeley, CA has also been included to show a similar trend. The increased methane yield correlates well with increased ratio of actual/theoretical yield, which is to be expected. What is surprising, however, is that the sample methane was at best 60% of theoretical based on its cellulose content assayed by chemical methods. It appears that a significant fraction of cellulose and hemicellulose remain inaccessible to microbial activity, perhaps due to barriers of lignin that eliminates microbial access to otherwise degradable fractions. This observation deserves further investigation as these inaccessible yet degradable fractions seem high.

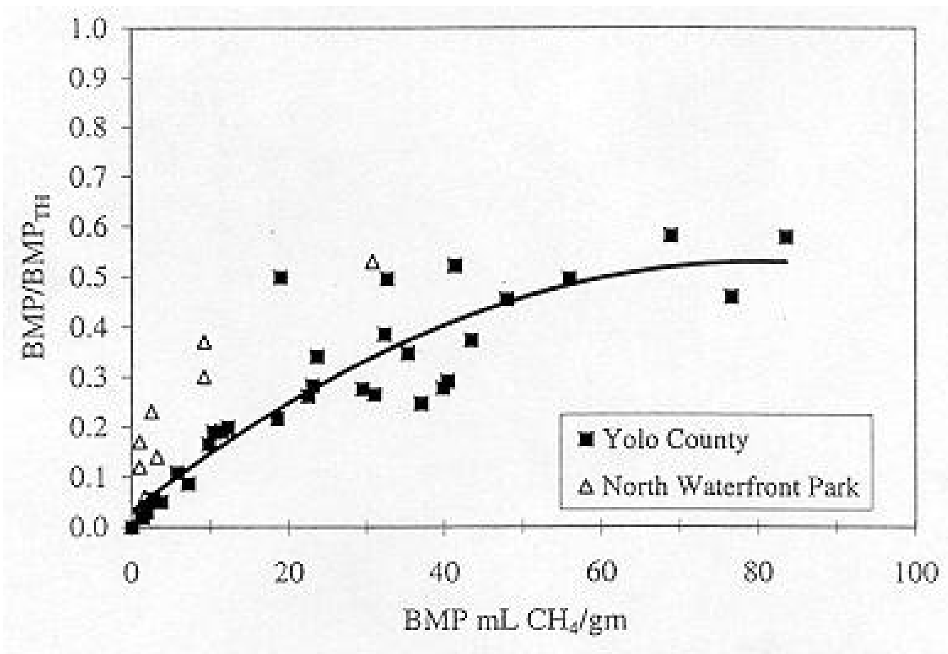


Figure 15 *Methane yield versus theoretical.*

Figure 16 shows data on pH versus ratio of (Cellulose plus hemicellulose) to lignin. There appears a good correlation, in which decreasing cellulose + hemicellulose to lignin ratio is associated with increasing pH.

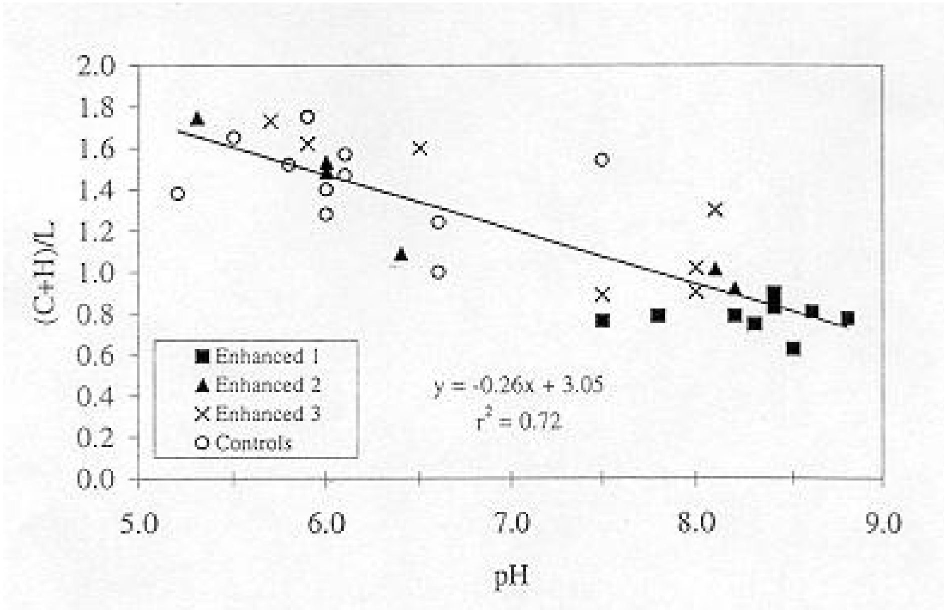


Figure 16 *Cellulose plus hemicellulose over lignin versus pH.*

Moisture content and pH of liquid from samples.

Figure 17 shows the relationship between moisture content and pH. A relation is seen in which increasing moisture content at the time of sampling is associated with higher pH. However, the relation is less clear-cut; also, from other studies, it is known that the correlation between moisture and pH will be a function of time and degree of decomposition of waste, and is not necessarily constant. In early stages, high moisture levels can be associated with low pH. This is because acids form rapidly. Methanogenesis will occur later but can take some significant time to consume the acids, and, as digestion progresses, the cellulose.

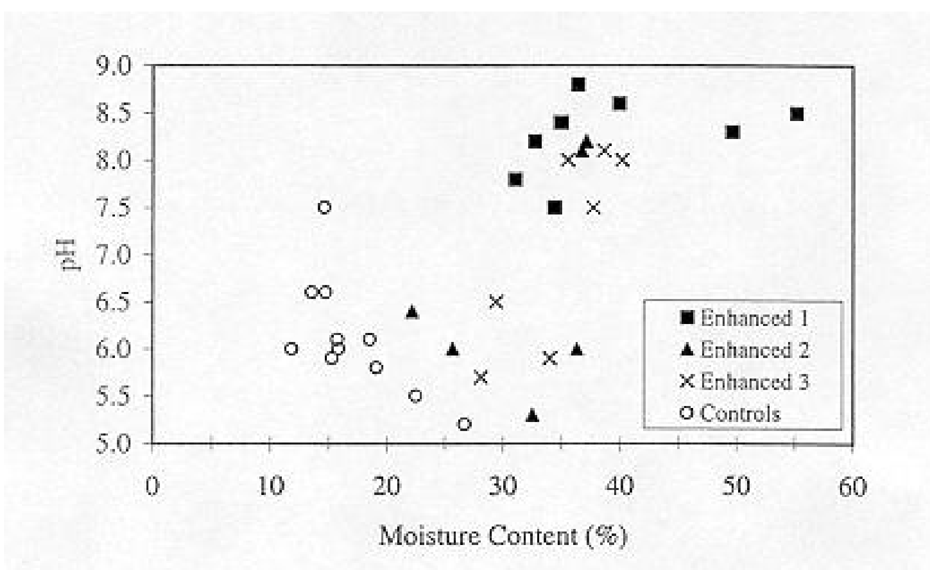


Figure 17 *pH versus moisture content.*

Biochemical methane potential analysis.
It needs to be emphasized here that the BMP test, in which waste is ground to fine particle size, may show more methane potential than exists with "as is" waste. This is because much of the "as-landfilled" waste may be in relatively large pieces of twigs and wood chops, etc. where lignin in the material protects it from bacterial access and breakdown. Once the material is ground up, bacteria would have better access to more cellulose and hence more methane can be generated from the same waste element. For relatively "pure" cellulose such as paper and cardboard this increased BMP due to size reduction represents rather little problem,. but effect will be more significant for lignaceous material such as wood, twigs and other such plant material. For this reason the BMP tests are to some degree qualitative rather than exact; however they do illustrate trends.

Additional drilling event observations.
Drilling wells into the test cells for waste proved extremely useful from several standpoints. For one thing, it showed that the "default" level of 25% waste moisture, often used, was high in comparison to the 17% moisture level actually observed. This implies, it is even more important for well-contained landfills, from which moisture is excluded, to receive moisture management in the form of supplementation.

Other interesting findings of Table 1 are the relative lack of moisture near the bottom of two enhanced cell test borings. This suggests, straightforwardly, that the enhanced cell did not receive enough moisture to elevate waste moisture levels to a sufficiently high optimum all the way to the bottom. Another phenomenon worth noting is the buildup of organic acids, shown by the low pH of a considerable number of test boring samples taken from the enhanced cell (Figure 14). Both of these situations would be expected to be relatively easy to remedy with additional moisture addition. Further moisture addition will have two desired effects: raising moisture levels closer to the optimum in relatively dry, deep layers of the enhanced cell and also (via recirculation) transporting organic acids from areas where they have built up to areas of active methanogenesis where they can be consumed. Recent increases in moisture addition rate, beginning in September 2000 can be seen in Figure 7.

REGULATORY AND POLICY ISSUES AND DEVELOPMENTS

The Yolo County Controlled Landfill project proceeded for some years, from 1991 to 1997, with rather little attention from regulators or the California Integrated Waste Management Board. It can be noted that the US EPA had for some time recognized potential benefits of controlling waste decomposition and stabilization in landfills. However at the same time, language of Federal code in 40CFR 258.28, and other regulatory language, suggested that the issues of moisture addition to landfills, and other issues, was a major "gray area" which needed to be addressed. In 1997, a Solid Waste Association of America (SWANA) committee began work on a "White Paper" which discussed the bioreactor as an option for landfilling of Solid Waste. This white paper (Pacey et al.) issued in 1998. Three of the five participating white paper co-authors (Pacey, Yazdani, and Augenstein) were from the Yolo County project.

Regulatory Involvement

By 1998, the Yolo Controlled Landfill Demonstration was beginning to show major potential for more rapid waste decomposition and volume loss, carbon sequestration and its effective equivalents, minimization of greenhouse methane emissions, maximum methane energy recovery and more rapid leachate stabilization. This led to evolving interest by several regulatory parties and other organizations.

California Integrated Waste Management Board Support

Available information has convinced the California Integrated Waste Management Board to offer both support and funding to explore the project, for which the project participants are deeply appreciative. (However the funding is less than needed to carry out the project, and more funds are being sought from NETL).

SWANA Survey

Although there are variations from state to state, a Solid Waste Association of North America (SWANA) survey (Guzzone and Gou, 1998) showed that many states are willing to consider or coming to accept "bioreactor" and "controlled landfills" as potential waste management options. Necessary liquids additions to landfills, previously opposed by many states' regulators, were discussed in the SWANA White Paper. The White Paper noted that liquid additions (particularly water, but also other nutrient materials) are not necessarily wastes but may instead be considered as allowed amendments under governing Federal code (40 CFR 258.28).

Earlier Federal Policy: Climate Change Action Plan item 37.

For some history, early in the decade, Federal policy in the 1993 Climate Change Action Plan (CCAP) had called for use of bioreactor landfills as one tool to address climate change. With issuance of the SWANA “White Paper" and performance proving out, it is becoming evident that the bioreactor landfill is providing the expected option.

Nomination for EPA Project XL

In 1999, the Yolo County project environmental potentials and merits were considered such by EPA that it became the first "controlled landfill decomposition" project of its kind to receive a nomination for inclusion in EPA's "Project XL". The Project XL process grants case-specific regulatory flexibility to explore processes which may offer superior environmental benefits. The Project XL process has consulted all involved state regulatory agencies and their consent to this scaleup appears assured. A copy of the Project XL agreement signed by the US EPA and all relevant California Regulatory agencies is included as Appendix A.

Solicitation of Comments on Bioreactor Landfills: Federal Register

Recently, potential of controlled landfilling for various environmental and waste management benefits has been such that the EPA in the Federal Register of April 6, 2000, has solicited comments on needed rule changes and other factors that may be needed or need consideration in controlled landfill implementation.

EPA Workshop on Landfill Bioreactors

Even more recently, the US EPA, recognizing the need for comments, held a workshop in Arlington, VA (Sept. 6-7, 2000) on needs and regulatory issues associated with implementation of “controlled” or "bioreactor" landfills. Proceedings of this workshop are promised and should be forthcoming shortly from ERG, Inc, of Lexington, Massachusetts.

Leachate Containment Integrity

One interesting body of information assembled for this US EPA workshop related to the degree of containment needed for "moisture added" bioreactors, and, more specifically, whether additional containment was actually needed at all. Information presented at the conference by the Geosynthetic Institute and Geosyntec, Inc, showed that essentially no or at most minimal problems had been encountered by the standard linings specified by current Subtitle D rules. The data covered over 100 U. S. Landfills comprising a total of over 200 cells. Thus, containment of liquid appears manageable and indications to date are that it is a lesser problem than first feared.

Other Policy and Regulatory Considerations

Other policy, regulatory, and energy developments should favor controlled landfilling. Policy initiatives include facilitation of renewable landfill-gas-fueled electricity, already supported by EPA's Landfill Methane Outreach Program. This would occur under various incentives including a proposed renewables portfolio standard, and the crediting of greenhouse gas abatement under any of several mechanisms that could provide revenue. The controlled landfill and variations on it are being discussed with regulators by a Solid Waste Association of North America (SWANA) committee that includes present authors. SWANA foresees benefits across all areas of the US because "garbage is everyone's problem". It is expected that further effort along lines such as SWANA's will also facilitate application of the technology.

Contribution to US Energy self-sufficiency

Landfill methane energy represents at least a modest fraction of the energy necessary to increase the United States' energy self-sufficiency and its further potential is to reduce oil imports by about 200,000 barrels/day. US energy self-sufficiency is an issue which has, among other things, implications in terms of both fuel costs to US consumers and economy, and also very substantial U.S. national security implications, given volatility of many oil producing regions from which the US imports its oil.

Distributed Generation Potential

Another important factor to be considered is that landfill gas power generation is "distributed" generation, usually almost ideally located, near population centers generating the waste and also using the electricity. Thus it has the potential to help reduce major US problems with congestion in long distance electricity transmission.

LARGE-SCALE DEMONSTRATION

It should be noted that the Yolo County Controlled landfill project has been under way since the California Energy Commission acceptance of the Yolo proposal in 1993, the construction and cell filling conducted in 1994-5 and then operations commencing fullscale in 1996. With the existing results, developing regulatory acceptance and support, as well as benefit potential, the process has advanced to the point that Yolo County is proceeding with scaleup. Yolo County expects several benefits from such scaleup However, for a project which in many ways is first of a kind, a scaleup must conduct measurements that are as detailed as possible and also establish that such operation can be conducted safely. Plans for scaled-up design development were included in the initial Phase II management plan prepared for NETL. Later, with need to prepare for fullscale operation, permission was obtained to purchase the sensors and other instrumentation needed during the start of construction, and then waste placement with instrumentation in the fullscale cells. This waste placement began in November, 2000.

Scaleup is also critical because important performance aspects can be scale-dependent. Such aspects include as one example the permeation of moisture into the waste. Observers have pointed out that permeation of moisture into the waste will slow since permeability of waste would decrease as depth and waste compaction increase. On the normal time scale of landfill decomposition, a time of two years to reach field capacity or 8 times longer than the observed demonstration cell hydration time would still allow very substantial acceleration compared to "business as usual". Other examples of factors that are scale dependent are the rates of heat generation in, and heat transfer from methane-enhanced waste and, generally the operation of controlled landfills on large scales. In essence, the need is to "prove out" operational aspects on a large scale to allow confident fullscale application.

In preparation for fullscale operation, Yolo County spent an amount conservatively estimated to be $750,000, over and above standard landfill construction costs, to enable the bioreactor operation as opposed to the conventional operation. An unexpected cost materialized when the California Central Valley Regional Water Quality Control Board reversed an earlier stance and decided (on short notice) that the high density polyethylene (HDPE) base liner needed a pea gravel layer above it and beneath the planned layer of shred tires. This was to avoid perceived risk of shred tire damage to the HDPE liner. The addition of this pea gravel layer added $300,000 to cost.

The project team is quite confident in its ability to scale up. However, many of the exact details are still in the planning stages and much of the scaleup detail is contingent on support. The general details of the fullscale operation are contained in the Project XL agreement included as appendix A to this report.

SUMMARY AND CONCLUSIONS

Over the past decade, beginning with its proposal in 1991, a project team comprising Yolo County, I E M, and other project team contractors has planned and operated two demonstration cells to test the concept termed "controlled landfilling". In controlled landfilling, generation of methane is managed through use of moisture and temperature for maximum control and to achieve rapid completion and maximum yield . The rapid generation of methane to completion is combined with high-efficiency recovery using low-permeability cover over porous layers at slight vacuum. Major objectives are to minimize the substantial greenhouse methane emissions from waste, and at the same time maximize the methane energy recovery from wastes. Several other environmental benefits are attained as well.

It is gratifying to note that results indicate that the initial project objectives have been met by showing that:

- necessary moisture distribution appears achievable through controlled, multipoint addition of liquid to the waste surface,
- the ability to control moisture flow within easily manageable bounds;
- favorable temperature elevation to an optimum range of 40-55 °C for methane generation is attainable;
- nearly all generated gas can be captured;
- numerous environmental benefits, including rapid stabilization of leachate quality and very significant waste volume reduction, can be achieved;
- controlled landfill technology should provide renewable methane at a cost under $1 /1000 cubic feet of methane contained in the landfill gas, and reduce greenhouse gas emissions at a cost of approximately US $1-5/tonne CO_2 equivalent (or $3-13/tonne COs carbon equivalent);
- controlled landfilling has the potential to reduce CO_2 emissions by up to 100 megatonnes for the US and with worldwide application, the potential should lie between 500 megatonnes and 1 gigatonne.

The controlled landfill demonstration is showing, among other findings, that it is possible to maximize carbon sequestration (or achieve its equivalent by alternate routes), minimize the greenhouse methane emissions by landfills and waste dumps which are normally very substantial, and maximize the recovery of landfill methane for energy from the very large amounts of waste that the world generates.

Most importantly to the NETL program, the data are continuing to show the amounts of CO_2 sequestration or its equivalent, with wide application, should lie in the range of several hundred million to as much as one gigatonne CO_2 equivalents.

REFERENCES AND BIBLIOGRAPHY

Ashare, E. D. L. Wise, and R. L. Wentworth. 1977. Fuel Gas Production from Animal Residue. Dynatech R/D Company. U. S. Department of Energy/NTIS

Augenstein, D. 2000. Bioreactor Landfills: Some Engineering Observations. Proceedings, First International Symposium on Landfill Research. Luleá, Sweden.

Yazdani, R., D. Augenstein, L. Sinderson and M. Byars. 2000. Yolo County Controlled Landfill Project XL. Presentation at EPA workshop on Landfill Bioreactors, Arlington,. Virginia.

Augenstein, D*. R. Yazdani, L. Sinderson, M. Byars and R Moore. June 2000. Yolo County Controlled Landfill Project. (*Note:* part of this reference and much of the conference was in the host country Russian) Proceedings, Second International Methane Mitigation Conference) Akademgorodok, Novosibirsk, Siberia, Russia, June 18-23. Sponsored by Russian Academy of Sciences, Siberian Branch, Host, with co-sponsorship and cooperation by the United States Environmental Protection Agency, the National Energy Technology Laboratory (NETL) of the U. S. Department of Energy, Advanced International Studies Unit, Center for Energy Efficiency, International Energy Agency Greenhouse Gas R/D Programme, International Centre for Gas Technology Information, and Natural Resources Canada. (*presenting)

Augenstein, D. R. Yazdani, K. Dahl and R. Moore. 1998. Yolo County Controlled Landfill Project. Proceedings, California Integrated Waste Management Board Symposium on Landfill Gas Assessment and Management.

Augenstein, D, D. L. Wise, R. L. Wentworth and C. L. Cooney. 1976. Fuel Gas Recovery from Controlled Landfilling of Municipal Wastes. Resource Recovery and Conservation 2 103-117.

Augenstein, D. Pacey, J. Moore, R. and Thorneloe, S. A. 1993. Landfill Methane Enhancement. Proceedings, 16th Annual Landfill Gas Symposium SWANA, Silver Spring, Maryland.

Augenstein, D, R. Yazdani, R. Moore and K. Dahl. 1997. Yolo County Controlled Landfill Demonstration Project. Proceedings from Second Annual Landfill Symposium. Solid Waste Association of America (SWANA). Silver Spring, MD

Augenstein, D, and J. Pacey, 1991. Landfill Methane Models. Proceedings of the Solid Waste Association of North America (SWANA) Annual Conference. SWANA, Silver Spring MD

Augenstein, D. D. L. Wise, N. X. Dat, and N. D. Khien. 1996. Composting of Municipal Solid Waste and Sewage Sludge. Potential for Fuel Gas Production in a Developing Country. Resources, Conservation and Recycling. 16 p 265-279.

Bogner, J. E., 1990. Controlled Study of Landfill Biodegradation Rates Using Modified BMP Assays. Waste Management and Research 8 p 329.

Booth, D. L. 1991. Integration of Landfill Gas Collection Systems with Geomembrane Cap. SWANA 14th International Landfill Gas Symposium, SWANA, Silver Spring Maryland.

Buivid, M. D. Wise, M. J. Blanchet, E. C. Remedios, B. M. Jenkins, W. F. Boyd and J. G. Pacey (1981) Fuel Gas Enhancement by Controlled Landfilling of Municipal Solid Waste. Resources and Conservation 6.

California Air Resources Board (CARB) 1990. Suggested Control Measure for Landfill Gas Emissions California Air Pollution Control Officers Association Technical Review Group.

Chynoweth, D. F., J. Owens, D. O'Keefe, J. Earle and R. Legrand. 1992. Sequential Batch Anaerobic Composting of the Organic Fraction of Municipal Solid Waste.

EPA (U. S. Environmental Protection Agency) 1995. Seminar on Bioreactor Landfill Design and Operation Wilmington, DE. March 23-24. EPA/600/R-95/146

Halvadakis, C. P., A. O. Robertson and J. Leckie. 1983. Landfill Methanogenesis: Literature Review and Critique. Stanford University Civil Engineering Report no, 271. Available from NTIS.

Hartz, K. E. , R. E. Klink and R. K. Ham 1982. Temperature Effects: Methane Generation by Landfill Samples. Journal of Environmental Engineering ASCE

Hellman, B. L. Zelles, A. Palojarvi and G. Bai. 1997. Emission of Climate-relevant Trace Gases and Succession of Microbial Communities During Open Windrow Composting. Applied and Environmental Microbiology.

Hill, S. E. 1996. Tier II emission testing in the Dallas-Fort Worth Ozone Non-attainment Area. Proceedings, SWANA's 19th Annual Landfill Gas Symposium, SWANA, Silver Spring Maryland)

Kraemer, T. H. H. Herbig, and S. Cordery-Potter. 1993. Gas Collection Beneath a Geomembrane Final Cover System. Proceedings, 16th Annual Landfill Gas Symposium, SWANA, Silver Spring MD.

Lee, G. F. and A. Jones. 1990. Managed Fermentation and Leaching. Biocycle, pp. 78-83.

Leszkiewicz, J. and P. Macaulay. 1995. Municipal Solid Waste Landfill Bioreactor Technology Closure and Post Closure. Proceedings, U. S. EPA Seminar on Bioreactor Landfill Design and Operation Wilmington, DE. March 23-24. EPA/600/R-95/146

Mehta, R. C. 2000. Comparison of Refuse Decompoistion in the Presence and Absence of Leachate Recirculation at the Yolo County California Test Cells

Moore, R. 1994. Impact analysis of Municipal Solid Waste Recovery on Landfill Gas Generation. Resource Management and Technology, Vol. 22, no. 2

Morelli, J. 1990. Landfill Re-use Strategies Biocycle.

Pacey, J. G., J. C. Glaub and R. E. Van Heuit. 1987. Results of the Mountain View Controlled Landfill Experiment; Proceedings of the SWANA 1987 International Landfill Gas Conference SWANA, Silver Spring, MD.

Pohland, F. 1989. Leachate Recirculation for Accelerated Landfill Stabilization Sardinia '89 (Proceedings of Sardinia Landfill Gas Symposium).

Pohland, F and A. B. Al-Yousfi. 1994. Design and Operation of Landfills for Optimum Stabilization and Methane Production. Proceedings, 7th International Symposium on Anaerobic Digestion, South Africa.

Rice, F. C. 1994. The Impact of Geomembrane Covers on LFG System Design and Operation. Proceedings, 17th Annual Landfill Gas Symposium SWANA, Silver Spring, Maryland. Also personal communications.

Teplitzky, A. 1995, 1996. Head, Residuals Management, U. S. EPA. Communications to Landfill Gas Division of Solid Waste Association of North America. Also, personal communications to authors (D. A.).

Vogt, W. G. and D. Augenstein. 1997. Comparison of Models for Estimating Landfill Methane Recovery. Final report to the Solid Waste Association of North America (SWANA) and the National Renewable Energy Laboratory (NREL) March.

Walsh, J. J. 1994. Preliminary Feasibility Investigations for Landfill Gas Recovery-Identification and Interpretation of Site Background Data. Proceedings, 17th Annual Landfill Gas Symposium SWANA, Silver Spring, Maryland.

Walsh, J J 1997. NSPS Tier II Testing. Initial Results now Complete. Presentation at SWANA's 20th Annual Landfill Gas Symposium, SWANA, Silver Spring Maryland. Paper available from J J Walsh, SCS Engineers, Covington, Ky.

Yolo County Public Works and I E M, Inc. Yazdani, R. R. Moore, K, Dahl and D. Augenstein. 1998. Trash to Cash. Yolo County Controlled Landfill Bioreactor Project. Progress toward a twenty-first century landfill. Progress Report to Urban Consortium Energy Technology Task Force (UCETF).

Zison, Stanley W. 1990. "Air Resources Board Suggested Control Measure Landfill Gas Emissions and Evaluation Guidelines Commentary Offered by Pacific Energy." Letter to Jim Behrman, Toxic Program Support Section, CARB.

APPENDIX

EPA Project XL Proposal

EPA PROJECT XL
Final Project Agreement for the Yolo County Accelerated Anaerobic & Aerobic Composting (Bioreactor) Project

Draft-July 21, 2000

Submitted by:

County of Yolo
Planning and Public Works Department
Division of Integrated Waste Management
292 West Beamer Street
Woodland, CA 95695
Ramin Yazdani, Assistant Director
Phone: (530) 666-8875
Fax: (530) 666-8728
Email: Ramin.Yazdani@ccm.yolocounty.org
Co-sponsors of the project with Yolo County are:
Institute for Environmental Management (IEM, Inc.)
Don Augenstein
Phone: (650) 856-2850
Email: Iemdon@aol.com
and
Solid Waste Association of North America (SWANA)
John Pacey
Phone: (925) 288-9898
Email: JPacey@theitgroup.com

United States Environmental Protection Agency

"...to protect human health and to safeguard the natural environment..."

Table of Contents for the Final Project Agreement

I. Introduction to the Agreement

A. Description of the Project and Its Purpose
B. Description of the Facility/Community/Geographic Area
C. Purpose of the Agreement
D. List of the Parties that Will Sign the Agreement
E. List of the Project Contacts

II. Detailed Description of the Project

A. Summary of the Project
B. Description of the Specific Project Elements

III. How the Project Will Meet the Project XL Acceptance Criteria

A. Anticipated Superior Environmental Performance
B. Anticipated Benefits (such as cost savings, paperwork reduction and operational flexibility)
C. Stakeholder Involvement and Support
D. Innovative Approaches and Multi-media Pollution Prevention
E. Transferability of the Approach to Other Entities or Sectors
F. Feasibility of the Project
G. Monitoring, Reporting, Accountability, and Evaluation Methods to be Used
H. Avoidance of Shifting the Risk Burden to Other Areas or Media

IV. Description of the Requested Flexibility and the Implementing Mechanisms

A. Requested Flexibility
B. Legally Implementing Mechanisms

V. Discussion of Intentions and Commitments for Implementing the Project

A. Intentions and Commitments
B. EPA, State, and Local Agency's Intentions and Commitments
C. Project XL Performance Targets
D. Proposed Schedule and Milestones
E. Project Tracking, Reporting, and Evaluation
F. Periodic Review by the Parties to the Agreement
G. Duration of the Project

VI. Legal Basis for the Project

A. Authority to Enter Into an Agreement
B. Legal Effect of the Agreement
C. Other Laws or Regulations That May Apply
D. Retention of Rights to Other Legal Remedies

VII. Unavoidable Delay During Project Implementation

VIII. Amendments or Modifications to the Agreement

IX. Transfer of the Project Benefits and Responsibilities to a New Owner

X. Process for Resolving Disputes

XI. Withdrawal From or Termination of the Agreement

A. Expectations
B. Procedures

XII. Compliance After the Project is Over

A. Orderly Return to Compliance if the Project Term is Completed and Not Extended
B. Orderly Return to Compliance in the Event of Early Withdrawal or Termination

XIII. Signatories and Effective Date

I. Introduction to the Agreement

A. Description of the Project and Its Purpose

The County of Yolo Planning and Public Works Department (Yolo County), proposes to operate its next 20-acre landfill module near Davis, California as a controlled bioreactor landfill to attain a number of superior environmental and cost savings benefits. In the first phase of this 20-acre project, a 12-acre module has been constructed. This 12-acre module contains one 9.5-acre cell, which will be operated anaerobically, and a 2.5-acre cell aerobically.

During the waste filling, horizontal gas wells will be constructed in the both the aerobic and anaerobic cells. Waste will be placed in 15-foot high lifts. The horizontal gas well spacing will be 50 feet on center in anaerobic cell and closer in the aerobic cell. Gas will also be extracted from the base layer of both cells during waste filling. The purpose of this extraction system design is to lower methane emissions that would normally occur to the atmosphere during filling in the anaerobic cells. An impermeable cover will be placed over each cell shortly after waste filling has been completed. Landfill gas will be collected from the anaerobic cell and the aerobic cell atmospheric air will be pulled or pushed through the waste. In the aerobic cell, it is expected that this will increase the rate of degradation but inhibit methane formation. Many gas and leachate parameters will be monitored during the operation of this cells to collect in-situ data as well as laboratory analysis.

Co-sponsors of the project with Yolo County are the Solid Waste Association of North America (SWANA) and Institute for Environmental Management (IEM, Inc.). As part of this proposal, Yolo County is requesting that U.S. EPA grant site-specific regulatory flexibility from the prohibition in 40 CFR 258.28 Liquid Restrictions, which may preclude addition of useful bulk or non-containerized liquid amendments. The County is proposing to supplement the liquid addition with ground water, but would like to obtain the flexibility to possibly utilize other liquids such as gray-water from a waste water treatment plant, septic waste, gray water, and food-processing wastes that are currently land applied. Liquid wastes such as these, that normally have no beneficial use, may instead beneficially enhance the biodegradation of solid waste in a landfill for this project.

Yolo County also requests similar flexibility on liquid amendments from California and local regulatory entities. Several sections of the California Code of Regulations (CCR), Title 27, Environmental Protection, address the recirculation of liquids in lined municipal waste landfills. While the regulations do not specifically endorse bioreactors, regulatory flexibility is provided.

B. Description of the Facility and Facility Operations/Community/Geographic Area

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

Adjacent land uses include a wastewater disposal area (spray irrigation fields) operated by Hunt-Wesson west of the site until December 1999, and the City of Davis Wastewater Treatment Plant lagoons located immediately east and south of the landfill, which will be continuing in operation. The Willow Slough By-pass runs parallel to the southern boundary of the site. The remainder of land uses adjacent to the site are agricultural (row crops).

There are approximately 28 residences scattered within a 2-mile radius of the landfill. The closest residence is located 1,600 feet south of the landfill and city treatment plant lagoons, on the West Side of Road 105 south of the Willow Slough By-pass.

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

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

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

C. Purpose of the Agreement

This Final Project Agreement (“ the Agreement”) is a joint statement of the plans, intentions and commitments of the U.S. Environmental Protection Agency (“EPA”), the state of California, and Yolo County to carry out this project approved for implementation at the county’s solid waste landfill site near Davis, California. This Project will be part of EPA’s Project XL program to develop innovative approaches while providing superior environmental protection.

The Agreement does not create legal rights or obligations and is not an enforceable contract or a regulatory action such as a permit or a rule. This applies to both the substantive and the procedural provisions of this Agreement. While the parties to the Agreement fully intend to follow these procedures, they are not legally obligated to do so. For more detail, please refer to Section VI (Legal Basis for the Agreement).

Federal and State flexibility and enforceable commitments described in this Agreement will be implemented and become effective through a legal implementing mechanism (e.g. site-specific rule, rule or permit modification).

All parties to this Agreement will strive for a high level of cooperation, communication, and coordination to assure successful, effective, and efficient implementation of the Agreement and the Project.

D. List of the Parties that Will Sign the Agreement

The Parties to this Final Project XL Agreement are the United States Environmental Protection Agency (EPA), County of Yolo Planning and Public Works Department, and the State of California.

E. List of the Project Contacts

County of Yolo, Planning and Public Works Department
U. S. Environmental Protection Agency
Solid Waste Association of North America (SWANA)
Institute for Environmental Management (IEM)
National Energy Technology Laboratory (NETL, previously FETC), U. S. Department of Energy
California State Regional Water Quality Control Board, Central Valley Region 5
California Integrated Waste Management Board
Yolo County Department of Environmental Health
Yolo-Solano Air Quality Management District

II. Detailed Description of the Project

A. Summary of the Project

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

In a Bioreactor Landfill, controlled quantities of liquid are added, and circulated through waste as appropriate, to accelerate the natural biodegradation and composting of solid and liquid waste components. 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 years, to 50 years or more). If the waste decomposes (i. e., is composted) in the absence of oxygen (anaerobically), it produces landfill gas (biogas). Biogas is primarily a mixture of methane, a potent greenhouse gas, carbon dioxide, and VOC's, which are local air pollutants. Methane is also a fuel. This by-product of anaerobic landfill waste composting can be a substantial renewable energy resource that can be recovered for electricity or other uses. Other benefits of a bioreactor landfill composting operation include increased landfill waste settlement and therefore 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 efforts, 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.

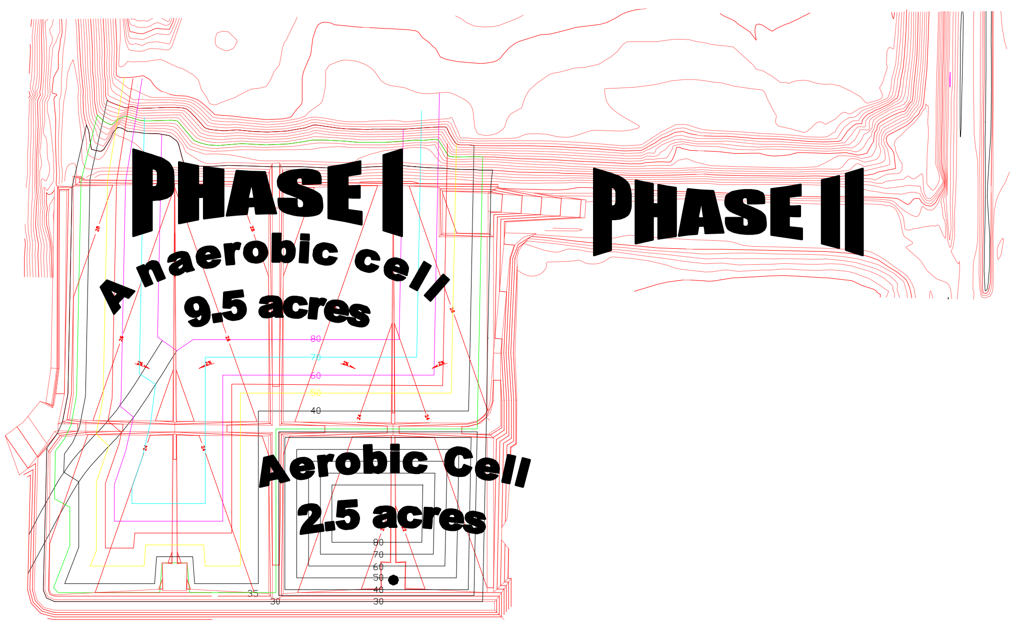
B. Specific project elements

Yolo County proposes to operate its next full-scale 20-acre landfill module with both anaerobic and aerobic bioreactor areas (also termed modules below). In the first phase of this 20-acre project, a 12-acres module has been constructed. One 9.5-acre cell will be operated anaerobically and the other 2.5-acre cell aerobically. The anaerobic and aerobic design and operations are summarized below:

DESIGN AND OPERATIONS OF PROPOSED MODULE D BIOREACTOR

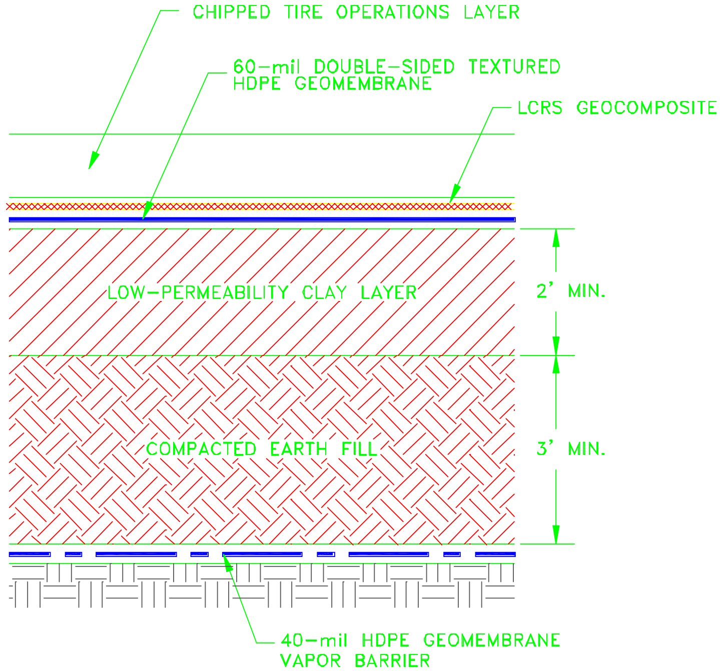
The bottom liner system was designed to exceed the requirements of Title 27 of CCR and Subtitle D of the Federal guidelines and was upgraded from other liner systems used previously at the site. The County believes that given the constructed configuration discussed herein and the stringent monitoring and operational requirements proposed for Module D, the proposed liner system will be suitable for use in the bioreactor operations.

Figure 1- Module D Expansion, Phase 1 & 2



Under current plans, the first phase of Module D will be further subdivided into the two independent bioreactor systems, the aerobic system and the anaerobic system. Module D was designed and constructed in a ridge and swale configuration to optimize landfill space and to maintain good drainage for the collection system. The blanket drainage layer slopes at 2% inward to two central collection v-notch trenches. Each of the trenches drain at 1% to their prospective leachate collection sumps located at the south side of the module. This grading configuration is an upgrade from previous designs at the site because it is steeper, thus, maintaining better drainage throughout its design life. Phase 2 of Module D will also be constructed in a similar manner as Phase 1 of Module D since it provides a better leachate drainage for the base layer.

Figure 2- Module D Bottom Liner Cross-section



Liner and Leachate Collection and Removal System (LCRS) Components

The prescriptive liner for Class III landfills consists, from top to bottom, of an operations/drainage layer capable of maintaining less than one foot of head over the liner, a 60-mil high density polyethylene (HDPE) liner, and 2 feet of compacted clay ($k< 1 \times 10^{-7}$ cm/sec).

The Module D liner and leachate collection system consists, from top to bottom, of a 2 foot thick chipped tire operations/drainage layer ($k> 1$ cm/sec), a blanket geocomposite drainage layer, a 60-mil HDPE liner, 2 feet of compacted clay ($k<6 \times 10^{-9}$ cm/sec), 3 feet of compacted earth fill ($k< 1 \times 10^{-8}$ cm/sec), and a 40 mil HDPE vapor barrier layer[1] (see Figure 2). The chipped tire operations layer was not placed during construction but will be placed immediately before waste placement.

As shown, the permeability of the clay liner, as constructed, was on the average about 6×10^{-9} cm/sec and the earth fill averaged about 1×10^{-8} cm/s. These two layers in effect provide a 5 foot 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.

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 groundwater offset and to minimize

[1] Golder Associates, "Final Report, Construction Quality Assurance, Yolo County Central Landfill, WMU 6, Module D, Phase 1 Expansion", December 1999.

potential leakage in these critical collection areas where head on the primary liner will be at its greatest. The liner and leachate collection system in the collection trenches and sumps consists from top to bottom of a minimum of 2 feet of gravel drainage material, a protective geotextile, a blanket geocomposite drainage layer, a primary 60-mil HDPE liner, a geosynthetic clay liner (GCL) (k< 5×10^{-9} cm/sec), a secondary 60-mil HDPE liner, 2 feet of compacted clay (k< 6×10^{-9} cm/sec), a minimum of 0.5 feet of compacted earth fill (k< 1×10^{-8} cm/sec), and a 40-mil HDPE vapor barrier layer (see Figure 3). The thickness of the compacted earth fill actually varies from a minimum at the south end of the trench of 0.5 feet to a maximum of about 2.5 feet at the upper, north end of the leachate collection trench. Leachate collection pipes were also placed in the collection trench and at other locations on top of the primary liner to transport leachate immediately to the sumps for recovery, removal, and recirculation, as needed.

LCRS and Liner Performance

As described above, the more rigorous Module D LCRS and liner system will outperform the Title 27 and Subtitle D prescriptive liner. The leachate collection and recovery system (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 and Subtitle D.

The LCRS system has been constructed with a geocomposite layer, which has over 10 times the required capacity and will maintain the head over the liner system to less than 0.3 inches during liquid application periods. In addition, the chipped tire layer will provide a level of redundancy in the event that the geocomposite becomes clogged or otherwise nonfunctional. The tire chips alone will maintain less than 4 inches of head over the primary liner. These issues are discussed in more detail in the following paragraphs.

For the anaerobic operation, it is estimated that the peak liquid addition, up to 10 gallons per minute (gpm) of liquid per 10,000 square feet (44 gpm per acre) of disposal area will be typically delivered to the waste once the module has reached its design height. Based on the demonstration cell performance the amount of liquid added would be in the range of 30 to 50 gallons per ton of waste. According to results of the bioreactor demonstration project by Moore et al[2], 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 gallons per day).

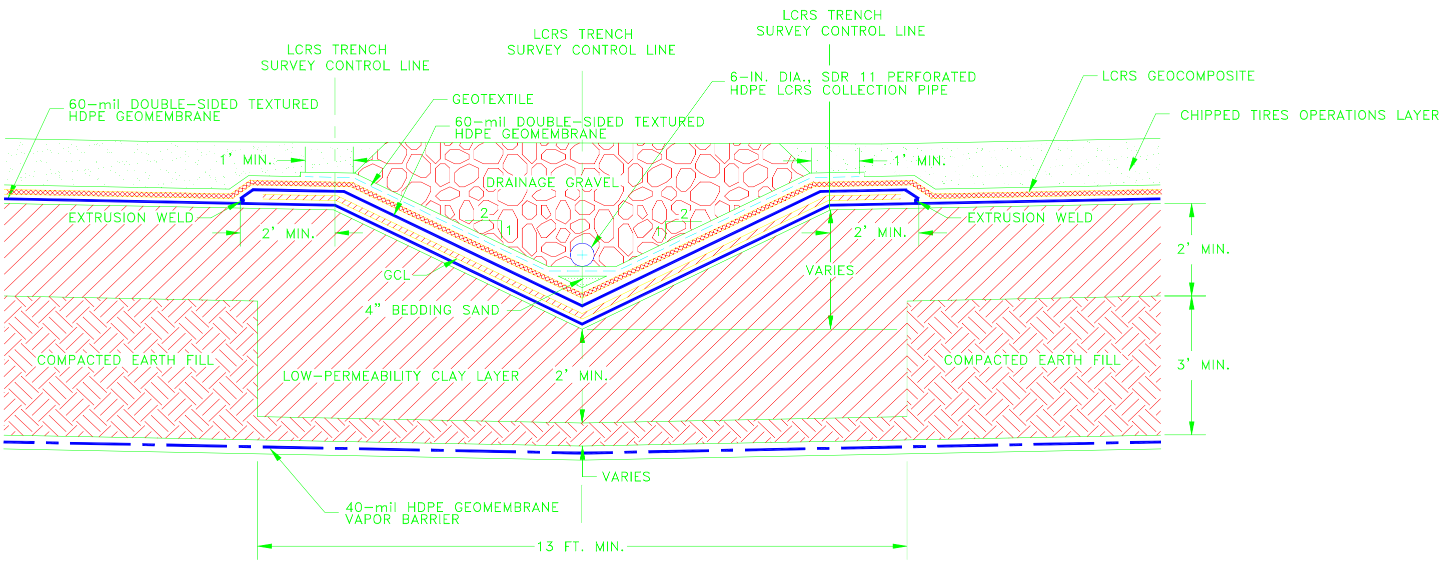
For the aerobic operation, liquid will be added to waste at a faster rate since the aerobic reaction uses much of the water in the evaporation of liquid added. It is estimated that the total water evaporated will range between 200 to 400 gallons of water per ton of waste.

Based on the estimated leachate production, drainage into the leachate collection layer will be about 4.6×10^{-4} gpm per square foot of disposal area. It is approximately 200 feet 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 D has a measured

[2] Moore et al, "Hydraulic Characteristics of Municipal Solid Waste Findings of the Yolo County Bioreactor Landfill Project.", Thirteenth International Conference on Solid Waste Technology and Management, Philadelphia, PA, November 1997.

capacity of 1.0 gpm per foot[3]. Therefore, the geocomposite has over 10 times the capacity required under peak flow conditions.

Figure 3- Module D Bottom Liner and Leachate Collection Trench Cross-Section



Although clogging of the geocomposite layer is not anticipated, the LCRS has been designed under the conservative assumption that geotextile clogging may occur. In the event that the geocomposite were to become clogged or otherwise nonfunctional, the proposed chipped tire operations layer with its high porosity will provide adequate drainage. Due to the large particle size of the chipped tires (>6 inches), the calculated effective permeability of the tire layer at the drainage slope of 0.02 is 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 one 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 one foot of head over the liner. Therefore, this system has over three times the required flow capacity at the allowable prescriptive level of one foot.

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 D 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 D, the clay liner has an average permeability on the order of 6×10^{-9} cm/sec. Using standard leakage rate analyses by Giroud

[3] Golder Associates, “Final Report, Construction Quality Assurance, Yolo County Central Landfill, WMU 6, Module D, Phase 1 Expansion”, December 1999.

and Bonaparte[4], the leakage from the Title 27 system (with one 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 cm^2 hole in the liner. With the Module D liner (4 inches 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 that leakage were to occur through the 5-foot thick primary composite liner, the 40-mil vapor barrier would provide a 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 southern portion of the cell located immediately beneath each of the leachate collection sumps. The will act as a vadose zone monitoring system for early detection of leakage across the entire Module D disposal area. This added feature provides another level of protection to the groundwater that standard Title 27 systems do not have.

In addition, the County hired Leak Location Services (LLC) to locate any pinholes that could have been in the leachate collection trenches on the primary liner system. LLC uses a high sensitive method using electrical charge to locate pinhole leaks very accurately. Using specialized equipment designed and built for locating liner leakage, LLC uses to verify integrity of liner system after completion of liner construction. Several small holes were found and repaired after this leak testing was done.

Specialized Design Considerations During Operation

Liquid will be applied during strategic periods to temporarily raise the moisture content of the waste to provide optimum conditions for rapid degradation and improved gas production. This liquid will initially consist of a mixture of leachate and condensate from other WMUs and ground water delivered through a series of pipes and drip irrigation or other application system either after the landfill reaches its design height or after an interim cover and gas collection system has been constructed to control landfill gas generated. The initial gas collection will be by horizontal wells, operated and tuned as are conventional wells, for earliest practical gas recovery. This essentially consists of extracting gas at the maximum rate consistent with keeping methane concentration near 50%. Recovery efficiency will be increased and surface emissions limited by a synthetic liner covering as much waste surface as possible during the filling phase, except the working face. After filling phase has been completed the entire surface will be covered with synthetic liner. At lease some fraction of the gas monitoring will be by gas chromatography to quantify the methane, nitrogen, carbon dioxide, oxygen, and other gaseous compounds of interest.

The typical chemical composition of potential liquid amendments are listed below in Table 1. The water will continually be introduced (as needed) to raise the moisture content within the waste to slightly above its equilibrated field capacity (estimated to be about 40% to 45% by wet weight basis). The liquid application system will be constructed such that liquid additions can be applied or discontinued at designated locations to control the moisture condition within the waste.

[4] Giroud, J.P. and Bonaparte, R., "Leakage Through Liners Constructed With Geomembranes – Part I. Geomembrane Liners." Geotextile and Geomembranes, Eslvier Science Publishers Ltd., England, 1989.

Moisture content will be monitored throughout the life of the module through the use of a network of moisture sensors to be installed during waste placement. The moisture sensor system used during the bioreactor demonstration project in Module B proved to be very effective and will be the basis for the layout in Module D. At this time, the moisture sensors are planned to be installed at 15-foot increments of depth at a spacing of about 75 feet on center. Using these sensors, the County can determine where liquid application can be increased or decreased to optimize the effectiveness of the system and to prevent build-up of head over the liner.

The quantity of leachate and additional liquids will be measured throughout the life of the module. Once leachate is produced, it will be re-circulated; thereby, reducing the amount of subsequent liquid additions. Liquid will be quantified using flow sensors installed on the leachate discharge line, re-circulation line, and liquid application line. These sensors will provide direct flow readout for determining flow rates in the pipelines and flow totalizing to quantify all of the liquid used and leachate produced.

Table 1- Yolo County's Typical Chemical Composition of Potential Liquid Amendments

Inorganics and Metals	Leachate & Condensate	Groundwater
Potassium (mg/L)	69.3	2.7
Nitrate/Nitrite as Nitrogen (mg/L)	<0.05	3.9
Chloride (mg/L)	785	427
Sulfate (mg/L)	190	278
Total Alkalinity as $CaCO_3$ (mg/L)	1920	950
Temperature	20.9	18.6
pH	7.10	8.26
Electrical Conductivity	5370	2070
Dissolved Oxygen (mg/L)	3.21	8.61
Bicarbonate (mg/L)	2340	628
Total Dissolved Solids (mg/L)	3365	1233
Ammonia (mg/L)	17	0.02
Total Kjeldahl Nitrogen (mg/L)	140	0.19
Cobalt (µg/L)	<50	<3.2
Copper (µg/L)	<2.1	<4.9
Iron (µg/L)	4950	<14
Manganese (µg/L)	1175	9.4
Nickel (µg/L)	77	20.1
Lead (µg/L)	50	5.0
Vanadium (µg/L)	20	8.3
Zinc (µg/L)	323	10.8

The head over the liner will also be monitored shortly after the first lift of waste has been placed using a network of pressure transducers and bubbler gages. These devices will be installed on the primary liner, immediately before waste placement, to provide measurements of the leachate depth.

In the event that the transducers indicate that the head is going to exceed the allowable value, the system will automatically start pumps to reduce the liquid level and shut-off valves to reduce the liquid application rate. A computerized control and monitoring system will be used to accomplish this task. This system which originated in the utility and petroleum industries, is often referred to as Supervisory Control and Data Acquisition Control (SCADA), such systems are now widely used in many different applications such as waste water treatment system. These measures would be used to reduce the liquid application rate across the entire module or specifically, in the area of head build-up. Generally, application of the liquid will only be continued until the gas generation phase of the unit it has stabilized, at which time leachate production and recirculation may already have stopped and the leachate should have stabilized some time earlier. The quality of the leachate will also be closely monitored to evaluate the system. Leachate will be monitored in accordance with the comprehensive program already as currently implemented at the site per Waste Discharge Requirements.

In addition to liquid delivery to the waste, air will be delivered to the aerobic half of the bioreactor disposal area. The aerobic decomposition of the waste and gas generation also requires the moisture condition be maintained slightly above equilibrated field capacity. However, the aerobic process is accomplished at a higher temperature and is somewhat more aggressive in the biodegradation activity. This requires a significant increase in the quantity of water necessary to achieve optimum biodegradation, as compared with the anaerobic process.

The degradation and gas generation of the waste is also related to the temperature within the decomposing waste. The effectiveness of both aerobic and anaerobic bioreactors is dependent on keeping the system within optimum temperatures; therefore, temperature gauges will also be installed to aid in operation of the system. As with the moisture sensors, temperature gauges were also placed in the waste of the demonstration bioreactor and proved to be very effective. The temperature gauge network will be placed in a similar pattern to the moisture sensors at designated intervals throughout the waste mass.

In the aerobic half, during filling, horizontal gas conduits will be installed in similar manner to those of the anaerobic bioreactor. However conduit spacing may be closer. After filling, chipped tires and conduits will be used to pull or push atmospheric air through the waste under a impermeable cover. It is expected that this will increase the rate of degradation but inhibit methane formation. Large-scale positive gas displacement meters, similar to meters used for the demonstration cells will monitor the gas quantity.

As with the aerobic half, horizontal gas wells will also be incorporated in the waste as filling proceeds in the anaerobic area. Waste will be placed in 15- foot lifts. The gas well spacing will be 50 feet on center or closer. Gas will also be extracted from the base LCRS layer via the conduit collection pipe as filling proceeds. The purpose of this extraction system design is to lower methane emissions that would normally occur to the atmosphere during filling.

Separation of the two bioreactor systems will be performed using a low permeability clay liner constructed below the aerobic cell and on top of the first lift of waste in the anaerobic cell. This layer may include but would not be limited to a compacted clay liner, or geomembrane. Leachate and gas collection system will be separated from the anaerobic cell. Final selection will be based on its ability to appropriately isolate each cell, ability to accommodate settlement, ease of installation, and cost.

Daily cover operations will be performed in a similar fashion to the methods currently employed at the landfill. This includes the use of alternative daily covers such as greenwaste and tarps. Final cover will consist of a gas piping collection system within a layer of chipped tires in lieu of gravel. The liquid injection system will also be placed within this layer to facilitate delivery of liquid to the waste. This layer will be overlain with a flexible geomembrane cover to control moisture conditions, control gas emissions, and satisfy regulatory requirements to control vectors, fires, odors, blowing litter, and scavenging.

As areas of the module reach their design grade, monuments will be installed to monitor settlement caused by degradation of the waste. These monuments will be checked bi-monthly at first and less often as the rate of settlement slows. Annual aerial topographic surveys will also be performed to aid in the evaluation of settlement and the effectiveness of the bioreactor system.

With all of these operational systems in place, the performance of the bioreactor and effectiveness of the LCRS and gas collection system can be thoroughly monitored. These operational systems far exceed the requirements of Title 27 and Subtitle D; thus, providing another basis for allowance of the Module D bioreactor project.

The instrumentation and monitoring frequency of the bioreactor project are listed in Table 2 and Table 3 respectively.

Table 2- Instrumentation Type and Location for the Bioreactor Project

Type of Instrumentation	Location/Quantity/Spacing	Description
• Pressure transducers • Pressure transducers	• **Anaerobic Bioreactor:** 1. Eight over the primary liner near the LCRS trench at 200 spacing 2. Two over the primary liner within the leachate collection sump • **Aerobic Bioreactor:** 1. Two over the primary liner at 200 feet spacing 2. One within the leachate sump	A series of pressure transducers and bubbler gages will be installed on top of the primary liner and near the LCRS trench in both the aerobic and anaerobic landfill cells to measure the head or depth of leachate above the liner. A gas pressure transducer in each cell will be used to correct the liquid head for gas pressure. Pressure transducers will be continuously monitored through a SCADA system which will control the liquid injection system to maintain less than four inches of head over the liner.
• Bubbler Gage for Liquid/Gas Pressure Measurement and Liquid/Gas Sampling	• **Anaerobic Bioreactor:** 1. Top of primary bottom liner-66 gages at 75 feet spacing 2. Top of the first lift of waste- 55 gages 3. Top of the second lift of waste-40 gages 4. Top of the third lift of waste-30 gages	Bubbler gages will be installed to measure liquid and gas pressure directly on top of the liner and at different depths within the waste. The tubes will also be used to measure gas pressure and sample gas and/or leachate from a specific location within the waste. The data from the leachate levels within the waste will assist

	5. Top of the final lift of waste-20 gages TOTAL= 211 gages	the County in the operation of the cell as well as provide valuable data on waste stability and pore pressure within the waste during liquid injection and recirculation.
• Bubbler Gage for Liquid/Gas Pressure Measurement and Liquid/Gas Sampling	• **Anaerobic Bioreactor:** 1. Top of the aerobic bottom liner-48 gages at 50 feet spacing 2. Top of the first lift of waste- 24 gages 3. Top of the second lift of waste-20 gages 4. Top of the final lift of waste-20 gages TOTAL= 112 gages	A compacted clay liner and a synthetic liner will be constructed 5 to 7 feet above the primary liner system over compacted waste for the bottom liner in the aerobic bioreactor. The leachate from the aerobic cell will be collected and removed into a separate manhole for recirculation and measurement. This will isolate the primary HDPE liner under the aerobic cell and protect this liner from higher temperature seen in the aerobic cell.
• Moisture and Temperature Sensors • Moisture and Temperature Sensors	• **Anaerobic Bioreactor:** 1. Top of primary bottom liner-66 temperature sensors at 75 feet spacing and 12 moisture sensors 2. Top of the first lift of waste-55 temperature and moisture sensors 3. Top of the second lift of waste-40 temperature and moisture sensors 4. Top of the third lift of waste-30 temperature and moisture sensors 5. Top of the final lift of waste-20 temperature sensors TOTAL= 211 temperature sensors and 137 moisture sensors • **Anaerobic Bioreactor:** 1. Top of the aerobic bottom liner-48 temperature and 12 moisture sensors 2. Top of the first lift of waste- 24 gages 3. Top of the second lift of waste-20 gages 4. Top of the final lift of waste-20 gages TOTAL= 112 gages	A series of moisture and temperature sensors will be installed within the waste mass to monitor the biological activity of each cell. Temperature and moisture sensors will be continuously monitored through a SCADA system. Temperature alarm will be set in the SCADA system to warn operator via telemetry when temperature change is 24 hours is greater than 2 degrees. This early warning system will enable the County to investigate the cause and reduce air injection or shout down the air injection system in the aerobic bioreactor.

• Gas Composition, Gas Pressure, and Gas Flow Rate	• **Anaerobic Bioreactor & Aerobic Bioreactor:** 1. Two gas pressure transducers under the final cover 2. Two gas flow meters in parallel to measure gas flow rate continuously 3. Temperature sensors to measure gas temperature at flow meters continuously 4. Gas composition will be monitored as listed in Table 3	Horizontal gas collection system will be constructed at 100 feet in the anaerobic bireoactor and 50 feet interval in the aerobic bioreactor. Four and six inch PVC pipes and chipped tire will be used to construct the gas collection system. This will be installed at every lift to either collect landfill gas or inject air in the landfill. Gas will be sampled from either the main collection pipe or each individual lift of waste to determine gas composition or measure gas pressure. The gas pressure and temperature will also be measured at the well heads when taking reading for gas composition weekly. Gas flow rate will be measured automatically continuously. If additional funding becomes available the County will investigate automation of CH_4, CO_2, O_2, and N_2 .
• Leachate Flow Measurement & Other Leachate Parameters	• **Anaerobic Bioreactor & Aerobic Bioreactor:** 1. Leachate input and output volumes 2. Leachate pH, dissolve oxygen, conductivity	The quality of leachate added or collected from the LCRS is measured by flowmeters from each cell. The SCADA system will be used to monitor and control quantities of leachate added and collected from each bioreactor cells. Some of the leachate parameters will be automated for continuous measurement such as pH, dissolved oxygen, and conductivity.

Table 3- Monitoring Parameters and Frequency for the Bioreactor Project

Monitoring Parameter	Frequency	Description
Leachate: • pH • Conductivity • Dissolved Oxygen • Dissolved Solids • Biochemical Oxygen Demand • Chemical Oxygen Demand • Organic Carbon • Nutrients(NH_3, TKN, TP) • Common Ions • Heavy Metals • Organic Priority Pollutants • Flow rate	 • Weekly • Weekly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Monthly, Quarterly • Continuously	Leachate samples will be collected from each cell (aerobic or anaerobic) sump and tested. For the first six months tests will be done monthly and the next six months will be done quarterly. After the first year test will be done semi-annually. The frequency of testing could vary depending on the level of funding available for the project monitoring.
Landfill Gas: • CH_4, CO_2, O_2, and N_2 • Gas temperature at well head • Hydrogen sulfide • NMOCs, VOCs • Surface integrity scan test • N_2O (for aerobic) • Flow rate	 • Weekly • Weekly • Quarterly, Semi-annually • Quarterly, Semi-annually • Quarterly, Semi-annually • Quarterly, Semi-annually • Continuously	Landfill gas will be tested routinely from both the aerobic and anaerobic cell. For the first year tests will be done quarterly and the following years will be semi-annually. Surface scan test will be conducted using NSPS surface monitoring method (section 60.755 (c) 3) to test for collection efficiency and surface integrity. The frequency of testing could vary depending on the level of funding available for the project monitoring.
Solid Waste Stabilization and decomposition: • Landfill surface topographic survey • Moisture Content • Biochemical Methane Potential • Cellulose • Lignin • Hemi-cellulose	 • Annually • Annually • Annually • Annually • Annually • Annually	Annual topographic survey will be done on the top surface of each cell. If funding is available solid waste samples may be collected to determine the degree of stabilization. Samples of waste may also be tested for heavy metals and organic pollutants.

<u>The full-scale Yolo County Bioreactor project will combine two key elements:</u>

a) Acceleration of waste decomposition and leachate treatment, via liquid amendments and recirculation through pipe network serving the waste mass. This is to accomplish rapid completion of composting, stabilization and generation of methane to the maximum practical yield.

b) Efficient capture of nearly all generated methane, withdrawn at slight vacuum from a freely gas-permeable shredded tire collection layer beneath low-permeability cover. The shredded tire collection layer has gas permeability from 3 to 5 orders of magnitude higher than overlying cover. Near-complete extraction with this approach has already been demonstrated in the 9000-ton test cell at the Yolo County Bioreactor Demonstration Project.

The planned anaerobic cell proposes larger-scale replication of the 9000-ton anaerobic controlled bioreactor landfill demonstration at Yolo. This demonstration has now operated for over three years. Some of the data from the demonstration project are summarized below:

(a) Enhanced methane/ gas recovery (an index of anaerobic composting) at a rate of an order of magnitude greater than that of the current landfill unit production. Based on the collected data to date, the anaerobic bioreactor stabilization time may be reduced by more than 30 years less than the current landfills expectations. Table 4 below summarizes some of the landfill gas data for the enhanced and control cell.

Table 4- Landfill Gas Data for the 9000-ton Bioreactor Demonstration Project

YEAR	1997	1998	1999
ENHANCED CELL LFG VOLUME (Million SCF)	12.2	24.8	30.7
CONTROL CELL LFG VOLUME (Million SCF)	9	14.9	15.2
ENHANCED CELL AVERAGE FLOWRATE (SCFM)	35	22	7
CONTROL CELL AVERAGE FLOWRATE (SCFM)	22	5	1
ENHANCED CELL AVERAGE METHANE CONTENT	53%	54%	53%
CONTROL CELL AVERAGE METHANE CONTENT	47%	45%	47%

(b) Collection is by extraction from a freely gas-permeable surface layer, kept at slight vacuum, overlying the waste and beneath a very low-permeability surface cover. This approach allows recovery of all gas generated beneath the permeable layer.

(c) With the same collection approach, reductions in emissions of local air pollutants in landfill gas by at least the same fraction that landfill methane is reduced.

Figure 4- Percent Settlement versus Time for the 9000-ton Bioreactor Demonstration Project

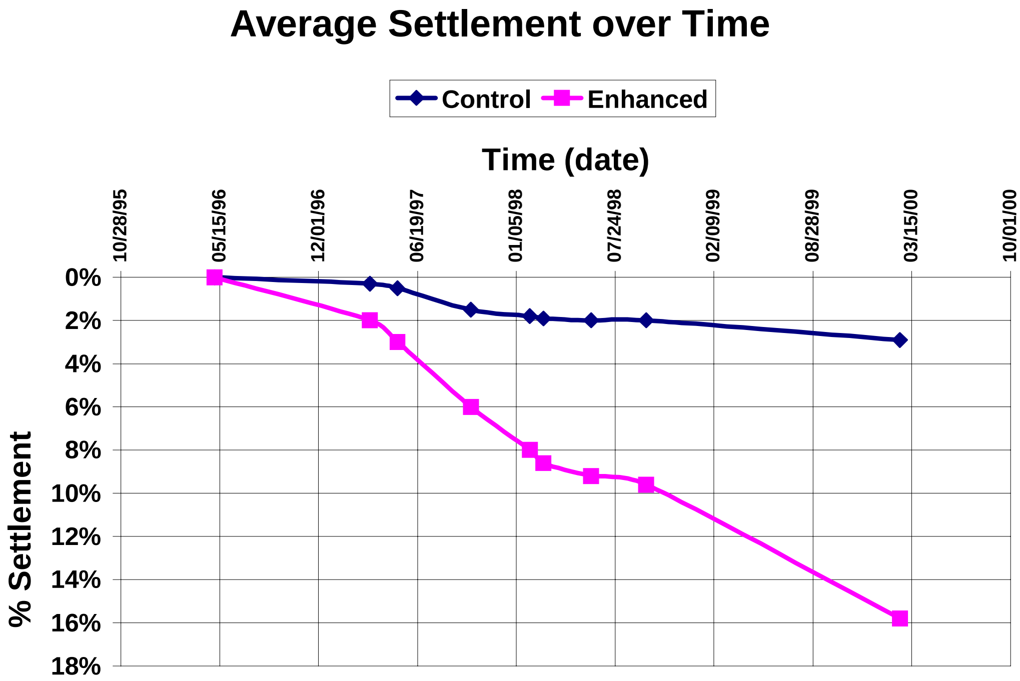
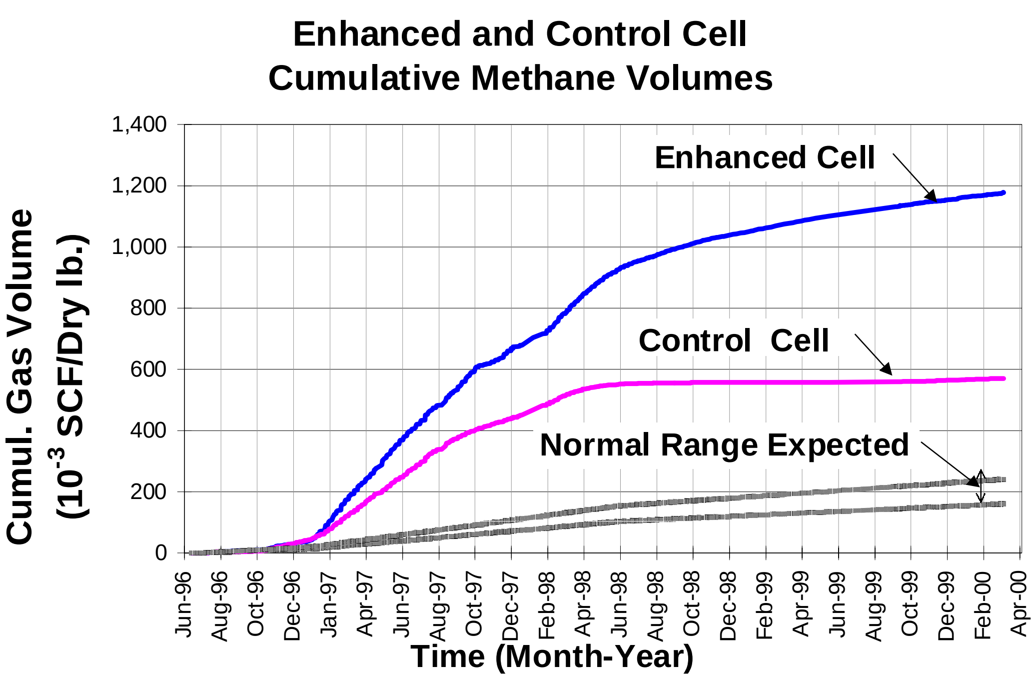


Figure 5- Cumulative Methane Volumes for the 9000-ton Bioreactor Demonstration Project



(d) Volume and waste mass loss of over 18% in the first 3 years of the enhanced operation, as compared to 3% for the control cell (see Figure 4). This suggests a difference of landfill life extension of over 15% possible by taking advantage of the extra air space made available.

(e) Bioreactor liquid additions can be slow and very carefully managed while still attaining excellent methane enhancement. In the Yolo anaerobic cell demonstration project liquid was carefully added at a slow rate. The highest liquid injection rate of 10 gpm resulted in an output leachate flow rate of less than 3 gpm for short periods, less than three days. Careful liquid injection rates resulted in liquid outflow rate that rapidly decreased and was easily controlled.

(f) No measurable leakage in the primary liner system of the enhanced cell. This is consistent with data from Othman et al showing primary composite liner leakage rates of 0-50 liters/hectare day. Most values in Othman et al are consistent with negligible or no leakage (below detection limits, less than 2 liters/hectare day) for monitoring periods within the first few years after base composite clay-geomembrane lining construction.

(g) Leachate pollutants stabilize rapidly, usually in under a year to concentrations well beneath those typifying the surrounding conventional landfill at the same site. Table 5 below shows typical leachate chemistry data over the past four years.

YEAR	1996	1997	1998	1999
pH	5.8	7.0	7.2	7.2
BOD (mg O/L)	5,020	820	140	80
COD (mg O/L)	20,300	2,860	3,130	2,650
TDS (mg/L)	19,800	7,600	7,500	7,250
TOC (mg/L)	9,830	611	1,130	1,080
Iron (mg/L)	152,000	933	504	206
Manganese (µg/L)	41,900	4,000	1,170	1,060
Calcium (mg/L)	1,400	480	220	198
Lead (µg/L)	ND	ND	ND	ND
Toluene (µg/L)	160	75	24	15

Table 5- Landfill Leachate Data for the 9000-ton Bioreactor Demonstration Project

The aerobic bioreactor differs from the anaerobic, only by introducing air to the landfill. Recent representative references on aerobic bioreactor processes include Johnson and Baker, 1999 and Bernreuter and Stessel. 1999.

Results indicate that "in-landfill" aerobic composting is feasible. Landfill methane energy is sacrificed, but advantages include the desired waste destruction as well as suppression of landfill methane generation by heat and oxygen. In contrast to anaerobic operation, significant waste fractions such as lignin and ligneous materials, and leachate COD components, not degradable anaerobically, are degradable aerobically. Thus it should be possible to achieve somewhat greater waste and leachate organics reduction by aerobic processing compared to anaerobic. These advantages of aerobic bioreactors are expected based on well-established fundamental scientific knowledge, but large-scale data to confirm advantages are limited. There are fewer key measurements to date on aerobic processes, and even basic data such as on material balances and flows are limited. However lysimeter tests, such as Stessel and Murphy, 1992 and other citations of Bernreuter and Stessel, 1999 summarizing ongoing field operations show that landfilled waste is degraded aerobically by passing air and liquid through landfills. Remaining questions include how fast and completely landfilled waste can be composted aerobically. Information for VOC and other emissions are not well established.

Contingency plan for failure of the primary liner system:
The primary liner system is contained by a secondary liner system that serves as a leak detection system. A sump is located at the low point of this system and the sump will be monitored for presence of liquid monthly. If any liquid is collected, samples will be tested to determine if there are any leaks in the primary liner system. If the test results from the sampled liquid indicates that there is a leak in the primary liner system then a pump will be installed in the sump to control liquid accumulation in the sump. The liquid level in the primary liner system will be evaluated and monitored to minimize liquid depth above the primary liner. The liner leakage rate and the leachate injection rate will be evaluated and reduced if necessary to control the rate of leakage.

Contingency plan for landfill fire:
Over 220 temperature sensors will be installed in both the aerobic or anaerobic bioreactor landfill to monitor and record landfill temperature continuously. The Supervisory Control And Data Acquisition (SCADA) system will be used to record any significant temperature fluctuations within the waste that is more than 2 degrees per day. If such temperature fluctuations are recorded the SCADA system will notify the operator that the system must be tested for CO presence. Gas samples will be collected and tested in the field for presence of CO, which will indicate possible internal fire. The location of the possible internal fire in the bioreactor will be determined from the recorded temperature by SCADA system. The rate of liquid injection in that area will be increased to reduce waste temperature. In the aerobic bioreactor the SCADA system will automatically turn off the air injection system to control the internal fire. If the liquid injection rate is not sufficient to reduce the temperature or it's not functioning properly, then a liquid injection well will be drilled from above. This well will be used to inject liquid in the area where possible fire is expected. The SCADA system will be used to continue monitoring the waste temperature after this treatment for an increase or decrease in waste temperature.

On top of the primary liner system, for the anaerobic bioreactor, four 600 feet long 3-inch perforated pipes will be installed to deliver cool water in order to reduce the liner temperature and protect the liner from damage. The leachate pump sumps for the anaerobic bioreactor have been designed to handle twice the volume of the anticipated liquid addition, without any significant liquid head build up over the liner. If necessary, for a short periods the pumps could be turned off so that liquid would build head over the liner and protect the primary liner system from excess heat. This method is not preferred over the other methods mentioned earlier. For the aerobic bioreactor, the bottom elevation of the cell is about seven feet from the primary liner system. Before any waste is place in the aerobic cell a low permeability clay liner will be constructed to separate the aerobic cell from the anaerobic cell and measure liquid and gas volumes accurately. This will also serve as a firebreak between the two cells. Portions of the clay liner within the leachate trench liner will be lined with a synthetic liner to reduce saturation of the clay liner. Similar method mentioned above for the anaerobic cell will be used in the aerobic cell to control fire in addition to stopping the air injection in the cell.

III. How the Project Will Meet the XL Acceptance Criteria

A. Superior Environmental Performance

1. Tier 1: Is the Project Equivalent?

The existing information on the Yolo County demonstration project identifies no significant adverse environmental impacts, that is, worsening of environmental impacts relative to conventional practice. Although leachate may be recovered in quantities at times greater than that with conventional practice it can be well controlled; further, all recovered leachate can be re-used, being re-imbibed by waste, in the process. The other issue to be considered is any extra pollutant increment emitted if there is gas energy use that is greater than would otherwise occur. Here there are several factors and tradeoffs to consider. Landfill gas energy use is accepted and specifically encouraged by EPA. The destruction by weight of VOC's by IC engines is estimated to be an order of magnitude greater than the weight of NOx emitted and it is still better for other energy uses. Gas energy will offset fossil fuel (the most likely "swing" energy that would be displaced) thus reducing pollutant and greenhouse emissions. Advanced power generation approaches such as fuel cells can limit pollutant emission to still greater extents in the future. It is also important to recognize that a major part of "greenhouse" and pollutant benefit comes from abatement of methane and VOC's.

This particular XL project will provide environmental performance at least equivalent to Tier 1, in all areas.

2. Tier 2: Superior Environmental Performance

For convenience the various aspects of superior environmental performance are summarized in Table 6. The benefits to Yolo County are potentially greater energy revenue from the anaerobic operation, which could result from more electricity generation or other energy uses, and landfill life extension. Present landfill capacity is sufficient until the year 2040, and the County would like to see its ability to landfill waste extended farther into the future. The County is also very interested in reducing the anticipated post-closure expenses and liabilities that are presently associated with conventional landfilling in addition to cost of leachate treatment system.

With a Bioreactor Landfill, superior environmental and waste management results include: a) Maximizing landfill gas control and capture of fugitive emissions. (b) Greater recovery of landfill gas (c) Landfill life extension and/or reduced landfill use, d) Leachate treatment and disposal benefits, e) More rapid waste stabilization. These are summarized in Table 6 and discussed further below.

a. Maximizing landfill gas control and minimizing fugitive methane and VOC emissions. Landfill gas as generated contains 55% to 60% methane, a potent greenhouse gas. In terms of climate effects methane is second in importance only to carbon dioxide. Landfill gas is a transporter of volatile organic compounds (VOC's) that are air pollutants. Landfill gas capture is maximized by a surface permeable gas collection layer overlain by a cover of soil with embedded membrane. Gas is withdrawn to maintain this permeable layer beneath surface containment under a slight vacuum. The capture of methane is further facilitated and eased by a shortened generation interval, from 30 to 50 years to between 5 to10 years through enhanced decomposition. Horizontal gas collection system will be installed as waste is placed and collection of gas will begin as soon as waste begins to generate landfill gas. In addition, the final synthetic cover liner will improve the overall collection efficiency of landfill gas system. With this gas capture approach, it is expected that fugitive landfill gas emissions will be reduced for reasons that include:

- Reduction in emissions through installation and operation of gas collection system before the final fill height has reached.

- Efficiency improvements with the proposed horizontal gas extraction method over vertical gas well efficiency.

- Reduction in long term emissions, from landfill gas generation occurring slowly beyond 30 years post-closure.

The demonstration project has already shown close to a tenfold increase in methane recovery rate compared to conventional landfills, which suggest a tenfold reduction in interval of methane generation. Available indications as well as basic physical principles suggest that capture effectiveness approaches 100% so long as slight vacuum is maintained within the permeable layer.

b. Expedited methane generation/recovery. Methane recovery is maximized by use of permeable layers as discussed above and also facilitated by methane generation over much shorter terms. This is expected to minimize long-term low-rate methane generation often lost to energy use in conventional landfill practice. The reliability of methane fuel recovery for energy generation should reduce the uncertainty and improves economics of landfill gas projects. Greater use of methane to full potential can add still more greenhouse benefit by reducing fossil CO_2 otherwise emitted with fossil energy use elsewhere.

A recently completed study for the Federal Energy Technology Center (FETC) (now the National Energy Technology Laboratory, NETL) of the U. S. Department of Energy indicates that wide application of controlled landfilling could reduce US greenhouse gas emissions by 50-100 million tons of CO_2 equivalent when both emission prevention and fossil CO_2 offsets are taken into account. This major reduction in CO2 (equivalent) emissions is also cost-effective. In the analysis for FETC (IEM, 1999), over a range of representative landfill conditions, greenhouse gas abatement was estimated as attainable at a cost of \$1-5/ton CO_2 equivalent which represents extremely low (by more than tenfold) cost compared to most other options presented in the recent EIA Report (USDOE Energy Information Agency. 1998)

c. Landfill life extension and/or reduced landfill use. The more rapid conversion of greater quantities of solid waste to gas reduces the volume of the waste. Settlement in the Yolo test cell is already over 18% in three years. Volume reduction translates into either landfill life extension and/or less landfill use. Thus bioreactor landfills are able to accept more waste over their working lifetime. Alternatively, fewer landfills are needed to accommodate the same inflows of waste from a given population

d. Leachate-associated benefits: Bioreactors promise more rapid leachate stabilization in terms of pollutant load, reduced leachate environmental impact, and elimination of need for most discharges to treatment facilities. The bioreactor processes, both anaerobic and aerobic, have been shown in studies at many scales to reduce the content of many leachate pollutants. These include organic acids and other soluble organic pollutants. Since a bioreactor operation brings pH to near-neutral conditions, metals of concern are largely precipitated and sequestered/ immobilized in waste. Thus free liquid concentrations and mobility of metals of concern are reduced compared to "conventional" landfill practice where more contaminated lower-pH leachate is often observed to be generated slowly for years. For example, in the Yolo test cell demonstration leachate reached near-neutral (pH 7) conditions within four months after liquid additions and recirculation commenced.

Although not a direct environmental benefit, a need for offsite leachate treatment should be avoidable altogether as long as waste landfilling continues concurrently with bioreactor operation. The additional leachate that would have to be treated at a wastewater treatment facility expansion could be avoided. Because bioreactors almost invariably require extra liquid for optimum performance, and leachate and condensate reintroduction are permissible (40 CFR 258.28), continuing operation of a landfill as a bioreactor allows generated leachate and condensate to be reintroduced so long as new dry waste continues to flow into the landfill. Additionally, calculations indicate that operation of even a small fraction of the landfill aerobically can consume leachate so long as generated, because of the high capacity of the aerobic reactions to evaporate liquid.

e. **Lessened long-term risk and need for monitoring**. The bioreactor approaches (anaerobic and aerobic) offer potential substantial reductions in postclosure care needs and costs. With present conventional practice, it is highly likely that gas management will be required for at least a mandated 30-year post-closure period. This entails all of the associated expense of continuing monitoring and gas well adjustment. Higher pollutant strength leachate must continue to be managed. A number of other management needs occur as waste continues to decompose, including dealing with subsidence, gas collection line breakage caused by subsidence, and the like.

f. **Landfill Gas Energy Project Potential**. Yolo County is considering several other alternatives for energy projects such as: (1) Self-wheeling of generated power, (2) Using increased generation at the landfill for sale to the grid (2MWe are being generated but the permit would allow up to 12 MWe), (3) Local boiler use of gas (4) Sale of power to the adjacent City of Davis Wastewater treatment facility, and (5) Sale of landfill gas to greenhouse farmer adjacent to the landfill. More predictable gas generation rate and higher collection efficiency will increase the economics of installing such projects and therefore would increase the number of projects that will be developed which would reduce the fugitive emissions from such sites.

g. **Landfill Mining Potential**: Although landfill mining is not listed in Table 6, the removal and re-use of waste for beneficial purposes, such as compost for alternative daily cover used on site in other landfill modules is a distinct possibility that County will be investigating in this project. If landfill mining were carried out, it would occur when sufficient stabilization has been achieved. For the anaerobic cell this could be beyond the expected 5-year term of the XL agreement. However, landfill mining or other beneficial use of the waste could also qualify for credit as composting. County has discussed this with the state regulators and agencies and will be conducting a mining pilot project to mine waste from the older section of the landfill. Feasibility of this operation will be determined to estimate the cost for possibly mining the aerobic cell within the 5 year period Project XL agreement period. If funds become available the County will explore mining the aerobic bioreactor to quantify the level of biodegradation and the amount decomposed matter that would be reclaimed from the landfill.

Table 6- Superior Environmental Performance

		Conventional Landfill (Yolo without XL)	Proposed Bioreactor Project (with XL)	
			Anaerobic bioreactor	Aerobic bioreactor
A	Expedited methane generation and recovery to control fugitive emission such as "greenhouse" methane and VOC's.	Fugitive gases due to emissions before gas collection system is in operation. Recovery of 55-80% of total gas generated because of slow gas generation over very long term (25-70 years). Less than 100% collection efficiency after installation of gas collection system.	Higher gas recovery efficiency than conventional gas collection system. Capture begins early in filling phase. Efficient recovery from permeable layers ongoing through entire gas generation cycle of 5-10 years. High generation rate over short period (5 to 10 years) allows near-maximum recovery	N/A- (little or no methane expected)
B	Methane generation/recovery	Recovery Ca. 55-80% total generated. Slow generation over very long term (25-70 years)	High generation rate over short period (5 to 10 years) allows near-maximum recovery	N/A- (little or no methane expected)
C	Life extension for 20 year landfill	0 years gained	For a 20-year "conventional" design, ca. 5 years additional life obtained	Over 7 years life extension expected.
D	Future Leachate Contamination Risks	Medium to high (organics and metals) over long term	Lower organics and lower metals for shorter term	Lower organics and lower metals for shorter term.

3. How We Will Measure the Superior Environmental Performance of our Proposal

Superior Environmental Performance will be measured using the baseline (Tier 1, without Project XL) against the actual results of the project (Tier 2, proposed Project XL). To determine specific bioreactor performance attributes of Table 6, monitoring plans are listed in Table 3 and are discussed below:

a. **Maximizing landfill gas control and minimizing fugitive methane /VOC emisssions**. Tests will be conducted to compare emission performance of the anaerobic and aerobic bioreactors to the conventional landfilling. An integrated combustible gas surface scan of the test cell versus the surrounding landfill, using the surrounding landfill as a control. NSPS emission guideline method (section 60.755 (c) 3) will be used to measure surface emission. The level of additional emissions testing will depend on future funds that will become available through grants from different state and federal agencies such as EPA, etc.

b. **Expedited methane generation/recovery**. This can be seen clearly from the comparison of the generated and recovered methane from the anaerobic bioreactor with the generated and recovered methane from the surrounding landfill.

c. **Life extension for a 20-year landfill**. This will be based on annual topographical surveys. Total volume loss occurring within this time interval will be calculated.

d. **Leachate contamination risk**. One measurement of this, comparison of leachate from the bioreactor and surrounding areas, is straightforward. However there could also be estimation of future risk from "entombed" waste. This could be inferred using generated gas data to indicate what fraction of waste remains undecomposed in the surrounding landfill vs. the bioreactor (i. e. greater normalized gas generation means more complete decomposition and less future risk).

e. **Landfill gas energy project potential.** An indicator of this will be the amount of gas generated from both bioreactor and conventionally filled waste at comparable intervals. Reduction in time of gas generation in the anaerobic bioreactor and increase in the volume of gas generated will be compared to the existing conventional landfill operation.

B. Flexibility and Other Benefits

As noted, project results (to date) from smaller-scale demonstration projects are very encouraging and have demonstrated a tenfold increase in landfill gas generation, increased landfill settlement, improved leachate chemistry, and highly cost-effective abatement of greenhouse gases. Economic analysis of the project shows that implementing bioreactor landfilling operations can have significant cost savings and environmental benefits for the Yolo County Central Landfill.

C. Stakeholder Involvement and Support

Stakeholder involvement and support for this concept has already been demonstrated by previous federal, state, and local support of this bioreactor concept. For example, in 1994, the Yolo County Planning and Public Works Department, initiated a bioreactor landfill demonstration project to evaluate the Bioreactor Landfill concept for its Central Landfill near Davis, California. The construction phase of the project was funded by Yolo and Sacramento Counties ($125,000 each), the California Energy Commission ($250,000), and the California Integrated Waste Management Board ($63,000). More recent grant funding for the monitoring phase of the project has been received from the U. S. Department of Energy through the Urban Consortium Energy Task Force ($110,000), and the Western Regional Biomass Energy Program ($50,000). Greenhouse gas and emission abatement cost-effectiveness studies have recently been completed with $48,000 in support from the Federal Energy Technology Center/National Energy Technology Laboratory (hereafter, NETL). Further support, $462,000 recently committed by NETL, is enabling operation of the test cells for approximately 2 more years as well as helping prepare for larger module operation.

On January 26, 2000 the California Integrated Waste Management Board committed Yolo County $400,000 for the construction and testing of the full-scale bioreactor demonstration project.

Concerning local support for this XL project, Yolo County has held several public meetings for the full-scale demonstration project. These meeting have been held during the regular Waste Advisory Committee meetings to locate potential members of the local stakeholder group. The County will convene periodic meetings of the stakeholder group to obtain comments on this proposal, as well as to brief the group on their progress during the duration of the XL agreement.

Yolo County has recognized the following as a list of potential stakeholders:

Direct Participants:

County of Yolo, Planning and Public Works Department
U. S. Environmental Protection Agency
Solid Waste Association of North America (SWANA)
Institute for Environmental Management (IEM)
California State Regional Water Quality Control Board, Central Valley Region 5
Yolo County Department of Environmental Health
Yolo-Solano Air Quality Management District

Commentors:

California Integrated Waste Management Board
California State Water Resources Control Board
California Air Resources Board
National Energy Technology Laboratory (NETL, previously FETC), U. S. Department of Energy
SWANA–California Gold Rush Chapter and Southern California Chapter
Yolo County Waste Advisory Committee
University of California at Davis
Geosynthetic Institute, Drexel University

Members of the General Public:

Yolo County Citizens
Natural Resources Commission
Sacramento County Public Works Department, Solid Waste Management Division
California Energy Commission

D. Innovation and Pollution Prevention

Yolo County intends, as part of this project, to continue our ongoing pollution prevention efforts. Regardless of whether a particular component is directly regulated as part of an XL agreement, the County will continue our process of reviewing all pollution prevention opportunities and will report on our pollution prevention progress.

E. Transferability

Yolo County believes that with the approval of this proposed bioreactor landfilling concept by Federal EPA and the state, many other public and private landfill owners and operators should be able to implement this type of technology. The technology is expected to yield substantial economic and environmental benefits for-nearly all regions of the U. S., and as noted, worldwide. Results from Yolo County's Bioreactor Landfill pilot project have already been shared among many other jurisdictions as well as the private sector throughout the U.S. and internationally. Results of the project have been published in technical and trade journals and magazines worldwide.

Following an evaluation of this XL Project by EPA, and the first progress report by the County, and assuming the overall success of the Project, the bioreactor landfill technology used in this project could be transferable to the large subset of landfills where conditions are favorable for actively managing the decomposition process and where groundwater protection and gas control are ensured. Based on early inquiries, application is likely outside as well as within the US.

F. Feasibility

The project sponsor, co-sponsors, and regulatory agencies as designated in the Final Project Agreement, agree to support the project, subject to any review procedures necessary to implement the legal mechanism for this project. Further, each XL participant has the financial capability, personnel and senior management commitment necessary to implement the elements of this Bioreactor Landfill XL Project.

G. Evaluation, Monitoring, and Accountability

The parties intend to implement as enforceable commitments, federal and state regulatory flexibility, monitoring, record-keeping, and reporting provisions of this FPA through a site-specific rulemaking to implement this project. The XL agreement will contain both enforceable and aspirational requirements and will establish certain limits and goals for Yolo County's performance. The County will ensure compliance with legal requirements and ensure implementation of processes seeking to meet aspirational goals. The project sponsor will establish a record keeping system to ensure compliance, as well as accurate reporting of environmental performance. While the nature and extent of such reporting will be subject to negotiation, Yolo County will make any such reports available publicly and will specifically discuss our performance with the local stakeholder group. The monitoring parameters, as discussed in Table 2 and 3, will be made available for EPA and stakeholders. Semi-annually and annually, Yolo County's project data will be summarized and posted on the EPA's XL Project web page.

H. Shifting of Risk Burden

No shifting of the risk burden will occur.

IV. Description of the Requested Flexibility and Implementing Mechanisms

A. Requested Flexibility

This section is primarily intended to describe federal flexibility needed for this XL project. It does also discuss State and local flexibility believed to be necessary to authorize this project. To the extent such action is necessary and appropriate, it will be provided as part of this project and subject to public notice and comment.

In general, Yolo County proposes to be able to undertake a proposed bioreactor landfill project that falls within the limitations established in the XL agreement. Yolo County is requesting specific flexibility under the current state and/or federal regulations requirements for liquid addition as described below.

Liquids Addition:

Yolo County is requesting that U.S. EPA grant site-specific regulatory flexibility from the prohibition in 40 CFR 258.28 Liquid Restrictions, which may preclude addition of useful bulk or non-containerized liquid amendments. The County is proposing to supplement the liquid addition with ground water, but would like to obtain the flexibility to possibly utilize other liquids such as gray waters from waste water treatment plant, septic waste, gray water, and food-processing wastes that is currently land applied. Liquid wastes such as these that normally have no beneficial use, may instead beneficially enhance the biodegradation of solid waste in a landfill for this project.

Yolo County also requests similar flexibility on liquid amendments from California and local regulatory entities. Several sections of the California Code of Regulations (CCR), Title 27, Environmental Protection, address the recirculation of liquids in lined municipal waste landfills. While the regulations do not specifically endorse bioreactors like the regulations in the State of Washington, regulatory flexibility is provided. This portion of the agreement will describe specific regulations in Title 27 regarding recirculation.

Title 27, Chapter 3, Subchapter 2, Article 2, Section 20200, Part (d)(3), *Management of liquids at Landfills and Waste Piles* states the following:

"Liquid or semi-solid waste (i. e. waste containing less than 50% solids, by weight), other than dewatered sewage or water treatment sludge as described in § 20220 (c), shall not be discharged to Class III landfills. Exceptions may be granted by the RWQCB if the discharger can demonstrate that such discharge will not exceed the moisture holding capacity of the waste either initially, or as the result of waste management operations, compaction, or settlement, so long as such discharge is not otherwise prohibited by applicable state or federal requirements".

The above regulation specifically allows the Regional Water Quality Control Board, Central Valley Region (RWQCB) the ability to grant an exception regarding the discharge of liquids into a Class III landfill providing the moisture holding capacity is not exceeded. The previous demonstration project at the Yolo County Central Landfill provided a working demonstration as to the feasibility of the proposed bioreactor project. Through monitoring, instrumentation, and testing, it was demonstrated that liquid could be added in such a way that the holding capacity of the refuse is not exceeded. The same equipment and procedures will be utilized for the Module D bioreactor. Specific sections of this agreement present plan details regarding the method of liquid recirculation.

It should be noted that the preceding Part in the regulations (Section 20200, Part (d)(2) addresses the discharge of waste containing free liquids and does not apply to this application. The County is not proposing to discharge wastes containing free liquids, but is instead proposing to add liquids or semi-solid waste to the refuse already in-place. While the regulations state that wastes containing free liquids must be discharged to a Class II waste pile, the addition of liquids to existing waste in a Class III landfill is allowed by the regulations if an exception is granted by the RWQCB.

Title 27, Chapter 3, Subchapter 2, Article 4, Section 20340, Part (g)(1,2,3), *Leachate Collection and Removal Systems* states the following:

"Leachate Handling – Except as otherwise provided under SWRCB Resolution No. 93-62 (for MSW landfills subject to 40CFR258.28), collected leachate shall be returned to the Unit(s) from which it came or discharged in another manner approved by the RWQCB. Collected leachate can be discharged to a different Unit only if:

1. *the receiving Unit has an LCRS, contains wastes which are similar in classification and characteristics to those in the Unit(s) from which leachate was extracted, and has at least the same classification (under Article 3 of this subchapter) as the Unit(s) from which leachate was extracted;*
2. *the discharge to a different Unit is approved by the RWQCB;*
3. *the discharge of leachate to a different Unit shall not exceed the moisture-holding capacity of the receiving unit, and shall comply with § 20200 (d)."*

The above section of Title 27 specifically allows the RWQCB to approve the discharge of leachate from other Units within a landfill to a receiving Unit as long as the wastes have similar classification and characteristics, the receiving Unit has a Leachate Collection and Removal System (LCRS), and the moisture-holding capacity of the refuse is not exceeded. These conditions are satisfied in that the wastes are similar throughout the landfill and Module D has a LCRS. Based on satisfying all of the conditions listed in the above regulatory requirement, the County is seeking approval from the RWQCB to discharge leachate generated from other Units within the Yolo County Central Landfill into Module D.

Title 27, Chapter 3, Subchapter 2, Article 5, Section 20937, Part (b)(4), *CIWMB – Control* states the following:

"A gas control system shall be designed to: Provide for the collection and treatment and/or disposal of landfill gas condensate produced at the surface. Condensate generated from gas control systems shall not be recirculated into the landfill unless analysis of the condensate demonstrates to the satisfaction of the EA, that it is acceptable to allow recirculation into

landfills which have a liner and an operational leachate collection system and the RWQCB approves such discharge pursuant to § 20200 (d).”

Based on the design and operation of the Module D bioreactor, the LCRS and liner system are in place to allow for the recirculation of gas condensate. The County has submitted the analysis of constituents within the gas condensate in the site monitoring reports. Based on these factors, the County is seeking approval from the RWQCB to recirculate the condensate.

In reviewing the regulations regarding the recirculation of leachate and gas condensate, it appears that the County has satisfied all criteria enabling the RWQCB to grant approval for leachate/condensate recirculation in Module D. However, as previously discussed, the refuse deposited at the Yolo County Central Landfill is relatively dry. In order to have proper operation of a landfill bioreactor, the waste must attain its moisture holding capacity. This moisture level can not be reached with the addition of leachate and condensate alone but can be reached with other liquid supplements. Such flexibility in liquids additions is justified based on composting performance, available controls, and multiple environmental safeguards that have already been demonstrated in the smaller-scale 9000-ton test program at the Yolo County Central Landfill.

B. Legally Implementing Mechanisms

To implement this Project, the parties intend to take the following steps:

1. EPA expects to propose for public comment and promulgate a site-specific rule amending 40 CFR 258.28 for Yolo county’s facility. This site-specific rule will describe the project requirements and any other aspects of the rulemaking. It is expected that the site-specific rule will provide for Withdrawal or Termination and a Post-Project Compliance Period consistent with Section XI, and will address the Transfer procedures included in Section IX. The standards and reporting requirements set forth in Section II (and any attachments to this FPA) will be implemented in this site-specific rulemaking.

2. The State under its relevant authority expects to promulgate the appropriate rule changes, permit modifications, etc. to implement this FPA needed by Yolo County for this project.

3. Except as provided in any rule(s), compliance order(s), permit provisions or other implementing mechanisms that may be adopted to implement the Project, the parties do not intend that this FPA will modify or otherwise alter the applicability of existing or future laws or regulations to Yolo county’s facility.

4. By signing this FPA, EPA, Yolo county, the state of California and its local authorities acknowledge and agree that they have the respective authorities and discretion to enter into this FPA and to implement the provisions of this project, to the extent appropriate.

V. Discussion of Intentions and Commitments for Implementing the Project

A. Yolo County’s Intentions and Commitments

Yolo County would like to operate its next 20-acre landfill module near Davis, California as a controlled bioreactor landfill to attain a number of superior environmental and cost savings benefits. The county is committed to working with federal, state, and local governments to demonstrate, with regulatory flexibility, how a bioreactor landfill can attain more desirable environmental results than a conventional landfill.

B. EPA's, the state of California's Intentions and Commitments

EPA intends to propose and issue (subject to applicable procedures and review of public comments) a site-specific rule, amending 40 CFR Part 258.28, that applies specifically to the Yolo county's solid waste landfill site in Davis. The site-specific rule will also provide for withdrawal or termination and a post-Project compliance period consistent with Section XI of this Agreement, and will address the transfer procedures included in Section IX. The standards and reporting requirements set forth in Section V.E. will be implemented in the site-specific rule.

C. Project XL Performance Targets

See Table 6, Superior Environmental Performance.

D. Proposed Schedule and Milestones

This project will be developed and implemented over a time period necessary to complete its desired major objectives, beginning from the date that the final legal mechanism becomes effective, unless it is terminated earlier or extended by agreement of all Project Signatories.
An expected timeline is shown in below, Table 7.

Table 7- Project XL Delivery Schedule

Project Task	Delivery Date
• RWQCB approved the revised Waste Discharge Requirement Permit	June 15, 2000
• Final draft FPA circulated to stakeholders for comments	June 22, 2000
• Comments received for final FPA • Begin instrumentation installation and waste filling in bioreactor	July 3, 2000
• Finalize FPA and distribute for signature	July 21, 2000
• All parties sign FPA document	July 31, 2000
• Federal Register for Yolo County XL Project permit revision begins	August 30, 2000
• First lift of waste in anaerobic bioreactor finished and begin waste placed in aerobic bioreactor	November 30, 2000
• Federal approval obtained for liquid addition	November 30, 2000
• Begin second lift of waste placement in anaerobic bioreactor • Monitor cell temperature and moisture • Place intermediate soil cover and start gas monitoring and collection	January 1, 2001
• Complete the following for the aerobic bioreactor: waste placement, instrumentation, data acquisition and control system, leachate injection system, air injection system, gas and leachate monitoring, and cover system	March 1, 2001
• Start liquid addition, air injection, and monitoring in aerobic bioreactor	April 1, 2001
• Complete placement of last lift of waste in anaerobic cell • Install gas collection and leachate injection in each lift of waste	November 1, 2001

• Monitor cell for start of landfill gas generation and operate gas collection system as soon as landfill gas is produced • Complete instrumentation, data acquisition and control system, leachate injection system, gas collection and monitoring system, and cover system	
• Begin liquid injection and continue gas collection in anaerobic bioreactor	December 1, 2001
• Data collection and reporting will continue	July 2000-July 2004

E. Project Tracking, Reporting and Evaluation

The project tracking, reporting and evaluation will be accomplished for project sponsors including EPA in accordance with, among other things, EPA requests and the reporting requirements set by the (to-be-determined) funding agencies. The topics tracked, reported and evaluated have been referred to earlier in the section on "how we would measure improved environmental performance" (see Table 3).

F. Periodic Review by the Parties to the Agreement

The Parties will hold periodic performance review conferences to assess their progress in implementing this Project. Unless they agree otherwise, the date for those conferences will be concurrent with annual Stakeholder Meetings. No later than thirty (30) days following a periodic performance review conference, Yolo County will provide a summary of the minutes of that conference to all Direct Stakeholders. Any additional comments of participating Stakeholders will be reported to EPA.

G. Duration

This Agreement will remain in effect for 5 years after signing, unless the Project ends at an earlier date, as provided under Section VIII (Amendments or Modifications), Section XI (Withdrawal or Termination), or Section IX (Transfer of Project Benefits and Responsibilities). The implementing mechanism(s) will contain "sunset" provisions ending authorization for this Project [X] years after the effective date of the [*implementing mechanism(s)*]. They will also address withdrawal or termination conditions and procedures (as described in Section XI). This Project will not extend past the agreed upon date, and Yolo county will comply with all applicable requirements following this date (as described in Section XII), unless all parties agree to an amendment to the Project term (as provided in Section VIII)."

VI. Legal Basis for the Project

A. Authority to Enter Into the Agreement

By signing this Agreement, all signatories acknowledge and agree that they have the respective authorities, discretion, and resources to enter into this Agreement and to implement all applicable provisions of this Project, as described in this Agreement.

B. Legal Effect of the Agreement

This Agreement states the intentions of the Parties with respect to Yolo county's XL Project. The Parties have stated their intentions seriously and in good faith, and expect to carry out their stated intentions. This Agreement in itself does not create or modify legal rights or obligations, is not a contract or a regulatory action, such as a permit or a rule, and is not legally binding or enforceable against any Party. Rather, it expresses the plans and intentions of the Parties without making those plans and intentions binding requirements. This applies to the provisions of this Agreement that concern procedural as well as substantive matters. Thus, for example, the Agreement establishes procedures that the parties intend to follow with respect to dispute resolution and termination (see Sections X and XI). However, while the parties fully intend to adhere to these procedures, they are not legally obligated to do so.

EPA intends to propose for public comment a site-specific rule making needed to implement this Project. Any rules, permit modifications or legal mechanisms that implement this Project will be effective and enforceable as provided under applicable law.

This Agreement is not a "final agency action" by EPA, because it does not create or modify legal rights or obligations and is not legally enforceable. This Agreement itself is not subject to judicial review or enforcement. Nothing any Party does or does not do that deviates from a provision of this Agreement, or that is alleged to deviate from a provision of this Agreement, can serve as the sole basis for any claim for damages, compensation or other relief against any Party.

C. Other Laws or Regulations That May Apply

Except as provided in the legal implementing mechanisms for this Project, the parties do not intend that this Final Project Agreement will modify any other existing or future laws or regulations.

D. Retention of Rights to Other Legal Remedies

Except as expressly provided in the legal implementing mechanisms described in Section IV, nothing in this Agreement affects or limits Yolo county's, EPA's, the State's, or any other signatory's legal rights. These rights include legal, equitable, civil, criminal or administrative claims or other relief regarding the enforcement of present or future applicable federal and state laws, rules, regulations or permits with respect to the facility.

Although Yolo county does not intend to challenge agency actions implementing the Project (including any rule amendments or adoptions, permit actions, or other action) that are consistent with this Agreement, Yolo county reserves any right it may have to appeal or otherwise challenge any EPA, state of California, or local agency action to implement the Project. With regard to the legal implementing mechanisms, nothing in this Agreement is intended to limit Yolo county's right of to administrative or judicial appeal or review of those legal mechanisms, in accordance with the applicable procedures for such review.

VII. Unavoidable Delay During Project Implementation

"Unavoidable delay" (for purposes of this Agreement) means any event beyond the control of any Party that causes delays or prevents the implementation of the Project described in this Agreement, despite the Parties' best efforts to put their intentions into effect. An unavoidable delay can be caused by, for example, a fire or acts of war.

When any event occurs that may delay or prevent the implementation of this Project, whether or not it is avoidable, the Party to this Agreement who knows about it will immediately provide notice to the remaining Parties. Within ten (10) days after that initial notice, the Party should confirm the event in writing . The confirming notice should include: 1) the reason for the delay; 2) the anticipated duration; 3) all actions taken to prevent or minimize the delay; and 4) why the delay was considered unavoidable, accompanied by appropriate documentation.

If the Parties, agree that the delay is unavoidable, relevant parts of the Project schedule (see Section V.) will be extended to cover the time period lost due to the delay. If they agree, they will also document their agreement in a written amendment to this Agreement. If the Parties don't agree, then they will follow the provisions for Dispute Resolution outlined below.

This section applies only to provisions of this Agreement that are not implemented by legal implementing mechanisms. Legal mechanisms, such as permit provisions or rules, will be subject to modification or enforcement as provided under applicable law.

VIII. Amendments or Modifications to the Agreement

This Project is an experiment designed to test new approaches to environmental protection and there is a degree of uncertainty regarding the environmental benefits and costs associated with activities to be undertaken in this Project. Therefore, it may be appropriate to amend this Agreement at some point during its duration.

This Final Project Agreement may be amended by mutual agreement of all parties at any time during the duration of the Project. The parties recognize that amendments to this Agreement may also necessitate modification of legal implementation mechanisms or may require development of new implementation mechanisms. If the Agreement is amended, EPA and Yolo county expect to work together with other regulatory bodies and stakeholders to identify and pursue any necessary modifications or additions to the implementation mechanisms in accordance with applicable procedures (including public notice and comment). If the parties agree to make a substantial amendment to this Agreement, the general public will receive notice of the amendment and be given an opportunity to participate in the process, as appropriate.

The parties to this FPA agree to evaluate the appropriateness of a modification or "reopener" to the FPA according to the provisions set forth below.

1. During the minimum project term, Yolo county may seek to reopen and modify this FPA in order to address matters covered in the FPA, including failure of the project to achieve superior environmental results, or the enactment or promulgation of any environmental, health, or safety law or regulation after execution of this FPA which renders the project legally, technically, or economically impractical. To do so, Yolo County will submit a proposal for a reopener under this section to EPA, California, and all applicable local agencies for their consideration. EPA, California, and all applicable local agencies will review and evaluate the appropriateness or such proposal submitted by Yolo County. EPA, California, and all applicable local agencies may also elect to initiate withdrawal or termination under Section VII of this FPA, which shall supersede application to this section.

2. In determining whether to reopen and modify the FPA in accordance with any reopener proposal(s) submitted by Yolo county under this section, EPA, California, and all applicable

local agencies will base their decision upon the following: (a) whether the proposal meets Project XL criteria in effect at the time of the proposal, (b) the environmental benefits expected to be achieved by the proposal, (c) the level of emissions or effluent included in the proposal, (d) other environmental benefits achieved as a result of other activities under the proposal, and (e) and adverse environmental impacts expected to occur as a result of the proposal.

3. All parties to the FPA will meet within ninety (90) days following submission of any reopener proposal by Yolo county to EPA, California, and all applicable local agencies (or within such shorter or longer period as the parties may agree) to discuss the Agencies' evaluation of the reopener proposal. If, after appropriate stakeholder involvement, the Agencies support reopening of this FPA to incorporate the proposal, the parties (subject to any required public comment) will take steps necessary to amend the FPA. Concurrent with amendment of this FPA, EPA, California, and all applicable local agencies will take steps consistent with this Section IV to implement the proposal.

4. It is noted at this point that the intent by Yolo County, upon successful results, to operate the ensuing landfill module as a bioreactor could be a "reopener". If this is agreeable to all parties to the present agreement, it would be most convenient to extend the agreement to cover subsequent module or modules at the Yolo County Central Landfill, with a minimum of stakeholder work.

IX. Transfer of Project Benefits and Responsibilities to a New Owner

The parties expect that the implementing mechanisms will allow for a transfer of Yolo county's benefits and responsibilities under the Project to any future owner or operator upon request of Yolo county and the new owner or operator, provided that the following conditions are met:

A. Yolo County will provide written notice of any such proposed transfer to the EPA, the state of California, and all applicable local agencies at least ninety (90) days before the effective date of the transfer. The notice is expected to include identification of the proposed new owner or operator, a description of its financial and technical capability to assume the obligations associated with the Project, and a statement of the new owner or operator's intention to take over the responsibilities in the XL Project of the existing owner or operator.

B. Within forty-five (45) days of receipt of the written notice, the parties expect that EPA, the state of California, and all applicable local agencies in consultation with all stakeholders, will determine whether: 1) the new owner or operator has demonstrated adequate capability to meet EPA's requirements for carrying out the XL Project; 2) is willing to take over the responsibilities in the XL Project of the existing owner or operator; and 3) is otherwise an appropriate Project XL partner. Other relevant factors, including the new owner or operator's record of compliance with Federal, State and local environmental requirements, may be considered as well. It is expected that the implementation mechanism will provide that, so long as the demonstration has been made to the satisfaction and unreviewable discretion of EPA, the state of California, and all applicable local agencies and upon consideration of other relevant factors, the FPA will be modified to allow the proposed transferee to assume the rights and obligations of Yolo county. In the event that the transfer is disapproved by any agency, withdrawal or termination may be initiated, as provided in Section XI.

It will be necessary to modify the Agreement to reflect the new owner and it may also be necessary for EPA, the state of California, and all applicable local agencies to amend appropriate rules, permits, or other implementing mechanisms (subject to applicable public notice and comment) to transfer the legal rights and obligations of Yolo county under this Project to the proposed new owner or operator. The rights and obligations of this project remain with Yolo County prior to their final, legal transfer to the proposed transferee.

X. Process for Resolving Disputes

Any dispute which arises under or with respect to this Agreement will be subject to informal negotiations between the parties to the Agreement. The period of informal negotiations will not exceed twenty (20) calendar days from the time the dispute is first documented, unless that period is extended by a written agreement of the parties to the dispute. The dispute will be considered documented when one party sends a written Notice of Dispute to the other parties.

If the parties cannot resolve a dispute through informal negotiations, the parties may invoke non-binding mediation by describing the dispute with a proposal for resolution in a letter to the Regional Administrator for EPA Region 9, with a copy to all parties. The Regional Administrator will serve as the non-binding mediator and may request an informal mediation meeting to attempt to resolve the dispute. He or she will then issue a written opinion that will be non-binding and does not constitute a final EPA action. If this effort is not successful, the parties still have the option to terminate or withdraw from the Agreement, as set forth in Section XI below.

XI. Withdrawal From or Termination of the Agreement

A. Expectations

Although this Agreement is not legally binding and any party may withdraw from the Agreement at any time, it is the desire of the parties that it should remain in effect through the expected duration of 5 years, and be implemented as fully as possible unless one of the conditions below occurs:

1. Failure by any party to (a) comply with the provisions of the enforceable implementing mechanisms for this Project, or (b) act in accordance with the provisions of this Agreement. The assessment of the failure will take its nature and duration into account.

2. Failure of any party to disclose material facts during development of the Agreement.

3. Failure of the Project to provide superior environmental performance consistent with the provisions of this Agreement.

4. Enactment or promulgation of any environmental, health or safety law or regulation after execution of the Agreement, which renders the Project legally, technically or economically impracticable.

5. Decision by an agency to reject the transfer of the Project to a new owner or operator of the facility.

In addition, EPA, the state of California, and all applicable local agencies do not intend to withdraw from the Agreement if Yolo county does not act in accordance with this Agreement or its implementation mechanisms, unless the actions constitute a substantial failure to act consistently with intentions expressed in this Agreement and its implementing mechanisms. The decision to withdraw will, of course, take the failure's nature and duration into account.

Yolo County will be given notice and a reasonable opportunity to remedy any "substantial failure" before EPA's withdrawal. If there is a disagreement between the parties over whether a "substantial failure" exists, the parties will use the dispute resolution mechanism identified in Section X of this Agreement. EPA, the State of California, and all applicable local agencies retain their discretion to use existing enforcement authorities, including withdrawal or termination of this Project, as appropriate. Yolo County retains any existing rights or abilities to defend itself against any enforcement actions, in accordance with applicable procedures.

B. Procedures

The parties agree that the following procedures will be used to withdraw from or terminate the Project before expiration of the Project term. They also agree that the implementing mechanism(s) will provide for withdrawal or termination consistent with these procedures.

1. Any party that wants to terminate or withdraw from the Project is expected to provide written notice to the other parties at least sixty (60) days before the withdrawal or termination.

2. If requested by any party during the sixty (60) day period noted above, the dispute resolution proceedings described in this Agreement may be initiated to resolve any dispute relating to the intended withdrawal or termination. If, following any dispute resolution or informal discussion, a party still desires to withdraw or terminate, that party will provide written notice of final withdrawal or termination to the other parties.

If any agency withdraws or terminates its participation in the Agreement, the remaining agencies will consult with Yolo county to determine whether the Agreement should be continued in a modified form, consistent with applicable federal or State law, or whether it should be terminated.

3.The procedures described in this Section apply only to the decision to withdraw or terminate participation in this Agreement. Procedures to be used in modifying or rescinding any legal implementing mechanisms will be governed by the terms of those legal mechanisms and applicable law. It may be necessary to invoke the implementing mechanism's provisions that end authorization for the Project (called "sunset provisions") in the event of withdrawal or termination.

XII. Compliance After the Project is Over

The parties intend that there be an orderly return to compliance upon completion, withdrawal from, or termination of the Project, as follows:

A. Orderly Return to Compliance with Otherwise Applicable Regulations, if the Project Term is Completed

If, after an evaluation, the Project is terminated because the term has ended, Yolo county will return to compliance with all applicable requirements by the end of the Project term, unless the

Project is amended or modified in accordance with Section VIII of this Agreement (Amendments or Modifications). Yolo County is expected to anticipate and plan for all activities to return to compliance sufficiently in advance of the end of the Project term. Yolo county may request a meeting with EPA, the state of California, and all applicable local agencies to discuss the timing and nature of any actions that they will be required to take. The parties should meet within thirty days of receipt of Yolo county's written request for such a discussion. At and following such a meeting, the parties should discuss in reasonable, good faith, which of the requirements deferred under this Project will apply after termination of the Project."

B. Orderly Return to Compliance with Otherwise Applicable Regulations in the Event of Early Withdrawal or Termination

In the event of a withdrawal or termination not based on the end of the Project term and where Yolo county has made efforts in good faith, the parties to the Agreement will determine an interim compliance period to provide sufficient time for Yolo county to return to compliance with any regulations deferred under the Project. The interim compliance period will extend from the date on which EPA, the state of California, and all applicable local agencies provides written notice of final withdrawal or termination of the Project, in accordance with Section XI of this Project Agreement. By the end of the interim compliance period, Yolo county will comply with the applicable deferred standards set forth in 40 CFR Part 258.28. During the interim compliance period, EPA, the state of California, and any applicable local agency may issue an order, permit, or other legally enforceable mechanism establishing a schedule for Yolo county to return to compliance with otherwise applicable regulations as soon as practicable. This schedule cannot extend beyond 6 months from the date of withdrawal or termination. Yolo county intends to be in compliance with all applicable Federal, State, and local requirements as soon as is practicable, as will be set forth in the new schedule.

III. Signatories and Effective Date

REFERENCES AND BIBLIOGRAPHY

1. Augenstein, D., R. Yazdani, K. Dahl and R. Moore. 1998 Yolo County Controlled Landfill Project. Proceedings, California Integrated Waste Management Board Symposium on Landfill Gas Assessment and Management, Ontario, CA. April

2. Augenstein, D., D. L. Wise, R. L. Wentworth and C. L. Cooney 1976 Fuel Gas Recovery from Controlled Landfilling of Municipal Wastes. Resource Recovery and Conservation 2 p 103-117

3. Johnson, W. and J. Baker. 1999 Operational Characteristics and Enhanced Bioreduction of Municipal Waste Landfill Mass by a Controlled Landfill Aerobic Process. Proceedings, 4th Annual Landfill Symposium, Solid Waste Association of North America (SWANA). SWANA, Silver Spring MD.

4. J. C. Bernreuter and Dr. R. I. Stessel. Review of Aerobic Biocell Research and Technology (Draft) Prepared for the Aerobic Process Subcommittee of the Solid Waste Association of North America, Bioreactor Committee, June 27, 1999.

5. Moore, R. K. Dahl and R. Yazdani. 1997 Hydraulic Characteristics of Solid Waste: Findings of the Yolo County Bioreactor Landfill Project. Thirteenth International Conference on Solid Waste Technology and Management. Philadelphia.

6. M. A. Othman and R. Bonaparte and B. A. Gross. 1997 Preliminary Results of Study of Composite Liner Field Performance. Proceedings, GRI-10 Conference on "Field Performance of Geosynthetics and Geosynthetic- Related Systems. R. M. Koerner., G. R. Koerner and Y. G. Hsuan, Eds. GII Publications Philadelphia, PA.

7. Reinhart, D. R. and T. G. Townsend. 1998 Landfill Bioreactor Design and Operation.

8. USDOE Energy Information Agency. 1998 "Impacts of the Kyoto Protocol on U. S. Energy Markets and Economic Activity," October

9. Walsh, J. W. G. Vogt, W. Held., R. Kinman, and J. Rickabaugh. 1983 Demonstration of Landfill Gas Enhancement Techniques in Landfill Simulators. Proceedings of 7th IGT International Symposium on Energy from Biomass and Wastes. IGT, Chicago

10. Yazdani, R., Moore, R. Dahl. K. and D. Augenstein 1998 Yolo County Controlled Landfill Bioreactor Project. Yolo County Public Works and I E M, Inc. Yolo County Public Works and I E M, Inc. report to the Urban Consortium Energy Foundation (UUCETF) and the Western Regional Biomass Energy Program, USDOE.

11. Yolo County Public Works and I E M, Inc. 1997 Methane Enhancement by Accelerated Anaerobic Composting at the Yolo County Central Landfill. Initial Test Cell Design, Engineering and Startup. Final Report to the California /Energy Commission, June 1997.

12. Chynoweth, D. F. J. Owens, D. O'Keefe, J. Earle and R. Legrand. 1992 Sequential Batch Anaerobic Composting of the Organic Fraction of Municipal Solid Waste. Report Prepared for the Southeastern Regional Biomass Energy Program.

13. Kayhanian, M. S. Hardy, G. Tchobanoglous, B. Jenkins, and D. Rich. 1994. Evaluation of a Two-Stage Anaerobic Composting Process for the Production of Energy. Report from Department of Civil and Environmental Engineering, University of California at Davis, to California Energy Commission. Contained in: Proceedings, Workshop on Anaerobic Composting Processes for the Production of Energy. Clifornia Integrated Waste Management Board, Sacramento. June 15, 1994

14. Stessel. R. I., and R. J. Murphy. 1992 A Lysimeter Study of the Aerobic Landfill. Waste Management and Research 10, 1992 pp. 485-503